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Special Issue Reprint

# Sustainable Cities and Regions

## Statistical Approaches

Edited by
Joanna A. Kamińska, Guido Sciavicco and Jan K. Kazak

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# Sustainable Cities and Regions – Statistical Approaches

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Editors

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Cover image courtesy of Jan K. Kazak

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# About the Editors

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Joanna A. Kamińska is Associate Professor at the Department of Applied Mathematics in Wrocław University of Environmental and Life Science (Poland) still looking for the area of application of statistical methods in environmental sciences. She holds a PhD in environmental engineering (2002), a professional degree in mechanical engineering (2007). She initially studied the heat balance of plants, mainly crops. Along with her engineering studies, her research interests focused on road safety, driving techniques and driver skills training (not only professional drivers). In the light of drivers' driving style, she prayed for traffic in the city with the analysis of travel times. She then turned her attention to pollution emitted by motor vehicles and began to study its impact on air quality in urban areas (since 2018). At the same time, she undertakes statistical analyses of the results of the thematically diverse issues carried out at the university. She is the author or coauthor of over 120 publications in scientific journals and conference publications.

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*Editorial*

# Sustainable Cities and Regions—Statistical Approaches

**Joanna A. Kamińska [1,*], Guido Sciavicco [2] and Jan K. Kazak [3]**

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Dynamic urbanisation leaves a significant mark on the broadly understood quality of life, regardless of the size of the city and the country or continent in which it is located. On one hand, economic progress favours the development of new technologies and the availability of many kinds of resources accessible almost without any limits to make life easier [1–5]. On the other hand, the development of urbanised areas, new transport networks, and higher demand for natural resources causes their depletion, pollution of different components of the environment, waste production, deforestation, landscape fragmentation, and biodiversity losses, leading finally to the deterioration of living conditions in the long term [6–11]. Some of these driving forces and pressures, as well as the responses of the natural environment, can be described by characterizing their regularities and patterns. Understanding the quantitative features of many components of socio-environmental systems makes it easier to undertake proper actions to mitigate undesirable phenomena. Therefore, various statistical and mathematical techniques (machine learning, regression, classification, spatial analysis, and others) can be widely used to solve crucial problems in the current development of cities and regions worldwide to face the challenge of sustainable development at different scales [12–17]. Mathematical modelling of socio-environmental dependencies allows the drawing of far-reaching conclusions supporting the decision-making process for a more sustainable future. Testing broadly understood statistical hypotheses leads to drawing conclusions about the significance of relationships.

Looking back, following mathematical rules has allowed humanity to achieve many watershed moments both in terms of architectonical objects as well as systems organizing many urban components which, at the time of completion, were considered impossible to implement. One such examples in architecture was Pantheon in Rome [18], which is presented on the cover of this book. When it comes to urban systems, advances in mathematics in Delos in ancient Greece have allowed hydraulic engineers to improve water distribution [19]. Other civilisations could also present their own examples confirming a strong relationship between mathematics and urban development. Similarly, in the current world, all solutions within smart cities and smart homes are possible to implement due to mathematical and statistical approaches. Mathematical algorithms are implemented in the controllers of almost all utility objects; being connected to the Internet, they create the Internet of Things [20]. Urban, rail, and air traffic control is supported or managed entirely by systems based on mathematics [21].

It is hard to imagine scientific research that does not use mathematics. Various statistical and mathematical techniques are widely used to solve crucial problems of the current development of cities and regions worldwide to face the challenge of sustainable development at different scales. In the present Special Issue entitled "Sustainable Cities and Regions—Statistical Approaches", some examples of the application of mathematics in four scientific areas are included. First is the socioeconomic issue, where articles deal

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with mediation analysis in the study of the impact of socioeconomic factors on health [22], indicators influenced on urban sustainability [23], convergence analysis of the sustainability of EU states' economies using cluster analysis [24], accessing economic independence using mutual information and kernel density information [25], and the verification of the impact of the location of residential properties in relation to poverty-stricken area and ecosystem services in streets [26]. This Issue also includes a spatial analysis example for an economic model which study's the spatiotemporal interaction between Kinjiangls county transformation over 10 years [27]. The second issue discussed is environmental elements modelling, covering a nonlinear model enabling the reconstruction of missing meteorological data [28], green and low-carbon rural development metanalyses with the use of graph analysis [29], and $PM_{2.5}$ and $PM_{10}$ prediction modelling with the use of a nonlinear autoregressive exogenous model [30]. The third topic is an issue of purifying the environment polluted by humans with the use of living organisms [31] and the analysis of the effectiveness of testing the level of its cleaning [32]. The fourth topic discussed is a real estate market seen through the prism vector autoregressive model to identify the interrelationships between the housing market based on Google Trends and housing process in Poland [33], and multiple linear regression for reading the residential real estate market based on intrinsic and extrinsic data [34].

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# Spatial and Statistical Analysis of Urban Poverty for Sustainable City Development

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**Abstract:** One of the main pillars of sustainable urban development at the local scale is to control the social aspect of urban equality of socio-economic systems. A number of studies confirm that poverty in urban space is accompanied by negative phenomena, such as high unemployment, social pathologies, increased crime rate, or the high level of the decapitalization of space, including the poor condition of housing and municipal infrastructure. However, there is a gap in defining the relation between urban poverty and city structure to control and preferably minimize social inequalities. The aim of the study was to empirically verify the impact of the location of residential properties in relation to poverty-stricken areas in the city. The research covered the housing market in one Polish city (Kalisz) in the years 2006–2018. By applying GIS technologies, we identified the location of each property in relation to poverty areas. The data was subjected to regression analysis, with the use of the hedonic approach based on exponential models. The analysis of data allowed us to conclude that location in a poorer area does affect the prices of new flats, which is not only a contribution to the development of science, but is also information that could be used by developers or property valuers to establish the prices of flats, as well as city managers to avoid pauperization of urban districts.

**Keywords:** spatial analysis; poverty areas; socio-economic inequalities; housing market; statistical analysis

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## 1. Introduction

Nowadays, more than half of the world's population lives in cities, and this rate is expected to rise to 60% in the next 10 years. Rapidly progressing urbanization processes have a huge impact on the natural environment, therefore, they are associated with the need for proper spatial planning, creating conditions for economic progress and social development.

Sustainable development of the cities is possible by taking into account the Sustainable Development Goals (SDG) [1], which include, among others, "Sustainable Cities and Communities" (Goal 11). From an urbanism point of view, it is important to ensure access for all to adequate, safe, and affordable housing and basic services in particular to different groups of persons. Currently, social inequalities are an increasingly serious problem in urbanization. The biggest urban challenges include overcrowding, low-quality infrastructure, housing scarcity, and poverty. Poverty prevention is another goal of sustainable development (No Poverty—Goal 1) that relates to conscious and sustainable urbanization. Overcoming challenges in a way that will allow cities to improve resource management and reduce pollution and poverty is influenced not only by government and local authorities, but also by enterprises and society.

Sustainable urban development supports the long-term prosperity of cities and their inhabitants. In some cities, the rapid expansion reflects unplanned urban sprawl, making the delivery of services costlier and inefficient. Urbanization reshapes cities and contributes to rising house prices, affordable housing shortages, and inflexible housing stock, which in turn threaten quality of life. The population continues to flow to cities, which means that, due to increased demand and rigid, limited supply in times of crises, housing prices are rising. This leads to a housing affordability crisis, which affects not only the poor, but also median income residents [2].

The possibility of improving the housing situation and counteracting social inequalities, including poverty, is largely dependent on the situation of the real estate market. Of course, there is no versatile solution to rising housing prices and the affordability of urban housing. While housing prices and affordability can be viewed from many different perspectives, the main factors to tackle this problem require a significant increase in housing supply and ensuring a better fit between the house and the resident.

Cities should focus on creating more housing, including a more diverse range of options so that the housing stock can better meet the needs of different household types and income levels. Particular attention should be paid to good density. By densifying cities in the right way, ensuring mixed use, green space, and good connectivity, we create vibrant, livable, and sustainable communities, while also reducing energy consumption and emissions and decreasing the infrastructure costs per resident, which is important from the economic, social, and environmental dimensions of the SDGs. Applying the principle of good density means, inter alia, planning space and investments in a sustainable manner, thus preventing ghettoization [3].

Local real estate markets play an important role in achieving the goals of sustainable urban development. All human activity takes place in a rare space that is considered as a rare good. Both limited supply and varied quality (attractiveness) of space in cities lead to differentiation of real estate prices. In order to shape the conditions of permanent and balanced spatial development, urban policy should monitor and influence the real estate market through regulations that favor economic rationality and at the same time protect the public interest.

Urban policy tools, such as e.g., revitalization programs, support for residents, and entrepreneurship, investment incentives, as a result, should lead to a sustainable level of real estate prices. In turn, the lack of control of factors negatively influencing real estate prices (such as concentration of poverty, environmental pollution, crime, noise, and traffic) may lead to the segmentation of space and the creation and aggravation of social inequalities.

One of the most urgent issues of the contemporary social policy of central and eastern European countries is the phenomenon of urban poverty, usually accompanied by the poor condition of housing resources, high unemployment, the occurrence of social pathologies, high crime rate, violence, and noise. With political changes in Poland, which started in the late 1980s, the process of progressive stratification of society began, accompanied by the growing diversification of the spatial scale of poverty. At the same time, researchers took more interest in studying the problem of poverty, which used to be neglected due to the lack of consent from socialist authorities [4]. Studies of poverty were conducted in different fields of science, with an emphasis put on various aspects of this notion. There are sociological, economic, psychological, and political concepts of poverty [5]. Much less attention has been paid to spatial issues in this regard.

The findings of spatial studies of the concentration of the poor and the distribution of poverty areas in cities showed that poor citizens mainly inhabited the central parts of American cities (inner cities), which were gradually becoming the subject of economic marginalization and spatial decapitalization. It was also observed that urban poverty had a class and racial character, and was combined with crime, youth's lack of social adaptation, drug addiction, illiteracy, family pathology, and the physical degradation of housing and municipal infrastructure. In turn, the rich, educated, and qualified population of high social and economic status resided in the outskirts of cities, transforming them into economically wealthy and relatively safe suburbs [6,7]. This type of dualization of urbanized areas is also clearly evident in contemporary cities, where sections of development and economic prosperity neighbor the areas of economic collapse. Therefore, it seems justified to pose a question about the influence of poverty on the urban real property market.

The analysis of the literature allows us to identify a number of factors determining housing prices, which are largely dependent on general location (in a broader context, with reference to a continent, state, city, or district) and the condition of the property's surroundings (e.g., the quality of space). Location is one of the key determinants of housing prices [8–12]. It can be perceived in a number of ways, e.g., as the distance from the city center, the vicinity of commercial and service centers, public space, greenery, accessibility, etc. [13–17]. Some authors see location as a three-level feature, consisting of the property's designation (the condition and/or the development potential, etc.), the character of its immediate surroundings and their influence on the property, the overall urban structure, and the interrelationships in the structure of the city's spatial development, be it those currently existing and those planned or likely to exist in the future [18]. Real estate properties are inseparably linked with a place, so they also differ in terms of micro-location. Thus, their prices are influenced by changes in the surroundings [19]. It is residential properties that are most strongly dependent on micro-location, while investment decisions in the commercial market often go beyond the local market [20]. Housing properties, especially in the countries of central and eastern Europe, where the historical conditions of their ownership structure are the explanation of the current low level of population mobility, are to a far higher degree subject to competition in different micro-locations of the local market [21]. It appears that researchers have not examined the impact of another determinant, i.e., the effect of the location in relation to poverty areas on the prices of flats. This is why the research problem in this article is the analysis of factors that affect housing prices, taking into consideration the issues of the location of difficult areas that have not been studied before. The aim of the research was to verify the impact of the location of urban properties in an area of poverty on their prices. In order to achieve this aim, we used a two-stage research procedure, in which we identified areas of poverty in one Polish city, after which we showed their role in determining prices in the housing market. We used three models of the socio-spatial structure in the city as theoretical concepts to identify areas of poverty: (1) the Burgess zone concentric model [22], (2) the Hoyt (sector) model [23], and (3) the multiple nuclei model by Harris and Ullmann [24]. The study was conducted in the housing market of a city of sub-regional character (Kalisz, Poland), and the analysis covered the years 2006–2018. The analysis of data allowed us to conclude whether location in an area of poverty has an impact on the prices of new flats, which is a valuable contribution to the development of science and reveals information that could be used by developers or property valuers to establish the prices of flats.

In the paper, we provided a review of the literature on the traditional and specific determinants of housing prices, after which we described the research procedure and data sources, and then discussed the obtained results and referred to the findings of other studies in this field.

## 2. Literature Review

### *2.1. Traditional Determinants of the Prices of Flats*

Urban properties are among the most frequently purchased ones, fulfilling the basic needs of human existence and at the same time being an investment. While the existing housing resources are impossible to move, new flats can be built in the place chosen by an investor—if it is available—and the decision on the location of new facilities is made after the analysis of various factors, including those referring to location.

Location refers to position in a specific place, which involves a number of factors. The influence of these factors on the prices of flats has been extensively examined in the literature. This influence may be analyzed from different perspectives, as the impact of (1) external factors from distant surroundings (macro-environment), (2) external factors from the close surroundings (micro-environment), and (3) internal factors (in the so-called ultra-environment) [25,26].

The most frequently analyzed factors in the literature are the macroeconomic ones. Factors in the macro-environment are important for the level of prices, rather than the prices of specific real properties. There is an increasing number of studies on the influence of economic, social, political, legal, and other processes in the urban area. The most commonly identified factors include:

- International economic situation—the global crisis has a negative impact on the situation in the real estate market [27,28].
- Investors' sentiment and the level of development of the national economy—there is a long-term relationship between the prices of flats and the gross domestic product per capita [29]; the prices of flats are indirectly (through an increase of demand) influenced by the wealth of the society [30] and the unemployment rate [31].
- Macroeconomic policy, especially in the conditions of the common market, which is the case of, for example, EU member states. The European Union influences, through a number of instruments (pricing and wage policy, interest and exchange rates, tax and customs policy), the fluctuations of the prices of flats in different countries. Research shows that the state's interference with the market significantly determines the balance of housing prices, but it appears that there are differences in the response to various types of policy [32], as well as spatial differences in the implications of policies pursued in the residential property markets [25,33]. The positive influence of the inflation level on the increase of housing prices is also observed [4,34].
- The state's housing policy—market limitations resulting from, among others, the housing policy or law regulations are difficult to observe, but they do have an impact on the housing market [35]; subsidies for the real estate market (government schemes) affect the dynamics of the prices of flats—residential property markets are not as volatile as other sectors of the economy, and the inertia of local real estate markets becomes particularly evident during violent changes. What affects the prices of residential properties in central and eastern European countries are factors that are specific to political transformation, connected with the demand for flats (financing the purchase through grants or aid schemes) [36]. Housing policy may promote the development of housing construction, but it may also contribute to an increase in the supply of flats and the ownership of wealthy citizens, deepening social and spatial inequalities [37].
- The banking system—the availability of diverse forms of providing loans for purchasing properties in the real estate market, including banks' credit policies, as well as the availability and interest rate of loans, affect the level of housing prices and determine the volume of sales [4,36], while changes in the value of financed properties may contribute to the instability of banks [38].
- The business cycle, which affects cycles in the real estate market, but these changes do not have to be strongly correlated. Most studies of cycles in this market concern the reference variable of the price of flats. The specific sectors of the market are heterogeneous, which means that some markets are more cyclical than others; moreover, housing shocks are usually short-term [39]. Changes in the prices of flats particularly depend on the geographical location of the urbanization degree and individual features of a flat (e.g., age and material) [40].

Factors in the micro-environment influence the level of development of local markets and their diversification. They include:

- Local economy, including the income of the population in this area and local employment level [41–43].
- Local tax policy—the level of taxes and the system of reliefs and exemptions may influence the supply and prices of flats to a negligible degree in the long-term, but are quite noticeable in the short-term [44].
- Spatial policy, which affects the investment potential of a given area, promoting the increase of supply or reducing it. Land control and zoning create the opportunities to build new flats, thus influencing their prices [35].
- Geographical environment—in this context, the characteristics of the climate, terrain, wind direction, insolation, and the amount of natural resources [4,45].

- The demographic situation of a region, the size of families, lifestyle, fashion, and local demand—these phenomena mainly have a short-term influence on the prices of flats [46,47].

The authors often focus on the features of properties that affect their prices. They are connected with the ultra-environment, and include:

- General location—location in a specific city, the distance from the central business district (CBD), and the property's surroundings, including natural environment, green areas, and accessibility [43,48–50], which is more important in areas inhabited by a low-income population [51]. In the post-socialist cities of central and eastern Europe, zones that are characteristic for socio-economic phenomena have developed: (1) central parts of cities (old-town buildings), (2) large-block housing estates (with an increased crime rate), and (3) suburban areas (rural areas annexed to cities in the last few decades, inhabited by poor indigenous people with a mentality different from that of urban residents) [8,52–54].
- The individual features of properties—the floor area, number of rooms, architecture, design, the size and characteristics of the garden, technical condition, age, quality of materials used, frequency of repairs, quality of installations, possibility of extension, and renovation are all significant determinants of prices [55,56].
- Lessees—the value of a property with a lessee may differ from the value of a property without a tenant [57].
- Easiness of sale (time needed to perform a transaction) and the availability of information about a property—there is a big difference between asking prices and transaction prices; when combined with the sellers' reluctance to reduce the price or delaying action in this regard, it prolongs the time in which the property is exposed in the market [58].

### *2.2. The Specific Determinants of the Prices of Flats*

The findings of various studies partly correspond with each other, confirming the influence of certain features on the value of residential properties, but the catalogues of attributes significant for this value differ depending on the market segment, the specific local market, and the time of the analysis. However, the influence of the location of a flat on its price is out of the question. Location is directly connected with the surroundings, in which, apart from other flats, there are public spaces (streets, squares, green and blue areas), the natural environment and its pollution (dust, noise), and the people who live and behave in a specific way—e.g., consistent or inconsistent with social norms (social problems—poverty, unemployment, alcoholism, homelessness, etc.) [59–63]. These factors may determine the quality of the location and its impact upon the prices of flats. The issue of the location of properties in areas affected by social problems and its influence on housing prices has been neglected by science, and has only been examined to a limited degree.

For example, the study conducted by American scholars [64] in Chicago, Illinois concerned the location of new flats in poor districts. Although they analyzed in detail the relationship between the price of flats and the type of building, distinguishing between three urban design types (enclave, traditional neighborhood development, and infill), the research covered only a sample of flats located in a poor district. What encourages investing in problem areas are low prices and the availability of land. Another benefit of developing poor areas is the social integration of the poor population with other residents. It is an added value for developers, who, apart from obtaining economic profit, may promote themselves as socially responsible companies.

Another US study carried out in St. Louis, Missouri [65], focused on the neighborhood and its transformation based on five neighborhood succession theories seen from different perspectives. (1) The bid rent function theory attempts to balance two contradictory desires in housing preferences: people would like to own larger flats, which are at the same time located close to the center of the city they work in. Therefore, the location value of flats is a difference between the consumption of land (in the form of housing) and the cost of commuting to the CBD. According to (2) the housing bundle theory, the characteristics of the neighborhood, including socio-economic ones, significantly determine the value of a property. (3) The broken window theory focuses on behavior norms and society's control over them. When people with low moral standards settle in a district, its reputation worsens. Consequently, flats located there become less attractive, and their price gradually falls. (4) Segregation theory is based on preferences with regard to the race of neighbors. Civil rights movements led to the protection of a race against discrimination. Despite this, some social/ethnic groups may still be discriminated against due to their disproportionately low income. Finally, (5) the game theory of real estate investment states that the value of a property is determined by its neighborhood. It is assumed that there are a number of real estate properties and owners in the neighborhood, which makes it difficult for them to find a common ground. Decisions concerning the location of new investments in an unfavorable environment are made autonomously by properties' owners, who, facing uncertainty, choose a safe option—they do not invest in the development of the property, as it gives them a higher potential return than investing while their neighbors are not doing the same. This model explains why the surroundings deteriorate rather than improve in many urban districts. In light of the above theories, we can conclude that the influence of the neighborhood on housing prices is an extremely complex issue.

Among the few scholars who examined the influence of location on housing prices were Spanish researchers [51] who used the case of the urban area in Valencia, Spain. They distinguished the following aspects: (1) accessibility and the vicinity of necessary or attractive objects, (2) the surroundings and the quality standards of nearby facilities, and (3) the socio-economic status of the neighborhood and immigration level. The authors point out that location combines a variety of factors, from employment prospects to leisure opportunities. Location in a specific place is connected with a sense of security among the potential buyers of new flats—it involves different attributes that translate into the benefits and satisfaction of buyers.

In another study, conducted in Columbus, Ohio [66], the authors analyzed the influence of crime rate on the prices of flats. To this end, they had gathered data concerning various types of crime (homicide, rape, robbery, assault, burglary, theft, and car theft), dividing them into three groups: crimes in general, violent crimes, and property crimes. The data was subjected to geocoding with the use of the location of an event as a spatial reference point. In order to discover whether the impact of crime differs among districts, they divided the sample into categories according to the income per inhabitant of the district in which the house was located. The authors found that, in the period under study, the crime rate decreased in the region with low income, while increasing in those with middle and high income. Poor areas had an approximately 50% higher share of flats occupied by owners (in contrast to flats for rent), and about two times fewer vacant properties than in districts in less attractive locations. Districts in an unfavorable situation also featured the highest population density, unemployment rate, and share of a population of 25 or more years of age. The inhabitants of housing estates with the highest income were predominantly of the Caucasian race (91%), with only 52% of the residents of low-income districts being white. The findings show that the influence of crime on housing prices differs depending on the type of district, thus leading to differences in the urban area. Violent crimes negatively affect the prices of flats in all districts. This influence is the strongest in low-income areas.

Although the theoretical concepts cited above apply to North American and western European cities, many of these findings are universal, and can also be observed in modern cities in developing countries. Therefore, taking into account some differences and specificity of central and eastern European post-socialist cities, the concepts were adopted as the theoretical framework of the research.

## 3. Materials and Methods

The research procedure aimed at accomplishing the aim of the paper consisted of two main stages. The first involved the identification of areas of the particular concentration of poverty in the city. The source material was obtained from the Municipal Social Welfare Centre (Miejski Ośrodek Pomocy Społecznej—MOPS) in Kalisz and the Citizen Affairs Department of the City Hall of Kalisz. Poverty concentration areas were detected with the application of GIS technologies in ArcINFO software.

In the latter stage, we verified whether the location of poverty concentration areas had an influence on housing prices. We applied regression models (OLSs), using SPSS software for analytic purposes. The analysis was based on data concerning the prices of residential properties sold, collected from the register of prices and values of properties run by the District Geodetic and Cartographic Documentation Centre in Kalisz.

### *3.1. Stage I—Poverty Concentration Areas*

In seeking poverty concentration areas in the city, we referred to the so-called statutory poverty line. In accordance with this definition, the poor are defined as household members who were provided with financial support as part of the public social welfare system because their income was lower than the statutory criterion of income per person in a family. From 2018, the criteria set out in the Regulation of the Council of Ministers of 18 July 2018 on the verified income criteria and the amounts of cash benefits from social assistance (Journal of Laws 2018, item 1358) were in force, according to which the right to receive cash benefits under social assistance was (1) a single-person household with a monthly income not exceeding PLN 701 (approx. EUR 160), and (2) a multi-person household with a monthly income not exceeding PLN 528 (approx. EUR 120) per person [67]. This definition is related to the European Commission's definition of poverty, understanding poverty as a relative concept, going beyond the lack of basic physical needs and aspiring to the standards of social participation or human functioning [68]. The category of the poor defined in this way allowed us to identify the address details of poor citizens and the location of the phenomenon of poverty within the city borders.

The empirical research was done on the basis of data obtained from the MOPS as the city's organizational unit for analyzing social problems on its territory and providing institutional support in this regard. Its database contains information about all beneficiaries of MOPS in the period under analysis, together with complete address details and the category that entitles them to seek aid.

First, the data concerning people whose income did not exceed the amount specified as the statutory poverty line were collected. We rejected the data that referred to people who received help due to their disability, orphanhood, homelessness, maternity protection, having a large number of children, home violence, chronic illness, and other cases that entitle one to apply for social assistance.

Finally, for analytical purposes, we used a query covering 410 households, in which more than 6000 social benefits a year were provided on account of low income. After that, we performed the geocoding of the address base of distinguished poor households.

When analyzing the distribution of the poor population in the city, we used three patterns of research procedure, thus referring to three classical models of the social and spatial structure of cities [69,70]—the Burgess zone concentric model [22], the Hoyt (sector) model [23], and the multiple nuclei model by Harris and Ullmann [24]. The classic models of the social and spatial structure of cities became the basis for the identification of poverty concentration areas, and then for the verification of the impact of poverty on housing prices.

In the first case, three concentric buffer zones around the pre-established central point of the city were marked. The historical center with the market and the town hall, which was also the administrative center of the city, was adopted as the central point. The successive buffer zones were set by equi-distances, with values changing every 0.5 km. In this way, 16 buffer zones were established. Then, the number of households and inhabitants who received financial aid from MOPS on account of poverty was identified in each of the concentric zones marked. The obtained results were compared with the analogical structure concerning the overall population of the city. Such an attempt to identify poverty was theoretically justified by the model originally proposed by Burgess [22], according to which the distance from the center is the fundamental factor determining the city's spatial structure, thus also the distribution of poverty within its space.

The second method was based on Hoyt's theoretical construct [23], according to which the city develops along its main travel links. As a result, it assumes the shape of a star, with clearly distinguished sectors radiating from the center. Thus, we divided the area of the city under examination into 16 sectors coinciding in the central point established before. The area of each sector was reduced by the area of the very center of the city, covering the historical Old Town, surrounded by town walls in Middle Ages, and now replaced by Planty park. Next, in each of the distinguished sectors, we counted the beneficiaries of social welfare and compared the obtained structure with the population structure according to the place of residence in each sector.

In the third approach to the identification of poverty concentration areas, we divided the territory of the city into a grid of squares with each side 0.2 km in length. In this way, 1860 fields with an area of 0.04 square meters were generated. In further analysis, they were treated as basic research units. Then, with the application of GIS technologies, we identified the number of poor people and the total size of the population in each basic field (square). By comparing the places of residence of poor citizens and the overall population of the city, we were able to identify poverty concentration areas, irrespective of the distance from the center, and travel links. Thus, the established areas may refer to the multi nuclei model developed by Harris and Ullman [24].

The quantitative measure of the concentration of the poor population in the city was the location quotient, which was calculated according to the following formula:

$$LQ = \frac{n_i \times p_k}{p_i \times n_k}, \quad (1)$$

where $n_i$ denotes the number of poor residents in a given basic field (square), $n_k$ is the total number of poor people in the city, $p_i$ is the size of the population inhabiting a given basic field, and $p_k$ is the total population of the city.

The location quotient determined in this way was a measure of the degree of poverty concentration in a given area (in relation to the degree of population concentration in this area). It was assumed that if the indicator values were above one, the poverty concentration in a given area was high. In such a situation, the share of poor people (as a percent of the total size of the poor population) was higher than the share of the population in this area (as percent of the total population of the city).

### *3.2. Stage II—The Regression Analysis of the Prices of Flats*

The verification of the influence of location in a poverty area on the price of a property was conducted by way of regression analysis. To this end, we built a database including all transactions in the urban area in the examined city in the years 2006–2018, and then selected the transactions in the primary market. We decided that flats in this market would be the best research material owing to their homogeneity in terms of the technical condition of buildings and the standards of flats. These attributes differentiate the secondary market to a far higher degree, constituting a significant price-setting factor. In regression models, however, they are a predictor that is difficult to quantify, as its values arise from subjective judgment.

We built a database consisting of almost 1000 records. From the initial database, we removed records that included incomplete information, e.g., it was impossible to learn about the characteristics of a flat. In the end, the regression analysis covered 879 flats from the primary market. The transaction price for one square meter was adopted as the dependent (endogenous) variable. A set of independent (exogenous) variables, in turn, included a wide range of market attributes (information about the date of sale of a flat, its location, address, district, floor area, the size and type of associated area, the number of floors, and location a poverty area). In the beginning, we tried to select the biggest possible number of independent variables, realizing that the set would be subject to reduction as a result of the verification of the significance of individual variables for further procedure. Potential independent variables were finally accepted or removed on the basis of statistical and formal criteria.

The set of potential independent variables included attributes connected with the location of a property in a poverty concentration rea. In accordance with the previously discussed procedure, the location in a poverty area was established in three ways:

1. Location in a concentric zone, in which there was a surplus of a poor population;
2. Location in a radiating sector, in which there was a surplus of a poor population;
3. Location in a basic field of the grid of squares, in which there was a surplus of a poor population.

As poverty areas delineated by way of different approaches overlapped, we estimated three independent regression models, each of which took into account a poverty area, delimited by a different method (respectively: the buffer model, the sector model, and the multiple nuclei model). A complete list of potential independent variables is presented in Table 1.

**Table 1.** Potential independent variables explaining the unit price of flats.

| Variable | Type of Variable | Characteristics and Variants of the Variable |
|---|---|---|
| Quarter | Quantitative | from 1 (1st quarter of 2006) to 52 (4th quarter of 2018) |
| District:<br>I, II, III, IV, V, VI, VII, VII, VIII, IX, X;<br>XI—base category | Qualitative (0/1) | 1—if a transaction was completed in a given district<br>0—otherwise |
| Floor area | Quantitative | Usable floor area of a flat in square meters |
| Associated floor area | Quantitative | Associated floor area in square meters |
| Cellar | Qualitative (0/1) | 1—if a transaction involved the sale of a cellar<br>0—otherwise |
| Garage | Qualitative (0/1) | 1—if a transaction involved the sale of a garage or a parking spot<br>0—otherwise |
| Number of rooms | Quantitative | Number of rooms in a flat |
| Number of floors | Quantitative | Number of floors in a building |
| Low block | Qualitative (0/1) | 1—if a transaction concerned a flat om a block of up to five floors<br>0—otherwise |
| Poverty area—zone | Qualitative (0/1) | 1—if a transaction was completed in a zone classified as a poverty area<br>0—otherwise |
| Poverty area—sector | Qualitative (0/1) | 1—if a transaction was completed in a sector classified as a poverty area<br>0—otherwise |
| Poverty area—grid | Qualitative (0/1) | 1–if a transaction was completed in a grid classified as a poverty area<br>0—otherwise |

Source: Authors' own study.

In the regression analysis, we used a non-linear approach, estimating exponential models described with the following equation:

$$y = \alpha_0 \cdot e^{\alpha_1 x_1 + \alpha_2 x_2 + \ldots + \alpha_k x_k}$$

where $y$ denotes the dependent variable (i.e., the transaction price for one square meter of a residential property), $x_1, x_2, \ldots, x_k$ are independent variables (market attributes of a property), and $\alpha_0, \alpha_1, \ldots, \alpha_k$ are the model's structural parameters.

The exponential model was subjected to log-linearization, then we estimated the linear auxiliary model using the least squares method and evaluated its quality. After that, we moved the estimated values of parameters to the main (exponential) model and calculated change rates $y$ according to a given $x_k$, in accordance with the following formula:

$$growth\ rate\ = (e^{\alpha_k} - 1) \cdot 100\% \text{ for } \alpha_k \neq 0.$$

This type of procedure is often applied in the literature on the issue of property mass valuation. Exponential models used for automatic valuation are better known as hedonic models [71–73].

## 4. Results

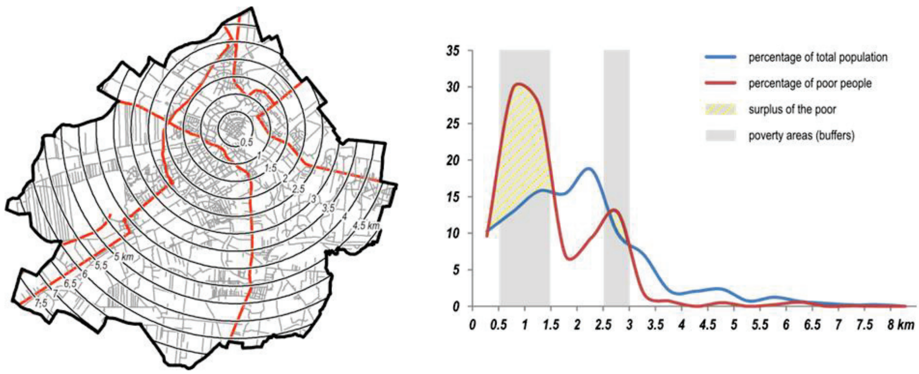
In accordance with the adopted research methodology, in the first stage, we distinguished poverty areas in the space of the examined city. We used three ways of establishing the boundaries of the problematic area. Then, we analyzed the influence of the flat's location in a poverty area and of other factors differentiating flats sold on the price for one square meter.

### *4.1. Poverty Concentration Areas*

The results of the analysis of poverty concentration in the successive distance zones have shown that the largest number of inhabitants who received benefits on account of poverty lived from 0.5 km to 1.5 km from the city center (over 55% of the total number of social welfare benefits). Quite a lot of residents covered by financial assistance were also identified in the distance zone from 2.5 km to 3.0 km (13%), and in the zones of up to 0.5 km and from 2 km to 2.5 km (almost 10% in each of these zones). Lower values of the analyzed phenomena were observed in the zone from 1.5 km to 2 km (7%). Distance zones of above 3.5 km featured far fewer inhabitants receiving social benefits (below 1%) (see Figure 1).

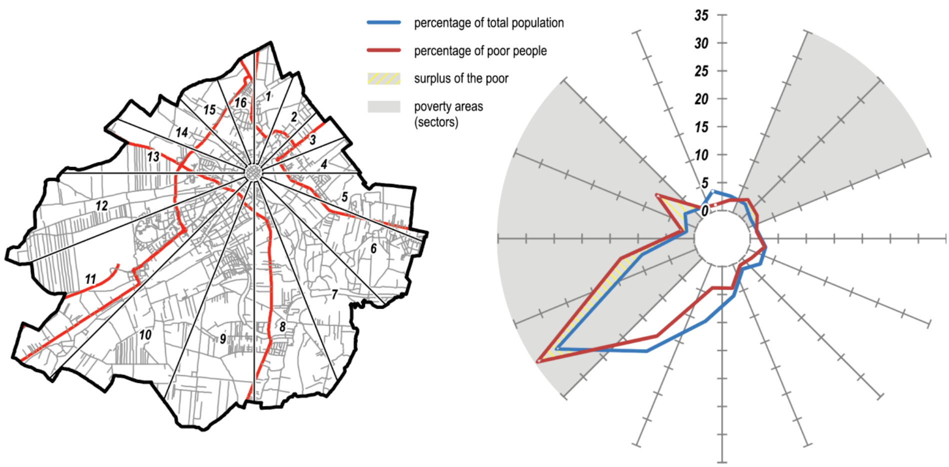
The curves illustrating the distribution of poor people and of the total population depending on the distance from the central point allow us to identify two characteristic areas (zones) that stand out regarding the poverty level. Within the distance from 0.5 km to 1.5 km from the city center, there was a relative excess of poor population in relation to the total number of inhabitants, with the highest surplus in the zone from 1.5 km to 1 km. The second area with a relative excess of poor residents was the zone between 2.5 km and 3 km. When we look at the zones from 1.5 km to 2.5 km and from 3 km to 6 km, the share of poor inhabitants was lower than the percentage of the total population, and the highest relative difference was observed in the distance from 2 km to 2.5 km. In more distant zones (more than 6.0 km from the center), covering the peripheral area of the city, the analysis has shown the relative balance of the two structures.

The graphic illustration of poverty concentration in radiating sectors shows that the eastern (sectors from 11 to 14) and northwestern (sectors 2 and 3) parts of the city were the areas with a particularly high intensity of a poor population. In the other parts, the percentage of the poor population was lower than the share of the total population. The highest surplus of the poor in relation to the total population was identified in sector 14, with slightly lower values in sectors 11 and 12 (see Figure 2).




(**a**) (**b**)

**Figure 1.** Poverty in the city space—buffer model: (**a**) concentric poverty areas in Kalisz; (**b**) the comparison of the distribution of the total population and poor population. Source: Authors' own study based on the data from the Municipal Social Welfare Centre and the City Hall in Kalisz.




(**a**) (**b**)

**Figure 2.** Poverty in the city—sectoral model: (**a**) radiating poverty zones in Kalisz; (**b**) the comparison of the distribution of the total population and poor population. Source: Authors' own study based on the data from the Municipal Social Welfare Centre and the City Hall in Kalisz.

The results of the analysis of poverty areas established on the basis of a square grid and location quotients showed that areas with a high poverty concentration could be found in the territory of the whole city, with quite clearly evident regularities (see Figure 3). More compact poverty areas tended to be located in central districts. This part of the square grid illustrating the concentration of poor residents basically overlapped with the concentric zones in the distance of 0.5–1.5 km from the city center. High values of the location quotient were also identified in the areas of the intermediate zone of the city, in highly urbanized areas. The other poverty zones were unevenly distributed in the peripheral parts of the city, and the concentration of poverty in these areas was often associated with quite a large number of council flats there.


**Figure 3.** Poverty in the city—square grid: (**a**) a grid of squares 200 × 200 m placed on the city of Kalisz; (**b**) poverty concentration areas (the surplus of the percentage of the poor population over the percentage of the total population of the city). Source: Authors' own study based on the data from the Municipal Social Welfare Centre and the City Hall in Kalisz.

Referring the obtained results to the functional and spatial structure of the city, we were able to identify certain regularities, characteristic of big cities in Poland and other post-socialist countries [8,74–76]. Taking into consideration different ways of delimiting poverty areas, we can observe that the poverty concentration marked mainly three specific problem areas: central parts of cities, areas dominated by large-block housing estates, and suburban areas. In central parts of cities, apart from representative city centers and service and commercial malls, there are also old and decapitalized buildings with a very diverse urban structure. Large-block housing estates built after World War Two are strongly diversified in terms of social characteristics and construction quality. In turn, in the outskirts of cities subject to intense suburbanization processes, two types of areas are now developing: rich residential properties owned by middle class and poor estates transformed from rural buildings. Similar conclusions related to the condition of poverty in Polish cities' social and spatial structures are offered in relevant publications—for example in Białystok, Gdynia, Poznań, Słupsk, and the cities of Upper Silesia [76].

### *4.2. Regression Analysis*

The estimated regression equations showed that the explained part of the variability of the unit prices of residential properties in the primary market was determined by the non-linear combinations of variables that described flats according to their floor area, the number of rooms, associated area, type of construction (low block), location in a specific estate, and location in a poverty area. The upward trend in prices in the primary market in the years under study was also statistically significant (Table 2).

Trends are consistent with the theory of economics and the logic of a cause and effect relationship. Larger flats had lower unit prices on average, but a bigger number of rooms on the same area stimulated the price for one square meter. The unit price also increased with each square meter of the associated area. On average, lower prices of flats in low blocks (up to five floors) stemmed from the specific nature of the local primary market—high blocks were predominantly upgraded apartment buildings (with a panoramic lift, spectacular views, etc.). Marks next to regression coefficients referring to the specific districts of the city show that ceteris paribus flats in District XI (considered the base category) were the most expensive, while the biggest minus percentage deviations were observed in District II. It is a large-blocks housing estate with undesirable neighborhood characteristics; although it is located close to the city center, it has post-war, modernistic architecture (prefabricated buildings in poor state), a high density with an insufficient number of parking places and garages, and is inhabited by older people, with an average age of over 50 years.

**Table 2.** Modelling unit prices (PLN/m$^2$) in the primary market, taking into consideration the poverty concentration factor.

| | **Buffer Model** | | **Sector Model** | | **Square Grid Model** | |
|---|---|---|---|---|---|---|
| | **Coeff.** | **Growth Rate** | **Coeff.** | **Growth Rate** | **Coeff.** | **Growth Rate** |
| Constant term | 8.168 *** | – | 8.269 *** | – | 8.244 *** | – |
| No. of quarter | 0.005 *** | 0.5% | 0.002 *** | 0.2% | 0.004 *** | 0.4% |
| Floor area [m$^2$] | −0.002 *** | −0.2% | −0.002 *** | −0.2% | −0.002 *** | −0.2% |
| Number of rooms | 0.052 *** | 5.3% | 0.047 *** | 4.8% | 0.053 *** | 5.4% |
| Associated area [m$^2$] | 0.007 *** | 0.7% | 0.007 *** | 0.7% | 0.007 *** | 0.7% |
| Low block | −0.167 *** | −15.3% | −0.158 *** | −14.6% | −0.2 *** | −18.1% |
| District I | −0.199 *** | −18.1% | −0.163 *** | −15.0% | −0.266 *** | −23.4% |
| District II | −0.320 *** | −27.4% | −0.334 *** | −28.4% | −0.431 *** | −35.0% |
| District III | −0.218 *** | −19.6% | −0.153 *** | −14.2% | −0.208 *** | −18.8% |
| District IV | −0.076 *** | −7.4% | −0.135 *** | −12.7% | −0.143 *** | −13.4% |
| District V | −0.061 *** | −5.9% | −0.036 * | −3.5% | −0.191 *** | −17.4% |
| District VI | −0.252 *** | −22.3% | −0.177 *** | −16.2% | −0.21 *** | −18.9% |
| District VII | −0.151 *** | −14.0% | – | – | −0.092 ** | −8.8% |
| District VIII | – | – | −0.172 *** | −15.8% | −0.325 *** | −27.7% |
| District IX | −0.199 *** | −18.0% | −0.198 *** | −17.9% | −0.202 *** | −18.3% |
| District X | −0.291 *** | −25.3% | −0.165 *** | −15.2% | −0.389 *** | −32.2% |
| Poverty area | −0.020 *** | −2.0% | −0.016 *** | −1.6% | −0.104 ** | −9.9% |
| R2/Adjusted R2 | 0.378/0.368 | | 0.345/0.334 | | 0.331/0.319 | |
| F (*p*-value) | 35.01 (<0.0001) | | 30.29 (<0.0001) | | 26.65 (<0.0001) | |
| AIC | −991.50 | | −952.57 | | −941.30 | |
| Standard Error | 0.1364 | | 0.1395 | | 0.1403 | |

Statistical significance: *** $p < 0.001$, ** $p < 0.05$, * $p < 0.1$. Source: Authors' own research.

The estimated regression models have shown that the location of a property in a poverty area had a statistically significant influence on the unit price of residential properties in the primary market. The probability of error in the evaluation of statistical significance in buffer and sector models was close to zero ($p$-values < 0.001), while, in the case of the square grid model, it slightly exceeded 3%. As expected, flats located in poverty concentration areas were cheaper, and the price drop fluctuated from about 1.6%, in the case of location in an area classified as a poverty area, with 2% in a zone distant from the city center that was recognized as a poverty area, to almost 10% in the case of a poverty area delineated on the basis of the square grid model.

The biggest price decreases in the case of the square grid model were the result of the most precise way of delimiting poverty areas. The buffer and sector models were more generalized, so the negative impact of poverty areas in these models is not so evident (although statistically significant). At the same time, we can assume that the latter models paid more attention to the neighborhood of problem areas—the established buffers and sectors, as larger areas, also took into account transactions located some distance away from the places of residence of the poor.

The applied measures of goodness-of-fit and model quality indicated that the buffer model came closest to the reality representative of the empirical data, while the model based on the square grid reflected this reality to the smallest degree. The values of linear determination coefficients of auxiliary models were from 33% (square grid model) to 38% (buffer model). It should be remembered that, in models estimated on the basis of cross-sectional data, R2 coefficients tend to be low, and do not attain as high of levels as in the case of the application of time series. However, considering the large size of the sample, we can say that low values of R2 do not mean that the model is low quality [77–79]. This is confirmed by the results of F tests, which verify the combined significance of all variables included in the models. The high statistical significance of the F tests showed that the estimated models are quite satisfactory and have a high cognitive value.

## 5. Discussion

The applied research procedure allowed us first to identify poverty areas in a medium-sized city in Poland. We discovered that some regularities concerning the distribution of poverty in the city space are consistent with the findings of previously published studies, according to which poverty areas in many post-socialist cities can be found in three characteristic locations: midtown housing estates, post-war districts of blocks, and peripheral areas of cities, which, despite being incorporated into the city's administrative borders, often retained their rural character. Poverty concentration in these areas is associated with the fact that council flats are often located there [8,74–77]. It is also pointed out in the literature that the largest concentration of poverty in Polish cities is observed in the areas inhabited by an older population, and the phenomenon of urban poverty is accompanied by prolonged unemployment, social pathologies, and crime. Poverty areas, analogically to slums in Western metropolises, are marked by a high degree of space decapitalization, high unemployment rate, their prolonged dependence on social welfare, deep material deprivation of residents, and the intensification of pathological behaviors, such as crime, alcoholism, family break-ups, and home violence [8,52–54,80–83].

All of these phenomena shape the urban space, influencing the development of housing and differentiating the prices of apartments in the specific locations. Despite this, issues concerning poverty and its concentration in various parts of the city have not been widely discussed in the literature so far. The findings of our study confirm that the prices of flats in the primary market do depend on their location in a poverty area. Regardless of the method of delimiting poverty areas, the constructed models show that unfavorable location in such an area contributes to a drop in housing prices. These results confirm some other researchers' findings [51,59–61,64–66].

Our paper is in line with the neighborhood succession theories discussed above. According to the bid rent function theory, people would like to live close to the city center and, indeed, flats located in the midtown district of the examined city (District XI) were the most expensive. In accordance with the housing bundle theory, the value of a property is determined by the characteristics of the neighborhood, including socio-economic ones, which is reflected by all of the models—a neighborhood classified as a poverty area negatively affects housing prices. Our models also confirm the tenets of the broken window theory—the prices of flats are inversely proportional to the occurrence of people who give a district a bad reputation. In the case of Polish cities, especially medium-sized ones, it is difficult to prove the thesis of the segregation theory—the share of foreigners of another race among the population is negligible. It is evident, in turn, that the presence of people with low income has a negative impact on prices.

The only theory that cannot be confirmed by our study is the game theory of real estate investment. It is based on the assumption that the value of a property influences its surroundings, but it is difficult to attempt discussion on this issue in the context of our research. Game theory refers to investors who are the owners of a property, obtain income from it, and consider further growth. Investment made by developers, in turn, consists of a complete change in the use of a property (undeveloped land, a multi-family building), which, consequently, should lead to sale rather than providing long-term income.

The identification of poverty areas in the city space is just an initial phase of research into the problems of social deprivation. In further stages, more attention should be paid to the factors and determinants of poverty concentration in the specific parts of urban space, and to the co-occurring phenomena (unemployment, homelessness, pathologies). Full analysis may be an important source of information for tasks in the field of social welfare and spatial policy in the city. The consequent actions may result in the reduction of socially negative processes and in the stimulation of social integration. They would also definitely influence prices in the urban area; thus, the economic effect of intervention would be revealed. The growth in the value of flats would enable sellers to obtain bigger profit, while the increased tax revenue to city budgets would stimulate local economy.

Our study is a contribution to a broader discussion on the determinants of prices in an urban area, with particular emphasis on the location factor. We can cite papers that analyze the influence of such disadvantages of localization, such as aircraft noise [59,84,85], rail noise level [61], road noise [60], traffic [86], pollution [87,88], or other environmental effects [89,90]. At the same time, a number of studies identify the advantages of localization, such as municipal transport accessibility [91,92], the vicinity of green areas [93], revitalization [78,94], and others. The presented study provides new arguments in the discussion on the complexity of the real estate market in terms of spatial non-linearity [95] and the diversification of property price determinants.

The identified relationships have a significant impact on the shaping of sustainable spatial development in cities. As shown, the concentration of poverty leads to lower housing prices. A decline in the attractiveness of some urban areas may result in a multiplier mechanism discouraging people from settling in and doing business in these places. This, in turn, will result in further pauperization and deterioration of socio-economic conditions. This may result in the segregation of urban space into attractive areas that attract the rich population and degraded areas with a high proportion of the poor. Thus, socio-economic inequalities in spatial terms may increase in urban space.

Large price differences in various areas of the city are unfavorable from the point of view of spatial development or the location of new investments. The concentration of poverty in selected areas makes it impossible to use land rent, which is an obstacle to the appropriate and intensive use of urban land. Urban policy, striving for sustainable development of urban areas, should focus on eliminating or reducing the concentration of poverty areas.

When making decisions concerning the location of new housing investments, developers are not only motivated by the shortage of flats, i.e., the potential demand for them, but they first of all seek profit opportunities. Location thus influences the prices of flats and, indirectly, the profitability of an investment. Important elements of localization at the construction stage are easy access, the availability of infrastructure, and the vicinity of the sources of supply. At the stage of sales, location becomes strictly linked with the condition of the property's surroundings and the wealth of the neighbors, which affect housing prices and, consequently, the developer's profit. Our study may be of value for active participants of the housing market (developers, property valuers, and estate agents), providing them with better possibilities of modelling price levels, as well as for local authorities, allowing them to forecast phenomena in the local development.

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# The Role of Energy Affordability in the Relationship between Poor Housing and Health Status

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**Abstract:** Housing quality is a well-established determinant for health and its relevance has been increasing in the context of sustainable development. Prior research has emphasized the importance of adequate housing for the health and comfort of householders. However, this link is still poorly characterized and understood regarding the vulnerable segments of the population. In this study, a mediation analysis is proposed to test and identify the role of energy affordability in the relationship between poor housing and health status. It resorts to microdata from the European Union—Statistics on Income and Living Conditions (EU-SILC) database, focusing on the analysis of Portugal as the case study. Research findings confirm the role of energy affordability as a mediator. The research findings supported the energy efficiency as a direct pathway with protective and preventive effect for poor health, followed by energy affordability as a mediated or indirect pathway. A complementary approach that addresses energy efficiency and energy poverty should be pursued to maximize health risk reduction.

**Keywords:** energy poverty; cold homes; perceived health status; energy efficiency; decomposition analysis; microdata; Portugal

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## 1. Introduction

A study by Velux (2018) concerning the impact of buildings on European citizen's health has emphasized that currently at least one in six Europeans lives in buildings with at least one of the following poor housing conditions: (1) dampness, (2) not enough daylight (too dark) or (3) thermal discomfort [1]. Simultaneously, energy poverty though widespread across Europe, presents an uneven distribution, with higher incidence in Southern and Eastern European countries [2]. In the former countries, energy affordability concerns or the ability to afford adequate energy services, such as lighting, seem to have a pronounced expression as a measure of energy poverty (e.g., [3]). Thus, despite the increasing publications demonstrating the relevance and multidimensional nature of this topic (see [4,5]), further policy integration efforts require the consideration of energy poverty links to other policy areas (see [6]). Recent studies, such as Magalhães et al. (2016) and Simões et al. (2016) provided empirical evidence of cold homes and fuel poverty regarding space heating and cooling in Portugal [7,8]. However, few studies have been conducted to assess how poor housing relates to contextual factors such as householder's age, income and health (e.g., [9]). A study by Horta et al. (2019) emphasized the high vulnerability of energy poor households in Portugal to indoor cold (in winter) and heat (in summer), and the relevance of considering 'socioeconomic context and the low quality of the housing stock' in its assessment [10]. The authors mention that the perception of thermal (dis)comfort and its acceptance by households may affect the recognition of the problem and its impacts on health and wellbeing, but to date, no assessment of these variables has been made.

The main objective of this study is to address this gap, i.e., to determine the role of energy efficiency and the energy affordability regarding the improvement of perceived health status. The aim was to show policy makers the main pathways to address the impacts of inefficient (poor) housing upon health. Moreover, the definitions adopted for the lack of energy efficiency and the energy affordability are aligned with those used to identify energy poverty, namely the 'struggle to heat or cool home' or the struggle to 'pay the energy bill on time', respectively (see [11]). Therefore, the assessment of the relationships between health status (dependent variable) and poor housing conditions, namely thermal discomfort (proxy for energy inefficiency) or ability to afford/pay to keep warm (proxy for energy affordability), as main independent variables, resorted to a mediation analysis.

To the best of our knowledge, no such study has been performed for Portugal. Additionally, the current study also aims to extend prior research, by zooming in on vulnerable segments of the population, such as the elderly. It aims to address this gap by applying a newly developed mediation analysis that extends traditional mediation analysis by considering binary outcome and binary mediators. This novel approach takes into consideration interactions between thermal discomfort and affordability to test and identify the role of energy affordability in the relationship between poor housing (indoor temperature perception) and health status for the case of Portugal. This statistical approach is known as 'four-way decomposition' analysis [12], and to our knowledge, it has not yet been applied in the context of poor housing and health. It will enable us to study indoor temperature perception (thermal discomfort) and affordability (ability to keep warm), their interconnection and subsequent link with health status. Taking into consideration and extending prior research, this study seeks to answer the following research questions:

- What is the relationship between thermal discomfort and poor health status, according to socioeconomic background (e.g., age or income), using affordability as mediator?
- What is the portion of the overall effect that is allocated to each component of the 'four-way decomposition' analysis?

This study addresses the case of Portugal using data from the European Union—Statistics on Income, Social Inclusion and Living Conditions (EU-SILC) microdata database (see [13]). The database can be provided to recognize scientific research centers and university institutions, for scientific purposes, upon a strict access and usage protocol. The present study resorts to 2012 ad hoc module [14] devoted to housing conditions. After this brief introduction to the subject, this paper continues by presenting a brief literature review (Section 2), after which the dataset and sampling approach (Section 3), and the theoretical framework for the modelling approach are described (Section 4). In the results (Section 5), the findings obtained are presented and discussed. The paper then concludes in Section 6 by presenting possible implications for the development of policies to tackle energy inefficiency and unhealthy housing quality.

## 2. Literature Review

In this section, a review of the relationships between poor housing and health is presented, followed by an overview of the proposed mediation modelling approach.

There seems to be compelling evidence of the association between poor housing and householder's health status. A wide range of adverse health effects has been reported and could configure a 'poor health status', from cardiorespiratory to mental health conditions. For instance, while studying the influence of the economic crisis in energy and environmental quality of low-income households in Greece, Santamouris et al. (2014) found a strong association between these parameters. The results showed that indoor temperatures were below minimum levels and that a high share of the households were not using heating at all [15]. In very low-income households, a high share of the population was diagnosed with poor mental health, namely depression issues. An increased risk of poor mental health was also evidenced in the UK by Pevalin et al. (2017), for people living in social housing with poor housing conditions and for extended periods of time [16]. Furthermore, a recent study at the EU level [17] has found that people who are exposed to poor housing conditions have a higher probability of reporting poor health (by 70% in contrast to non-exposed). Based on the analysis of the correlation between health and poor housing, exposure to damp or cold homes reported the highest correlation to poor health (1.7 times higher than non-exposed).

A comparison between two social housing neighborhoods in Porto, Portugal, was conducted by Ramos et al. (2018). This study looked to understand the impact of indoor humidity and temperature conditions on quality of life, resorting to a Short Form Health survey (SF36) [9]. The results showed that the rehabilitated neighborhood had increased satisfaction of householders along with improved indoor hygrothermal conditions. As a matter of fact, a review undertaken by Fisk et al. (2020) emphasized that the improvement indoor temperatures and the presence of damp and mold promote a shift in householder's perception concerning thermal comfort and health status. Obtained results point towards an improvement in these aspects after energy efficiency retrofits [18]. These examples also reenforce why World Health Organization (WHO) considers the improvement in the exposure to low and high indoor temperatures as one of the major areas to reduce health risks from poor housing quality [19].

Additionally, few studies have resorted to mediation analysis to test the role of a third variable concerning the relationship between poor housing and health (e.g., [20,21]).

Recent studies have explored the effect of neighborhood on the health of building occupants. Chan and Liu (2018) found that, in Hong Kong, occupant's health is significantly affected by neighborhood qualities (building density and height, cleanliness and greenspace). A statistically significant correlation between neighborhood qualities and health was mediated by indoor environment, namely visual and acoustic comfort and indoor air quality) [22]. Rodrigues et al. (2021) found that the impact of neighborhood socioeconomic disparity in self-rated health is mediated by violence in poor or disadvantaged neighborhoods in Brazil [23]. Regarding poor housing, Heyman et al. (2005) investigated if energy efficiency was a mediator between socio-economic status and the risk of poor health in the UK. His findings supported that objective energy efficiency indicators, such as energy efficiency ratings, made an important contribution to the relationship between lower socioeconomic status and poorer health [20]. More recently, Boomsma et al. (2017) established an indirect effect of poor housing (damp, cold and mold) on health through energy affordability in the UK. The authors claim that houses experiencing cold, damp and mold issues reported more difficulty in paying energy bills and that this concern affect in turn their mental health and wellbeing [21].

The relationship between the thermal comfort, low energy consumption and aging population is still largely missing, in an increasingly aging population and climate change context [24].

In contrast to the abovementioned context, studies from the health sector have often resorted to mediation analysis to assess the impacts on health from different environmental exposures. For instance, Discacciati et al. (2019) and Lee et al. (2018) used the four-way decomposition approach to study the role of birth outcomes (e.g., birth length) in explaining the impact of the exposure to manganese on child neurodevelopment [25,26]. Higher pollutant concentrations were associated with lower cognitive score, and this effect was mediated through child length. Mediation and interaction was found between birth length being associated with the other two variables (manganese exposure and cognitive score). Though recently developed, the four-way mediation approach has been increasingly used given its advantage to simultaneously allow to estimate beyond the mediation and to focus also the interaction effects (see [25–28]).

Overall, despite this increasing evidence, research linking poor housing to socioeconomic background and health impacts is still largely underdeveloped. Additionally, the resource to newly developed approaches could provide additional insight regarding these associations on whether part of the effect of poor housing on health results from the influence of affordability. The next section presents the database, and the chosen modelling approach are presented.

## 3. Materials and Methods

A detailed description of the data and modelling approach is presented in this section.

### *3.1. Dataset and Variables: Data Sources and Survey Description*

The European Union—Statistics on Income, Social Inclusion and Living Conditions (EU-SILC) is considered a reference database at the EU level, covering variables from different topics at the household and householder levels, namely income, poverty, social exclusion, housing, labor, education and health [29]. The present work resorted to a specific dataset or ad hoc module that provides the most recent data on poor housing conditions, namely regarding the indoor temperature perception for cold and heat. This is a variable of interest in the study of the relationship between poor housing and health status that is not provided on a regular basis.

EU-SILC provides annual statistics of two main types: cross-sectional, i.e., specific to a given time or time period, and longitudinal, i.e., measures 'individual-level changes' over a maximum of a four-year period [13]. Though the ad hoc modules are also developed on a yearly basis, they feature different yet relevant topics regarding social cohesion and inclusion. Among those subjects of interest is the 2012 module on housing conditions, featuring additional aspects of building characteristics, such as space in the dwelling, heating facilities and accessibility to basic services.

In Portugal, the initial sample size for 2012 cross-sectional ad hoc module edition included a total of $n$ = 6257 houses and $n$ = 13,584 householders. A sequence of filters was applied to the initial sample size, in order to obtain the final sample ($n$ = 6031 houses and householders) for the modelling approach, as illustrated in Figure 1.

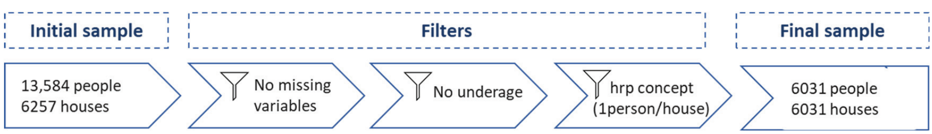


**Figure 1.** Filters from initial to final sample.

The filters correspond to the exclusion criteria through which the final sample was obtained. They consist of three simple steps: the first filter excludes missing information from variables of interest at the house or householder levels (e.g., house type or education); the second filter excludes data from multiple household members below the minimum age for interviews. Additionally, because answers at house level are given by a single respondent, the third filter applies household representative person (hrp) concept to match house and householder file, reducing the sample to one person per house (1 person/house). The hrp concept is commonly used by national and Eurostat level databases [30,31]. Furthermore, the use of a single respondent potentially avoids subjective bias [32]. This set of filters has accounted for a drop of 7553 people and 228 houses from the initial sample.

### *3.2. Dataset and Variables: Dependent and Independent Variables and Summary Statistics*

Information regarding building characteristics or poor housing conditions socioeconomic variables, as described in Table 1.

**Table 1.** Variables or socioeconomic and housing conditions.

| **Variables** | **General Health** | **House Type** | **Tenure status** | **Damp & Rot** | **Lack of Daylight** | **Ability to Keep Warm *** | **Heating Facilities** | **Warm during Winter **** | **Cool during Summer** | **Surface Area** | **Urbanization Level** | **Gender** | **Age** | **Birthplace** | **Marital Status** | **Education Level** | **Household Size** | **Economic Status** | **Income Quintile** | **Chronic Conditions** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | | | | | | | | | | | | | | | | | | | | |
| Dependent | √ | | | | | | | | | | | | | | | | | | | |
| Independent | | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Data collection | | | | | | | | | | | | | | | | | | | | |
| Permanent | √ | √ | √ | √ | √ | √ | | | | | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Occasional | | | | | | | √ | √ | √ | √ | | | | | | | | | | |

* Proxy for energy affordability; ** Proxy for energy efficiency
√ (shaded) poor housing conditions √ socioeconomic conditions

Information regarding building characteristics or poor housing conditions (e.g., damp and rot; house type or heating facilities) are collected at the house level. Meanwhile, most socioeconomic variables are collected at the householder level (e.g., gender, education level, economic status or general health). Among these variables is, for example, the ability to keep the household warm, which is more related to the energy affordability issue, since it is derived from the EU SILC question "Can your household afford to keep its home adequately warm?". Therefore, it may be considered as a proxy for energy affordability, representing householders' energy service concerns, namely for heating needs (see [21]). Therefore, henceforth 'ability to keep warm' will be designated as 'energy affordability'. Other variables are collected for a given year and for a particular subject, namely regarding living condition topic, known as the ad hoc modules.

Among the complementary 'ad hoc' living condition variables (e.g., 'surface area'; 'warm during winter'; 'cool during summer' and 'heating facilities'), for this analysis 'warm during winter' and 'cool during summer' are taken as the perception of indoor temperature during winter and summertime. Moreover, these variables may be considered as proxies for energy efficiency; henceforth, 'warm during winter' is re-named 'thermal comfort', and likewise, 'not warm during winter' becomes known as 'thermal discomfort'.

The key concern behind the 'thermal discomfort' variable is whether the house is sufficiently insulated and equipped with energy efficient appliances against cold [14]. Therefore, though not explicitly, this question provides us with information regarding specific poor housing conditions that complement other more explicit variables for poor housing conditions, such as the presence of 'damp and rot'. It is expected that the perceived thermal discomfort derived from the lack of wall insulation/heating inefficiency and damp walls could adversely affect health status, particularly for vulnerable segments of the population. These (poor) housing quality variables have been used consistently in the study of the relationship between energy and thermal comfort in Portugal (e.g., [10]). They have been further considered by Simões et al. (2016) as key defining features that need to be addressed regarding energy poverty, along with other socioeconomic variables such as income [8]. Furthermore, according to Carmichael et al. (2020), besides low efficiency rating associated with the lack of wall insulation, two other pathways are known to influence cold exposure; they are the heating facilities and excessive damp that reduces thermal insulation [33]. For the current study, we argue that the focal poor housing condition is thermal (dis)comfort, which could be considered a proxy for energy efficiency or lack of it. Other poor housing conditions, such as 'damp and rot' and the type of 'heating facilities' are included in the model as additional independent variables (covariates).

Among socioeconomic variables is the dependent variable that captures the self-perceived health status, i.e., how a person perceives their general health. It results from a broader question ("How is your health in general?"), and as such, it is expected to depict different health dimensions ('physical, social, emotional as well as biomedical signs and symptoms') [13,34]. It is measured as an ordinal variable, ranging in scale from 1 to 5, where 1 corresponds to very good health and the other extreme 5 corresponds to very bad health. In between the upper and the lower ends of the scale are the intermediate values (2 to 4), denoting a good, fair or bad health status. Similarly, to prior works (see [35–37]), this variable has been dichotomized between good and bad health status, taking the value of 0 if the person is in good health (encompassing fair, good and very good categories) or 1 if the person is in poor health (encompassing bad and very bad categories). This transformation of the dependent variable helps to better accommodate high degree of distribution skewedness [36]. Moreover, besides being a common practice, this conversion into a binary variable enables the application of the four-way decomposition analysis, suitable for binary, continuous or count variables (see [32]).

According to [38], one of the main advantages of using the EU-SILC database is that in a single database, several covariates or independent variables that can influence health status are available. Therefore, although poor housing conditions are the main explanatory variables, in this study, other typical socioeconomic variables are controlled for. For instance, low-income households are known to account for a substantial share of cold homes in several countries (e.g., [7,39,40]). The equivalized disposable income is used by Eurostat as a poverty indicator [41]; based on this concept, income quintile groups are computed to better identify different income groups. The data for total equivalized disposable income for each person are ordered, and based on cut-off points, it is possible to split the sample into five groups equally represented by 20% of individuals, from the lowest income (1st quintile) to the highest income (5th quintile) [42].

The present study takes special interest in the analysis of the elderly population, with age variable ranging from 17 onwards to over 65 years of age. In many countries, there is an increasing trend in terms of aging population and growing incidence of non-communicable or chronic diseases, namely heart disease, stroke, cancer, diabetes and chronic respiratory diseases [43,44]. In this sense, in contrast to previous studies, the presence of chronic disease is considered among independent or explanatory variables to account for person-specific unobserved factors related to health. This variable is binary and assumes the value of 1 for the existence of chronic disease or 2 otherwise. It looks to answer the following question "Do you have any longstanding illness or health problem?", accounting for a health condition that is permanent and may require a long-term supervision, observation or care [13]. Householder education level and occupation are also taken into consideration. Given that it has been acknowledged that senior citizens, often retired, tend to spend greater amounts of time indoors [45]. Controlling for overall socioeconomic variables could contribute to avoid bias due to unobserved heterogeneity, according to [25]. A full listing of available variables and detailed description is provided at Eurostat's metadata [46]. A summary of sample statistics is available, in Table 2.

Most people in the sample seem to live in detached houses (40.82%) in comparison to building flats. This higher share of houses is plausible given that rural areas are emphasized at the urbanization level, when compared to urban and peri-urban areas. Rural areas are characterized by sparsely populated areas in contrast to urban densely populated areas. As expected, there seems to be a much higher incidence of homeowners versus tenants. Regarding poor housing conditions, although the majority of houses are not affected by the damp walls, lack of daylight or the ability to keep the household warm (all above 70%), the share of houses that do suffer from these issues is still high (with the exception of lack of daylight, all variables are above 20%). Additionally, non-fixed heating systems seem to prevail against fixed heating systems. Meanwhile, the share of houses without any heating is high (17.87%) and well above the share of central heating systems. Given this background, the perception of thermal comfort during the winter is slightly above the discomfort felt during the wintertime (54.04% vs. 45.96%). Thermal discomfort during wintertime is more relevant than thermal discomfort during the summertime. Almost twice the share of people feel more comfortable during the summer than otherwise (66.14% vs. 33.86%).

**Table 2.** Summary statistics.

| | Independent Variables | Categories | Percentage (%)/Mean |
|---|---|---|---|
| Poor housing conditions | House type | Detached house * | 40.82 |
| | | Semi-detached or terraced house | 23.41 |
| | | Flat in a building ≤ 10 dwellings | 22.17 |
| | | Flat in a building ≥ 10 dwellings | 13.60 |
| | Tenure status | Owner * | 50.90 |
| | | Owner (mortgage) | 24.76 |
| | | Tenant (market rate) | 9.90 |
| | | Tenant (reduced rate) | 7.11 |
| | | Free accommodation | 7.33 |
| | Damp and rot [1] | Yes * | 22.09 |
| | | No | 77.91 |
| | Too dark | Yes * | 10.94 |
| | | No | 89.06 |
| | Energy affordability | Yes * | 71.85 |
| | | No | 28.15 |
| | Heating facilities | Central heating * | 9.75 |
| | | Other fixed heating | 33.99 |
| | | Non-fixed heating | 38.39 |
| | | No heating at all | 17.87 |
| | Thermal comfort | Yes | 54.04 |
| | | No * | 45.96 |
| | Cool during summer | Yes | 66.14 |
| | | No * | 33.86 |
| | Surface area ($m^2$) | continuous | 102.85 [2] |
| | Urbanization level | Urban * | 34.29 |
| | | Peri-urban | 28.24 |
| | | Rural | 37.47 |
| Socioeconomic background | Gender | Male * | 45.60 |
| | | Female | 54.40 |
| | Age | (17–35) * | 9.35 |
| | | (36/44) | 14.94 |
| | | (45/54) | 19.33 |
| | | (55/64) | 18.47 |
| | | (≥ 65) | 37.90 |
| | Birthplace | Local * | 94.35 |
| | | Other (EU) | 1.26 |
| | | Other (Non-EU) | 4.39 |
| | Marital status | Never married * | 13.43 |
| | | Married | 62.44 |
| | | Widowed | 15.90 |
| | | Divorced | 8.22 |
| | Education level | Primary education * | 49.25 |
| | | Secondary education | 24.85 |
| | | Tertiary education | 11.29 |
| | | No formal education | 14.61 |
| | Household size (equivalized nº of household members) | continuous | 5.29 [2] |

**Table 2.** *Cont.*

| Independent Variables | Categories | Percentage (%)/Mean |
|---|---|---|
| Economic status | Working full-time * | 32.58 |
| | Working part-time | 2.04 |
| | Unemployed | 9.02 |
| | Students | 1.72 |
| | In retirement | 39.26 |
| | Permanently disabled | 1.77 |
| | Fulfilling domestic tasks and care responsibilities | 7.03 |
| Income quintile [3] | 1 (poorest) * | 13.73 |
| | 2 | 27.05 |
| | 3 | 27.32 |
| | 4 | 14.42 |
| | 5 (richest) | 17.48 |
| Chronic disease | Yes * | 45.25 |
| | No | 54.75 |

* Reference category for Section 4. [1] includes also leaking roof, damp walls/floors/foundation or rot in window frames or floor. [2] Mean. [3] contribution percentages for each quintile to overall equivalized disposable income.

Regarding the householder profile, the sample is composed by a higher share of women (54.40%), over 30% from older age ranges (≥65 years of age) and that was mostly born locally. To a large extent people have a lower education level (49.25% of the sample has primary education as highest education level attained) and are currently retired (39.26%). As previously mentioned, income is represented here according to income quintiles. Income quintiles enable us to study income inequality through group comparison, i.e., those in high income with middle income and low income. While the 1st income quintile, the bottom 20% with very low income, accounts for 13.73% of total disposable income, the 2nd quintile is the next lowest and accounts for a greater amount of disposable income (27.05%). However, the 3rd quintile, medium low, accounts for the greatest share of disposable income (27.32%). The 4th and 5th quintiles account for a greater amount of income in comparison to the 1st quintile but below the values reported for the 2nd and 3rd income quintiles. Concerning health background, over 50% of householders do not present any chronic illness. The first step for the modelling approach is undertaken in the next section, with the model specification.

### 3.3. Model Specification

In the 'counterfactual approach', a novel mediation analysis is proposed to understand what the role of the energy affordability in the relationship between poor housing conditions (thermal discomfort) and health status is. With this purpose in mind, a newly statistical model design, the four-way decomposition approach, developed by [25,47] was followed.

A mediation analysis implies that an exposure affects an outcome. This approach has been largely applied in medical and epidemiological field to study environmental exposures (e.g., [25]). Poor housing is often associated with environmental exposures such as damp or cold. In this case, poor housing conditions become the exposures in the mediation analysis, i.e., the exposure to poor housing conditions causes poor health. However, in the context of mediation analysis, the effect or impact of poor housing on health might follow different paths, implying an additional variable between the exposure and the outcome—a mediator. In Figure 2, consider the poor housing condition, with exposure to the cold (thermal discomfort) directly affecting health status (1); an alternative or indirect pathway (2) is if the thermal discomfort, as a proxy for lack of efficiency, affects a third variable, which could be energy affordability, and this variable affects the outcome, becoming the mediator between the exposure (thermal discomfort) and the outcome (health status). This assumption seems plausible since thermal discomfort from inefficient cold homes could lead to an increase in the use of energy and could compromise energy affordability by increasing households' energy expenditure for heating purposes.

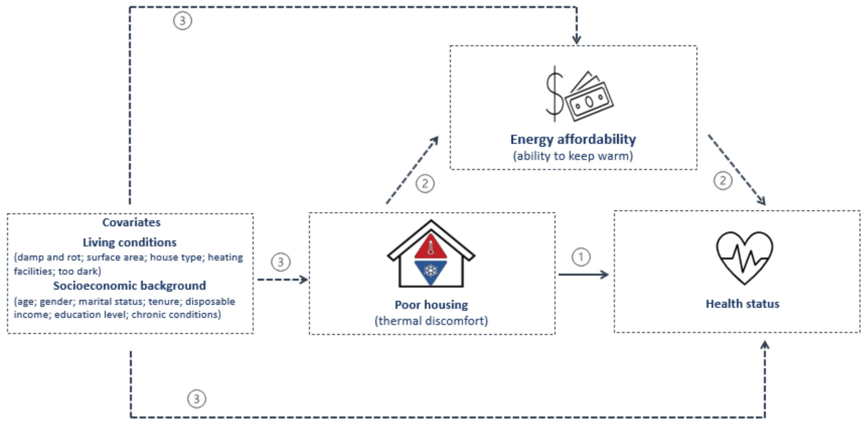


**Figure 2.** Mediation-directed acyclic graph with socioeconomic and living conditions covariates.

Pathways (1) and (2) in Figure 2 configure the 'conventional' mediation analysis, the more recent approach; the four-way decomposition approach enables us to consider covariates, such as the socioeconomic background variables; in this case, the example of age, is represented as pathway 3. Moreover, it is necessary to control these covariates, as they can affect both mediators and outcome, since for instance, the elderly may have different thermal comfort and health requirements. Additionally, the interaction between exposure and mediator is also taken into consideration, which is plausible given that cold homes could be considered houses that are difficult to heat, affecting the energy affordability (ability to keep warm). Similarly, the inability to keep warm could also influence thermal comfort perception, since energy affordability issues could lead householders to endure thermal discomfort to reduce their energy expenditures and to prevent the adoption of energy efficiency alternatives. Overall, there are four main variables of interest in this mediation analysis: the outcome variable (Y); the exposure (A), which can also be seen as a treatment variable and is hypothesized to have direct and indirect causal effects on the outcome; the mediator (M), which is hypothesized to be causally affected by the exposure/treatment (A) and that alternatively directly affects the outcome variable (Y); and the covariates (C) [48].

Poor housing conditions, such as the exposure to thermal discomfort could be addressed through energy efficiency measures, as their use could promote the transition from thermal discomfort towards thermal comfort. In this sense, the presence or absence of housing energy efficiency could be considered a 'treatment' for the exposure to poor housing conditions. Departing from this principle, we extend the VanderWeele's four-way decomposition method [47] to better understand the relationship between poor housing conditions (a proxy for the absence of energy efficiency), expressed as 'thermal discomfort' perception, versus 'thermal comfort' perception (a proxy for the presence of energy efficiency) and health status. Moreover, the interpretation of obtained results takes this approach into consideration.

Mediation analysis enables us to partition the total effect of thermal discomfort on health status into a direct effect (pathway 1) and an indirect effect (pathway 2) (see [37]). Resorting to the four-way decomposition, these effects can be further decomposed under a counterfactual approach. Vanderweele (2016) claims that total effect can provide additional information regarding the portion of the effect that (a) is only due to mediation; (b) that is only due to interaction; (c) that is due to both mediation and interaction; and (d) that is due neither to mediation nor to interaction [12,47]. A detailed definition of these effects is given in Table 3.

**Table 3.** Definition and interpretation of decomposition effects (adapted from [25,37]).

| Decomposition Effect | Counterfactual Definition | Interpretation | | Contextual Definition |
|---|---|---|---|---|
| Total Effect (TE) | $Y_a - Y_{a^*}$ | Total effect of exposure A (changing from $a^*$ to $a$) on the outcome Y | Overall effect | What is the risk of poor health among those transitioning from thermal discomfort to thermal comfort? |
| Controlled Direct Effect (CDE) | $(Y_{am} - Y_{a^*m^*})$ | Effect of exposure A (changing from $a^*$ to $a$) on the outcome Y, intervening to fix the mediator M to m | Due neither to mediation nor interaction | What is the risk of poor health among those transitioning from thermal discomfort to thermal comfort, if everyone is able to keep warm (has the same level of energy affordability)? |
| Reference Interaction ($INT_{ref}$) | $(Y_{am} - Y_{am^*} - Y_{a^*m} + Y_{a^*m^*})\,(M_a)$ | An additive interaction that operates only if the mediator is present ($M_{a^*} \neq 0$) when exposure is a | Due to interaction only | What is the risk of poor health among those with thermal discomfort and affordability issues (inability to keep warm), if thermal discomfort does not have an effect on the energy affordability? |
| Mediated Interaction ($INT_{med}$) | $(Y_{am} - Y_{am^*} - Y_{a^*m} + Y_{a^*m^*})\,(M_a - M_{a^*})$ | An additive interaction that operates only if the exposure A (changing from $a^*$ to $a$) has an effect on the mediator M $(M_a - M_{a^*} \neq 0)$ | Due to mediation and interaction | What is the combined risk of poor health among those with thermal discomfort and affordability issues (inability to keep warm), if thermal discomfort has an effect on the energy affordability? |
| Pure Indirect Effect (PIE) | $(Y_{a^*m} - Y_{a^*m^*})(M_a - M_{a^*})$ | Effect of the mediator (changing from $m^*$ to $m$) on the outcome Y when exposure A is a, multiplied by the effect of exposure A (changing from $a^*$ to $a$) on the mediator M | Due to mediation only | What is the risk of poor health among those transitioning from thermal discomfort to thermal comfort and no affordability issues, if thermal discomfort has an effect on the energy affordability? |

*Y* is the outcome (poor health); M is the mediator the ability to pay; A is the exposure thermal discomfort; ($a^*$) is the reference level of exposure (thermal discomfort); ($a$) is the level of thermal comfort, the level of actual exposure and ($m$) is being able to keep warm/affordability or the level of the mediator at which the four-way decomposition is computed.

Table 3 denotes 'chain of risk' similarly to [27]. The four-way decomposition can be explained by Equation (1) [12,26,49].

$$TE = CDE + INT_{ref} + INT_{med} + PIE \quad (1)$$

where TE denotes the total effect, decomposed into its four components: CDE (controlled direct effect), representing the effect neither due to mediation nor to interaction; ($INT_{ref}$), known as the reference interaction and representing the effect only due to interaction; and ($INT_{med}$), or mediated interaction, which is the effect due to mediation and interaction; and finally, PIE (pure indirect effect), due to mediation alone. It should be noted that, controlling for covariates, such as age, gender, income and education level, or the damp and rot, ensures that the assumptions of no unmeasured confound between exposure and outcome, between mediator and outcome, and between exposure and mediator are ensured. Additionally, the mediator–outcome confounders should not be affected by the exposure. Therefore, and similarly to prior studies, the results were interpreted under the assumption that covariates (potential confounders) were controlled for and that the exposure does not affect any of the mediator–outcome covariates.

The counterfactual approach is also based on outcome and mediator models, upon which the decomposition into its four components takes place. The regression model for the outcome (health status) is a function of the exposure (thermal discomfort), the mediator and their interaction. The regression for the mediator (energy affordability) is a function of the exposure. Both models are controlled for covariates (living conditions and socioeconomic background variables). Based on [26,47], the mediator and outcome model, allowing for exposure–mediator interaction, can be expressed by Equations (2) and (3):

$$\text{Outcome Model} : \text{logit}\ \{\text{P} = 1\,|\text{a}\,, \text{m}, \text{c}\} = \theta_0 + \theta_1 \text{a} + \theta_2 \text{m} + \theta_3 \text{am} + \theta_4' \text{c} \tag{2}$$

$$Mediator\ Model : logit\{M = 1|a, c\} = \beta_0 + \beta_1 a + \beta_2' c \tag{3}$$

where $\theta_1$ to $\theta_p$ and $\beta_1$ to $\beta_p$ are the model's coefficients, a is the exposure (thermal discomfort in Figure 2), M and m are the mediator (energy affordability), and c is a set of covariates (socioeconomic and other living conditions in Figure 2). The mediation was run with the reference level of exposure (a*) set at presence of poor housing (thermal discomfort), the mediator was set at the m level, and affordability or ability to keep warm level and the covariates were set at average levels. Mediation analysis is further decomposed into its four components automatically by resorting to the 'med4way' command in STATA software, recently developed by [25,26].

## 4. Results

In this section, the results from the statistical modelling are presented and discussed, namely regarding the energy efficiency (CDE) and the energy affordability (PIE) pathways.

A detailed summary of the components of the four-way decomposition is provided in Table 4. It shows the reduced output, which provides estimates of the total effect (TE) of thermal discomfort on health. It also shows the attributable proportion (PA), which results from the contribution of the different components to the total effect (TE). PA is an estimate of which share of the total effect of thermal discomfort on health is due to the direct effect, to the mediation effect or to the interaction effect.

There seems to be a negative association between the presence of poor housing conditions and poor health, for both samples, with high significance level. This means the overall effect of transitioning from thermal discomfort (reference level) to thermal comfort implies a reduction in the health risk (of poor health status). This reduction is more accentuated for the elderly (β = −0.332, SE = 0.076; $p \leq 0.001$) than for the overall sample (β = −0.282, SE = 0.058; $p \leq 0.001$). Figure 3 proposes a path diagram, where the black full lines illustrate the contribution of each decomposition effect and the grey dotted line illustrates its absence, with the respective coefficients and significance levels.

**Table 4.** Model coefficients for 'counterfactual' approach.

| Overall Sample Decomposition Effects | β Coefficients (Std. Err.) | *p*-Value | PA (%) | Elderly Sample Decomposition Effects | β Coefficients (Std. Err.) | *p*-Value | PA (%) |
|---|---|---|---|---|---|---|---|
| Total effect (TE) | −0.282 (0.058) | ≤0.001 | 100 | Total effect (TE) | −0.332 (0.076) | ≤0.001 | 100 |
| Controlled direct effect (CDE) | −0.180 (0.069) | ≤0.008 | 64 | Controlled direct effect (CDE) | −0.236 (0.087) | ≤0.008 | 71 |
| Reference interaction ($INT_{ref}$) | 0.047 (0.105) | ≤0.801 | −17 | Reference interaction ($INT_{ref}$) | 0.071 (0.130) | ≤0.587 | −21 |
| Mediated interaction ($INT_{med}$) | −0.031 (0.027) | ≤0.802 | 11 | Mediated interaction ($INT_{med}$) | −0.048 (0.089) | ≤0.590 | 14 |
| Pure indirect effect (PIE) | −0.118 (0.030) | ≤0.001 | 42 | Pure indirect effect (PIE) | −0.119 (0.085) | ≤0.008 | 36 |

*Proportion attributable (PA) (%)*

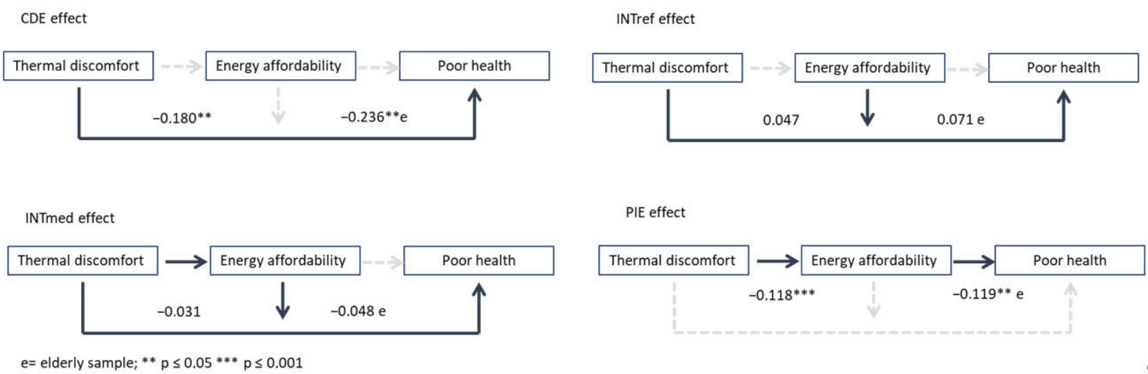


**Figure 3.** Path diagram for decomposition effects (adapted from [50]).

As illustrated in Figure 3, the only statistically significant paths are the direct and indirect pathways, through the contribution of CDE effect and PIE effect, respectively. Similarly to the overall decomposition effect (TE effect), in Table 4, the coefficients for CDE and PIE effects are smaller for overall population (CDE $\beta = -0.180$ SE = 0.069; $p \leq 0.008$; PIE $\beta = -0.118$, SE = 0.030; $p \leq 0.001$ than for elderly population segment (CDE $\beta = -0.236$, SE = 0.087; $p \leq 0.008$; PIE $\beta = -0.119$, SE = 0.085; $p \leq 0.008$).

Furthermore, the relevance of the role of exposure (thermal discomfort) and mediator (energy affordability) that underly the abovementioned decomposition effect is better understood in the results from the outcome and mediator models (see Table S1 in the Supplementary Materials). The obtained coefficient for thermal discomfort in the mediator model with positive and highly significant coefficients implies that exposure to thermal discomfort increase the likelihood of poor health for both general population (coeff. = 1.465 (0.070), $p \leq 0.001$) and the elderly (coeff. = 1.600 (0.111), $p \leq 0.001$).

Meanwhile, energy affordability also presents a highly significant but negative coefficient in the outcome model for both general and elderly population segments (coeff. = −0.430 (0.107), $p \leq 0.001$ versus coeff. = −0.377 (0.142), $p \leq 0.008$). The negative coefficient implies that people with the ability to pay for keeping the house warm show a lower likelihood of poor health status. The interaction between thermal discomfort and energy affordability was non-significant, similarly to decomposition effects in Table 4.

The most significant results from decomposition approach (CDE and PIE effects) are further explored in the next section.

## 5. Discussion

The obtained results seem plausible, given that on one hand, other studies have suggested that the elderly tend to spend more time indoors [45]; therefore, they might be more exposed to indoor environment. On the other hand, the elderly population often tends to suffer from chronic conditions [51,52], which could make them more susceptible to small variations in indoor temperature and thermal comfort or discomfort. Therefore, it seems possible that given the different characteristics of the sampled population, it could be affected differently by the same poor housing condition. The obtained results reinforce the relevance of adequate housing for this segment of the population and the need to understand what this means for this segment of the population.

The controlled direct effect (CDE) also shows a negative effect. This implies that, had we intervened, excluding energy affordability issues, the harmful effect of thermal discomfort on health status would be reduced by 64% in the overall sample and 71% in the elderly sample. Taking into consideration that the CDE effect is reflective of the improvement of thermal discomfort that results neither from mediation nor from interaction, this implies that the adoption of energy efficiency alternatives seems to significantly reduce health risks from poor housing, particularly among vulnerable population segments. The health risk reduction associated with the CDE effect seems plausible, given the energy inefficient nature of the building stock in Portugal (see [7]). Additionally, recent empirical studies have pointed out that households in different geographic locations of the country could be considered cold homes (see [53,54]) and, therefore, could possibly foster thermal discomfort perception. Therefore, it is expected that a large share of households might benefit from the thermal comfort resulting from the adoption of energy efficiency measures, as proposed by CDE effect. Besides reinforcing the notion of cold homes and the extensive need for renovations to fulfill thermal comfort and safety requirements (e.g., [7,54]), the CDE further suggests that energy-efficient alternatives that can be used for climate change adaptation may also present benefits in terms of health.

The decomposition results also show that the only other significant pathway towards the improvement of indoor temperature perception is the indirect pathway. According to the pure indirect effect (PIE), tackling issues related to affordability or the inability to keep the house warm could also contribute to further reduce the risks of thermal discomfort on health by 42% in the overall sample and by 36% for the elderly sample. Moreover, this result is relevant for policymakers since the inability to keep warm or affordability issues might be viewed in this context as a proxy for energy poverty. This result also emphasizes the relevance of socioeconomic context, along with living conditions. The obtained results are in accordance with prior studies that have emphasized that Portugal is amongst the European countries that are affected by this issue (see [10,55]). Other effects, namely for interactions ($INT_{ref}$) and ($INT_{med}$), were non-significant.

Overall, obtained results have shown that the relationship between poor housing conditions, namely thermal discomfort, and health status seem to be partly mediated by the ability to keep the household warm. This risk seems to be greatly reduced, for the overall population and its vulnerable segments (the elderly), using housing energy efficiency alternatives. The relevance of housing energy efficiency beyond energy and emission reduction in the climate change mitigation context has been established. The decrease in the CDE and PIE coefficients showed if upon action to improve thermal discomfort, either in a direct or indirect manner, a reduction in the health risk posed by poor housing exposure could be possible. Measures focusing exclusively on energy affordability issues (PIE effect) might not be enough, given that the greatest impact in reducing health risk from thermal discomfort is reached directly through the adoption of energy efficiency measures (CDE effect). More importantly, obtained results seem to emphasize that the maximization of the potential health benefits is better realized by eradication of thermal discomfort promoted by energy efficiency, followed by alleviation of thermal discomfort where the affordability issues (i.e., inability to keep warm) is also tackled. Furthermore, obtained results seem to convey that a complementary approach that promotes the adoption of energy efficiency alternatives while taking into consideration the energy poverty/socioeconomic background should be undertaken. These results are aligned with Declós and Vidal (2021) findings that reinforce that efficiency and affordability housing initiatives should strive both for climate and housing cost neutrality [56]. In this setting, the development of urban living laboratory (ULL) to study urban interventions in the context of sustainability, as suggested by [57], could be of interest.

It should also be noted that, a sensitivity analysis, based on resetting the mediator level, was performed to test robustness of obtained results. Though differences were found in the coefficients of CDE, no differences in terms of sign of the coefficient and significance level were found in the total effect (TE) nor at the mediator level (PIE), reinforcing obtained results. A similar result was obtained by [49]. Therefore, answering the proposed research question the energy affordability seems to be a valid mediator between poor housing and health status. However, the causality assessment based on mediation analysis should be cautious since misclassification of health status due to self-diagnosis might also be reasonable and should not be disregarded. Discacciati et al. (2019) has warned about this potential source of bias [25]. Additionally, due to the aggregate nature of the data available on the database the use of localized climate data was compromised, as well as the ability to establish more detailed links to energy and building characteristics, since information regarding construction age, building materials, possible energy efficiency interventions was lacking. It should also be noted that, the restrictions of the current database, regarding the availability of a proxy for energy affordability during summertime, limits the study of the mediation effect to the wintertime. Still, the relevance of summertime period and the exposure to heatwaves is becoming an increasingly recognized subject for indoor thermal comfort research (see [58,59]).

## 6. Conclusions

A mediation analysis was made to better understand whether the relationship between thermal discomfort and health status is further explained through an underlying association with energy affordability. Based on data from Eurostat's European Union -Statistics on Income, Social Inclusion and Living Conditions (EU-SILC) database, the relationship between thermal discomfort and health status was assessed, to test the role of the energy affordability as a potential mediator. This analysis contributes for policy makers not only to identify the impact of thermal discomfort on health but also, most importantly, to acknowledge the main pathways to address negative impacts. For that purpose, VanderWeele's four-way decomposition approach was adapted and extended to the energy efficiency field. The findings show that suggest that the ability to keep warm is a valid mediator for the association between poor housing and health. The mediator or PIE effect accounted for 36% reduction of health risk for the elderly and 42% for overall population.

The greatest risk reductions for incurring in poor health are reached directly via energy efficiency. The results show a 71% health risk reduction for the elderly and 64% for overall population by promoting the transition from thermal discomfort to thermal comfort. These results have relevant policy implications, namely that, in order to achieve health benefits, the development of energy efficiency policies need to be complemented with socioeconomic background information, namely energy poverty status. Therefore, policies need to be targeted towards people who cannot afford them without assistance.

This work emphasized the need to further develop quantitative indicators (for energy and health fields) and their integration into existing databases and related cost–benefit analysis. For instance, the lack of information regarding energy affordability for summertime hinders the possibility to properly understand the impact of thermal discomfort from heat on health, which is imperative in the context of climate change and increasing exposure to extreme events such as heatwaves. Additionally, relevant variables for this study such as thermal discomfort are only available when ad hoc modules for living conditions take place. This fact prevents continuous monitoring of energy-related issues, such as energy efficiency, energy poverty and climate change, ultimately preventing policy makers to access best available information for decision making process. Besides self-reported health status, the use of different health metrics regarding mental health, chronic conditions and wellbeing is required for future research. Collaboration with local health services is crucial to develop databases that contemplate objective medically assisted health indicators, use of healthcare services and medication. Collaboration with local municipalities is also critical to identify and monitor poor housing conditions (e.g., inadequate indoor temperature and dampness) as well as an opportunity to gather information regarding energy poverty status at community level. We further argue that there is a pressing need to incorporate health in energy and climate change policies for housing, under the penalty of the potential benefits from the improvement of thermal discomfort passing unnoticed at policy level, potentially increasing instead of decreasing the risk for health.

Ensuring that measures that promote building renovation and renewable energy in buildings do not become an additional cost burden and a health hazard for vulnerable population segments could, upon further research, contribute towards promoting and accelerating a just energy transition.

A holistic approach is essential to promote Sustainable Development Goals (SDG). That requires the development of policies that encompass living conditions, energy efficiency, health and an aging population. The inclusion of health impacts into prominent policies such as energy and urban planning is recommended.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su142114435/s1, Table S1: Outcome and the mediator model coefficients.

**Author Contributions:** Conceptualization, F.L., P.F. and V.L.; methodology, F.L.; software, F.L.; validation, P.F. and V.L.; formal analysis, F.L., P.F. and V.L; investigation, F.L., P.F. and V.L.; resources, F.L., P.F. and V.L.; data curation, F.L. and V.L.; writing—original draft preparation, F.L.; writing—review and editing, V.L. and P.F.; supervision, V.L. and P.F. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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*sustainability*

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# Evaluating Urban Sustainability in Uzbekistan: A Novel Formula for Empirical Analysis

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**Abstract:** Urban sustainability has become a critical issue in the past few decades due to rising urbanisation and mounting environmental problems. This article aims to develop a novel formula for assessing urban sustainability in Uzbekistan, a country with very little recent research in the field of sustainable development. The formula was created specifically for the setting of Uzbekistan to evaluate urban sustainability by taking into account a variety of socioeconomic and environmental aspects specific to the discussed region. The article provides a thorough review of the research on urban sustainability, with an emphasis on evaluation techniques and their use in the Uzbek context, which not only contributes to the development of the theoretical framework for the research but also identifies the knowledge gaps in the assessment of urban sustainability in Uzbekistan. Utilising this newly developed formula, an empirical analysis of urban sustainability in Uzbekistan urban settings was conducted, offering comprehensive insights and suggestions for urban planning and policymaking. The results of this research are expected to advance the discussion about urban sustainability on a global scale as well as act as a catalyst for additional research in the area.

**Keywords:** urban sustainability; sustainable urban development; evaluation; sustainability assessment; Uzbekistan

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## 1. Introduction

As the world continues to experience rapid urbanisation, population increase, and escalating environmental issues, urban sustainability is becoming an increasingly important concern [1,2]. In recent years, scholars have sought to define and measure urban sustainability to better comprehend its many facets and support efficient policymaking [3,4]. The Central Asian nation of Uzbekistan, which has a substantial urban population, is no exception to this pattern [5]. There has not been any recent research on the assessment of urban sustainability in Uzbekistan, despite the country's rising understanding of the significance of this issue [6].

This research aims to fill this knowledge gap by creating and applying a new method for assessing urban sustainability in Uzbekistan. The developed formula takes into account a variety of socioeconomic and environmental elements adapted to the specific national setting. Due to the absence of research on urban sustainability in Uzbekistan, this research attempts to advance the discussion about urban sustainability on a global scale and offer valuable insights and policy recommendations for the region.

The rationale for this research is rooted in several key factors that underscore the importance of urban sustainability evaluation in Uzbekistan. First, the country's urban areas are under increasing strain due to substantial socioeconomic, infrastructure, and environmental issues brought on by rapid urbanisation [1,5]. A thorough grasp of urban sustainability is necessary to support evidence-based decision-making and better policy results with this growing concern [2,7]. Additionally, since urban sustainability is a multifaceted idea encompassing social, economic, and environmental concerns, creating an evaluation framework specific to Uzbekistan's urban contexts is crucial. Last but not least, this research can assist Uzbekistan in harmonising its urban planning and management practices with international sustainability goals, such as the Sustainable Development Goals (SDGs) and the New Urban Agenda (NUA), given the growing global emphasis on sustainable urban development [8,9]. Uzbekistan can promote a more sustainable urban future by utilising the study's findings, improving the well-being of its residents, and fostering sustainable growth in the area.

The structure of this article is as follows: A thorough assessment of the research on urban sustainability is presented in Section 2, emphasising evaluation techniques and their use in the Uzbek setting. Part 3 discusses the procedure for gathering data and choosing samples and how the unique formula for evaluating urban sustainability was developed. Urban sustainability in Uzbekistan is empirically analysed in Section 4, while Section 5 looks at the implications of the findings and potential directions for future research.

Urban sustainability assessment has received much attention lately, with much research concentrating on creating and assessing instruments for sustainable cities. Unfortunately, urban sustainability evaluation literature primarily focuses on industrialised nations, focusing little on underdeveloped areas such as Uzbekistan. Most currently used assessment instruments were created and tested in Europe and North America and might need to be revised in the setting of Uzbekistan. This creates a sizable gap in the literature, making it challenging to analyse urban sustainability in Uzbekistan due to a lack of region-specific assessment methodologies. In addition, assessment methodologies that consider regional specifics are necessary due to Uzbekistan's particular social, economic, and environmental setting. As a result, it is necessary to create evaluation instruments tailored to the Central Asian context, specifically Uzbekistan.

## 2. Literature Review

### *2.1. Concept of Urban Sustainability*

Due to its complexity and the increasing importance of ever-growing urban surroundings, urban sustainability has become a crucial topic in recent years [10]. Despite its widespread use, urban sustainability remains a controversial concept, with various scholars offering different definitions and interpretations [3,11]. To ensure the long-term viability, resilience, and well-being of urban regions, urban sustainability is widely defined as the integration of social, economic, and environmental factors [12,13].

Nowadays, with more than half of the world's population living in cities, urbanisation is a worldwide phenomenon. Significant environmental and socioeconomic problems brought on by rapid urbanisation include increasing greenhouse gas emissions, air and water pollution, biodiversity loss, and social inequality. Urban sustainability evaluation is becoming more and more crucial to addressing these issues. To make sure that the demands of the present and future generations are addressed while limiting adverse effects on the environment, urban sustainability assessment examines the social, economic, and environmental aspects of urban growth. An evaluation of urban sustainability can assist policymakers in identifying areas that need improvement and prioritising initiatives to solve these problems. Many factors, including land use, infrastructure, energy use, waste management, air quality, and water quality, go into assessing urban sustainability.

Nevertheless, the concentration of population in urban areas can result in lower per capita resource usage, which may contribute to more sustainable resource consumption. Moreover, urban areas often serve as hubs of intellectual and professional energy, fostering innovation and collaborative efforts towards sustainable development. Therefore, while the article primarily addresses the challenges of urbanization, it is important to recognize and emphasize the potential benefits and opportunities it brings. The application of the methods discussed should take into account this balanced perspective, as well as the interconnectedness of the various aspects of urbanization.

### *2.2. Urban Sustainability Assessment and Carrying Capacity*

Environmental carrying capacity is a crucial aspect to take into account when evaluating urban sustainability. Environmental carrying capacity is the extent to which an ecosystem can sustain a certain amount of human activity without suffering material harm [14]. Many indicators can be used to measure environmental carrying capacities, such as air and water quality, land usage, and biodiversity [15].

Because urbanisation can have detrimental effects on the environment, such as pollution, deforestation, and biodiversity loss, the health and well-being of urban dwellers and the ecosystems they depend on may be seriously harmed by these adverse effects. To ensure that urban areas are sustainable over the long term, evaluating the environmental carrying capacity is crucial. Environmental carrying capacity ensures that urban development is within the limits of the environment to support human activity. Policymakers can identify areas that require improvement and prioritise interventions to address these areas. In this article, we try to incorporate some elements from the environmental carrying capacity evaluation as it addresses the environmental pillar of sustainability.

### *2.3. Dimensions and Challenges of Urban Sustainability*

Urban communities' wellness, equity, and inclusiveness are critical considerations in social sustainability [16]. Housing, health, education, social cohesion, and cultural preservation are among a few of the many facets it covers [17]. Contrarily, economic sustainability focuses on the long-term stability and growth of urban economies, taking into account elements such as employment, income distribution, and economic resilience [18]. To preserve ecosystems and improve human health, environmental sustainability focuses on conserving and managing natural resources and reducing waste and pollution [4,19].

To achieve balanced and comprehensive urban development, all three aspects of urban sustainability must be integrated [20,21]. Over time, the idea of urban sustainability has evolved, embracing new components such as governance, technology, and innovation [3,4]. In addition, the role of social norms and culture in determining urban sustainability is becoming more widely acknowledged, highlighting the necessity of region-specific methods and solutions [13,22].

Urban sustainability is a multifaceted concept that seeks to tackle the social, economic, and environmental issues that urban areas face in a comprehensive and integrated way. While there is no commonly accepted definition [11,12], urban sustainability is usually regarded as the goal of long-term resilience, well-being, and prosperity in urban environments, with respect for context-specific elements and the interconnectedness of many characteristics in social, economic, and environmental fields.

Understanding the state of urban regions today and using that knowledge to direct future policy and planning initiatives requires a critical appraisal of urban sustainability [2]. The performance of urban sustainability has been evaluated using a variety of indicators and tools in the literature [20]. Indicator-based frameworks, composite indices, and qualitative methodologies are the three primary categories into which these approaches can be generally grouped [23,24].

Key performance indicators (KPIs) are used in indicator-based frameworks to measure many aspects of urban sustainability [2]. These metrics might be qualitative, such as with inhabitants' satisfaction with public services, or quantitative, such as with CO2 emissions or green space per person [25,26]. The selection of indicators is essential because they must be relevant, quantifiable, and responsive to the unique circumstances of the investigated urban areas [27,28].

Composite indices provide a simplified and readily conveyed assessment of urban sustainability performance by combining many variables into a single value [29]. The Global City Indicators Facility (GCIF), the European Green City Index (EGCI), and the Sustainable Development Goal (SDG) Index are a few examples of composite indexes [30,31]. Even though composite indices provide a clear and succinct picture of urban sustainability, they may oversimplify complicated problems and conceal inconsistencies across dimensions or sub-indicators [23]. Yet, advocates of composite indices assert that two of their significant advantages are how simple and straightforward they are [32]. Although composite indices may indeed oversimplify complicated topics and conceal inequalities between dimensions or sub-indicators, they can be helpful communication tools to involve the public and politicians in concerns of urban sustainability [33]. Composite indices enable city comparisons and aid in identifying best practices and areas for improvement by combining various indicators into a single value [34]. Moreover, the limitations of composite indices can be addressed through methodological refinements and the incorporation of supplementary analyses [35]. For instance, combining composite indices with more detailed indicator-based frameworks can provide a more nuanced and comprehensive assessment of urban sustainability, balancing the strengths and weaknesses of both approaches [36].

Furthermore, as they often require the integration of diverse data sources and expertise from various fields, creating and using composite indices can encourage interdisciplinary study and cooperation [37]. In this way, composite indices might work as catalysts for improving urban sustainability theory and practice [35]. Thus, in this research, we attempt to develop a composite index.

Qualitative approaches such as case studies, interviews, and focus groups provide insights into local perspectives, experiences, and context-specific aspects that may affect urban sustainability results, which can be used in conjunction with quantitative analyses [22,38]. These techniques are beneficial for capturing urban sustainability's social and cultural aspects, which could be challenging to measure using traditional metrics [13,39].

### *2.4. Sustainable Development in Uzbekistan*

The difficulties and opportunities associated with urban sustainability take on a particular dimension due to the unique circumstances of Uzbekistan. Uzbekistan, a nation in Central Asia that is rapidly urbanising, presents a complex range of economic, social, and environmental problems that call for specialised policies and evaluation frameworks [40].

Sustainable development in Uzbekistan has gained significant attention in recent years as the nation attempts to balance its rapid economic growth with environmental protection and social development.

During the Soviet era, Uzbekistan experienced extensive industrialization and urbanization, which has contributed to many environmental and socioeconomic challenges. The overuse of water resources, soil degradation, and poor air quality remain pressing issues, exacerbated by the rapid growth of urban centres such as Tashkent, Samarkand, and Bukhara.

In recent years, the government of Uzbekistan has taken steps to promote sustainable development, including the adoption of the 2030 Agenda for Sustainable Development, which outlines 17 Sustainable Development Goals (SDGs). This agenda has guided the country's efforts in areas such as poverty alleviation, climate change mitigation, and responsible resource consumption.

Additionally, Uzbekistan has actively sought international cooperation to support its sustainable development initiatives [40]. The country has partnered with organizations such as the United Nations Development Programme (UNDP), the World Bank, and the Asian Development Bank (ADB) to implement projects that focus on sustainable urban planning, renewable energy, and environmental protection.

Urban sustainability in Uzbekistan is highly dependent on economic growth as the nation transitions from a resource-based to a more diversified and knowledge-based economy. Infrastructure, education, and innovation spending are crucial for fostering long-term economic growth and raising living standards in urban areas [41,42]. Yet, attaining balanced and fair development is still challenging due to persistent income and resource availability differences between various regions and socioeconomic groups [6].

Since rising urbanisation and industrialisation have increased pollution, resource consumption, and the deterioration of natural ecosystems, environmental issues are also a top priority in Uzbekistan [43]. Climate change makes these issues worse, making the nation particularly susceptible to water scarcity, temperature swings, and extreme weather occurrences [44]. The complex interdependencies between urban systems, natural resources, and global environmental processes call for integrated and flexible policies to address these environmental concerns.

In Uzbekistan, many challenges fall under the social dimension of urban sustainability, including housing, public health, safety, and social cohesion [45]. Due to the demands that rapid urbanisation has placed on housing and social infrastructure, there are frequent informal settlements and poor living conditions [6]. It is essential to ensure that all urban residents have fair access to quality housing, public services, and social opportunities to promote social sustainability and improve residents' well-being [41].

Despite these insights, the literature on urban sustainability in Uzbekistan remains scarce and fragmented, with limited empirical evidence and few evaluation frameworks tailored to the country's specific context. This research gap highlights the importance of further research to create and implement context-sensitive evaluation methods, such as the suggested formula, to enhance the understanding and practice of urban sustainability in Uzbekistan.

## 3. Materials and Methods

The first step in this research involved identifying the key factors affecting Uzbekistan's urban sustainability. A comprehensive literature review explored the existing knowledge on urban sustainability in the country and its specific challenges and opportunities. We conducted a systematic literature review using the PRISMA method, after which 28 papers were selected for the final analysis. The PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is a widely recognized approach for conducting literature reviews, specifically in the field of social sciences. It provides a systematic and transparent framework that enables researchers to identify, appraise, and synthesise relevant studies, reducing the risk of bias and ensuring reliability of the review's findings. Based on this review, a list of potential factors was generated by tagging of the selected documents, encompassing economic, environmental, and social dimensions. Initially, 32 indicators were chosen for the analysis, followed by the exclusion of 3 indicators due to the non-availability of data.

To ensure the validity and relevance of the identified factors, a panel of experts in the field of urban sustainability was assembled, considering their diverse backgrounds, expertise, and experience in the Uzbek context. The selection criteria for the panel of experts were as follows:

1. Expertise in urban sustainability: The experts chosen had demonstrated knowledge and experience in the area of urban sustainability, including research, practice, and policymaking.
2. Experience in the Uzbek context: The experts were familiar with the unique challenges and opportunities related to urban sustainability within the Uzbekistan setting, which ensured the findings' relevance and applicability to the local context.
3. Minimum years of experience: The experts were required to have a minimum of five years of experience in the field of urban sustainability or a related area, demonstrating a depth of understanding and a track record of engagement in the field.
4. Previous involvement in relevant projects or research: The experts had previously participated in projects, research, or initiatives related to urban sustainability, showcasing their ability to contribute valuable insights to the study.
5. Recognized contributions to urban sustainability initiatives: The experts were selected based on their achievements or recognitions in the field, which could include awards, published research, or leadership roles in urban sustainability projects.

Initially, the invitation was sent out to 18 experts. However, 8 experts did not respond to the invitation. By applying these selection criteria, a diverse and knowledgeable panel of 10 experts was formed, comprising 2 government representatives, 2 representatives of international organisations (UN), 1 representative from KPMG's sustainability consulting department, 3 academics, 1 journalist specialising in ecological problems of the country, and an owner of a social-change-related business. The experts were asked to confirm the selection of the indicators. They were offered to include indicators they deemed necessary or exclude the ones presented to them. The experts agreed to exclude one indicator: the percentage of children enrolled in primary education. This indication showed no variance throughout the years and was not believed to be relevant since extremely high enrolment in primary school was changing dramatically towards the end of the school years and the beginning of higher education.

Following agreement on the final list of indicators, they were divided into 4 groups and 1 subgroup according to their thematic connections and potential interdependencies. This categorisation sought to make it easier to analyse and explain the results later and to give the evaluation framework a more explicit structure.

The expert panel assessed the importance of each aspect in the context of urban sustainability in Uzbekistan using a Likert scale ranging from 1 (least important) to 10 (most important). This step was intended to compile the collective wisdom and insights of the experts and weigh the various elements under their perceived importance. Once the ranking was complete, the results underwent statistical analysis depicting descriptive statistics: including range (minimum and maximum values), mean, standard deviation, and variance. Then, using the results, we calculated the weights for each indicator. Applying this methodology corresponds to transforming actual averages into coefficients ranging from 0.8 to 1.2, where the worst performer obtains a score of 0.8 and the best performer a 1.2.

Once the weights were calculated, we ran the descriptive statistics on each indicator and performed a correlation analysis to ensure no high correlation between any two indicators was detected. Then we normalised the data for each indicator from 15 years using this formula:

$$x_{in}^{s} = \frac{x_{in} - x_{min}}{x_{max} - x_{min}}$$

where $x_{in}^{s}$ is the normalised value of the stimulative variable; $x_{min}$ is a minimum value of stimulative raw data value; $x_{max}$ is a maximum value of stimulative raw data value; and $n$ is the country, i—year.

Finally, based on the expert evaluations, a model incorporating all the selected indicators and their assigned weights was developed to assess urban sustainability in Uzbekistan. This formula was designed to provide a quantitative measure of urban sustainability performance, taking into account the unique challenges and opportunities faced by the country's cities.

Later, we repeated the steps mentioned above (descriptive statistics, correlation, data normalisation) with data from other countries to detect the minimum and maximum possible values in this methodology.

## 4. Results

Based on the most relevant papers on drivers of sustainability [25,29,46,47] and analysis of data availability, we selected 29 indicators to be included in the formula. These indicators were then grouped into four categories: environment, economy, awareness, and society, with a subgroup "gender equality and female empowerment". Gender equality and female empowerment were highlighted as a separate subgroup due to the deterioration in this field caused by barbaric social norms, discriminatory laws and regulations, and a very strong patriarchal structure of the society. The classification of the selected factors is presented in Figure 1. "Awareness" is not commonly used in sustainability assessment; however, it is believed to be an important factor in promoting sustainability as it acts as a first step in the creation of a sustainability culture. Burksiene et al. emphasise the importance of integrating sustainability into both individual and societal beliefs, values, and behaviours and suggest that culture can be a key element in fostering an understanding of sustainability and that incorporating cultural policy into social systems can shift values towards sustainable behaviour [48].

We decided to use uneven weights for each factor in accordance with studies on the methods for developing composite indices [49–51] based on the information gathered from experts in the following step of this research. The authors contacted ten experts in the area of sustainable development in Uzbekistan to evaluate the importance of each indicator. Some experts come from academia, while others have practical experience in the field of sustainable development in Uzbekistan. Such selection was motivated by the need to gather various perspectives that result from the divergent experiences of practitioners and scientists.

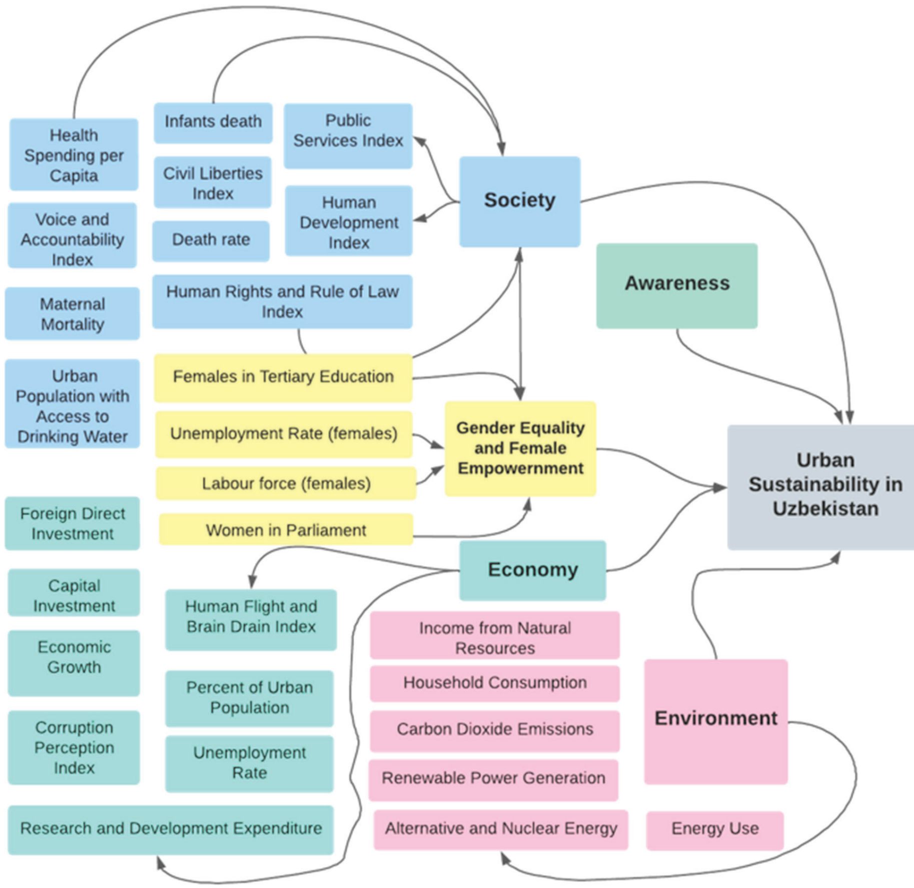


**Figure 1.** Indicators selected for inclusion in the formula and their classification (developed by authors).

When adjusting weights to the indicators based on the experts' evaluation, the individual indicators in each area were normalised on a 1-to-7 scale and aggregated by averaging the normalised scores so that all indicators' scores were calculated for each year [52]. In the second step, these scores were normalised again on a 0.8-to-1.2 scale. Applying this methodology corresponds to transforming actual averages into coefficients ranging from 0.8 to 1.2, where the worst performer obtains a score of 0.8 and the best performer a 1.2 [50]. Thus, we developed the following formula with adjusted weights:

$$US = f\,(0.944\ HFBDIt,\ 0.98\ PSIt,\ 1.06\ HRRLIt,\ 1\ HDIt,\ 1.08\ WPt,\ 1.04\ RWMTEt,$$

$$1.03\ PUPt,\ 1.01\ HSpCt,\ 0.9\ DRt,\ 1\ UPDWt,\ 0.97\ MMt,\ 1.04\ IDt,\ 0.95\ AEt,\ 1\ RDIt,$$

$$1.04\ CPIt,\ 0.98\ CLRIt,\ 0.96\ EpCt,\ 0.99\ CDpCt,\ 0.98\ INRt,\ 0.99\ RPGt,\ 1.02\ EGt,$$

$$1.03\ CIIt,\ 1.03\ HCt,\ 0.99\ Ut,\ 1\ UFt,\ 0.96\ LFFt,\ 0.96\ FDIt,\ 0.98\ VAIt,\ 1.05\ At)$$

where:
*US*—Urban sustainability;
*HFBD*—Human flight and brain drain index, 0 (low)–10 (high);
*PSI*—Public services index, 0 (high)–10 (low);
*HRRLI*—Human rights and the rule of law index, 0 (high)–10 (low);
*HDI*—Human Development Index (0–1);
*WP*—Women in parliament, percent;
*RFM*—Ratio of female to male students in tertiary level education;
*PUP*—Percent urban population;
*HSpC*—Health spending per capita;
*DR*—Death rate per 1000 people;
*MM*—Maternal mortality per 100,000 live births;
*UR*—Unemployment rate, percent;
*ID*—Infant deaths per 1000 live births;
*UPADW*—Percent urban population with access to drinking water;
*ANE*—Alternative and nuclear energy, percent of total energy use;
*RDE*—Research and development expenditure, percent of GDP;
*CPI*—Corruption Perceptions Index, 100 = no corruption;
*CLI*—Civil liberties index, 7 (weak)–1 (strong);
*EUpC*—Energy use per capita;
*CDE*—Carbon dioxide emissions per capita;
*INR*—Income from natural resources, percent of GDP;
*RPG*—Renewable power generation, billion-kilowatt hours;
*EG*—Economic growth: the rate of change of real GDP;
*CI*—Capital investment as a percent of GDP;
*HC*—Household consumption as a percent of GDP;
*ERF*—Unemployment rate for females;
*LFF*—Labour force, per cent female;
*FDI*—Foreign direct investment, percent of GDP;
*VAI*—Voice and accountability index (−2.5 weak; 2.5 strong);
*A*—Awareness;
$t$ = at year t.

The data for each indicator were then normalised to be included in the calculation. A correlation analysis was performed to ascertain the statistical significance of each of the indicators mentioned above before data normalisation. No two independent variables were found to be highly linked, so no multicollinearity conundrum was encountered.

We have proposed a formula for evaluating urban sustainability in Uzbekistan. However, for the final results of such evaluations to make sense, we need to provide the maximum and the minimum possible values that would reference the actual level of urban sustainability. While some indicators already provide possible maximum and minimum values, such as Human Development Index or Corruption Perception Index, others, such as "research and development expenditure", 'economic growth', etc., do not. So, to provide such values, we needed to conduct a comparative analysis.

To obtain minimum values, we took data from Afghanistan. It is one of the countries Uzbekistan borders, and it is arguably the least developed in that region. The following reasons can additionally explain the choice of this country:

Historically, Afghanistan and Uzbekistan have a lot in common. These two states share a border and have some cultural ties [53]. Afghanistan is home to over 3.5 million ethnic Uzbeks, the second-largest Uzbek population [54]. These many Uzbeks in Afghanistan have some power to form cultural and social norms similar to the ones in Uzbekistan. While Uzbekistan was a part of the USSR, for many years, Afghanistan experienced the rise of communism and was ruled by the Communist Party, which was supported by the USSR [53]. This fact brings similarities in political background. Additionally, these two countries are very similar regarding nature reserves [55].

Once the necessary data were obtained, we calculated the value that resulted in 3, which would be our minimum reference point. Similarly, we calculated the maximum value, which resulted in 1. As the reference for maximum values, we took data on Finland because it was voted the most successful in reaching sustainability goals [56] and the second most sustainably competitive country [57]. Then, when the minimum and maximum possible values were calculated, we could proceed with the evaluation of urban sustainability in Uzbekistan. Statistical analysis of these calculations is presented in Table 1.

**Table 1.** Statistical results of the evaluation of urban sustainability in Uzbekistan.

| Indicator | Value | Weights | Value × Weight | Normalised |
|---|---|---|---|---|
| Human flight and brain drain index | 5.2 | 0.944 | 4.91 | 0.0048202 |
| Public services index | 4.6 | 0.98 | 4.34 | 0.00439364 |
| Human rights and the rule of law index | 7.6 | 1.06667 | 7.17 | 0.00652647 |
| Human development index | 0.72 | 1 | 0.68 | 0.00163517 |
| Women in parliament | 33 | 1.08571 | 31.15 | 0.02458445 |
| Ratio of female to male students in tertiary-level education | 0.83 | 1.04 | 0.78 | 0.00171338 |
| Percent urban population | 50.44 | 1.03 | 47.62 | 0.03698332 |
| Health spending per capita | 101.2 | 1.01 | 95.53 | 0.07307085 |
| Death rate, per 1000 people | 5.4 | 0.9 | 5.10 | 0.00496239 |
| Maternal mortality per 100,000 live births | 28 | 0.97333 | 26.43 | 0.02102973 |
| Infant deaths per 1000 live births | 19.6 | 1.04 | 18.50 | 0.0150578 |
| Percent urban population with access to drinking water | 86.1 | 1.03 | 81.28 | 0.06233559 |
| Alternative and nuclear energy, percent of total energy use | 1.6 | 1 | 1.51 | 0.0022608 |
| Research and development expenditure, percent of GDP | 0.12 | 1 | 0.11 | 0.00120861 |
| Corruption perceptions index | 28 | 1.04 | 26.43 | 0.02102973 |
| Civil liberties index | 6 | 0.98 | 5.66 | 0.00538896 |
| Energy use per capita | 1405 | 0.96 | 1326.32 | 1 |
| Carbon dioxide emissions per capita | 2.7 | 0.98667 | 2.55 | 0.00304284 |
| Income from natural resources, percent of GDP | 13.5 | 0.98 | 12.74 | 0.01072104 |
| Renewable power generation, billion-kilowatt hours | 6.4 | 0.99 | 6.04 | 0.00567334 |
| Economic growth: the rate of change of real GDP | 7.4 | 1.02 | 6.99 | 0.00638428 |
| Capital investment as a percent of GDP | 32.4 | 1.02667 | 30.59 | 0.02415789 |
| Household consumption as a percent of GDP | 62.4 | 1.03 | 58.91 | 0.04548621 |
| Unemployment rate | 13.3 | 0.98667 | 12.56 | 0.01057885 |
| Unemployment rate for females | 39.44 | 1 | 37.23 | 0.02916293 |
| Labour force, percent female | 2.9 | 0.96 | 2.74 | 0.00318503 |
| Foreign direct investment, percent of GDP | −1.58 | 0.96 | −1.49 | 0 |
| Voice and accountability index | 27.2 | 0.984 | 25.68 | 0.02046098 |
| Sustainability awareness | 7.16 | 1.048 | 6.76 | 0.00621365 |

Source: (developed by authors).

The normalised values in Table 1 are added up to give us 1.45206814, which can be rounded up to 1.5. Uzbekistan is in the middle of the sustainability spectrum, which ranges from 1 to 3, with 1 being the highest level of sustainability and 3 the lowest. It indicates that even while Uzbekistan has made significant strides toward attaining sustainable urban development, plenty can still be done to raise the country's ranking.

## 5. Discussion

Our assessment of Uzbekistan's urban sustainability provides crucial insights into the country's current sustainability situation. The extensive methodology created for this study considers several variables that impact urban sustainability and enables a deeper comprehension of the opportunities and problems Uzbekistan is now facing.

The findings suggest that Uzbekistan falls somewhere in the middle of the urban sustainability scale. This result is consistent with how the nation performed in recognised indices, such as the Global Sustainability Competitiveness Index [57] and the Sustainable Development Report Calculations [56], which also emphasise the need for additional advancements in several sustainability-related areas.

It is important to keep in mind the larger context of urban sustainability when evaluating these findings, particularly in connection to the four major categories—environment, economy, awareness, and society—as well as the subgroup of gender equality and female empowerment. By focusing on these critical areas, policymakers, urban planners, and other stakeholders can develop targeted interventions and strategies to support more sustainable urban development in Uzbekistan.

The logical step here would be to compare the findings from our research with other ones. However, a simple search on Scopus, Web of Science, or even Google results in almost no relatable content. The only article that is somewhat close to the scope of this paper is the one by Irnazarov and Kayumova [56], in which authors attempted to assess the potential for the introduction of smart city projects in six major cities of Central Asia (Almaty, Astana, Ashgabat, Bishkek, Dushanbe, and Tashkent). While the authors evaluated some sustainability factors, no overall urban sustainability assessment was performed. Apart from the article, as mentioned earlier, no relevant literature on the evaluation of urban sustainability, not only in Uzbekistan, but also in the whole of the Central Asian region, was found by the authors, which highlights the research gap in this area.

The results of this study have various ramifications for the future course of research. Our evaluation strategy, for instance, may be used to assess urban sustainability in neighbouring states, such as Tajikistan, Turkmenistan, Kazakhstan, and Kyrgyzstan, since they share similar political, cultural, and environmental backgrounds. This might contribute to improving the precision and applicability of urban sustainability assessments in the Central Asian region. Thus, future research might concentrate on comparing the findings of this study with those of other nations in the region. Such comparative assessments could assist in locating shared difficulties and ideal procedures that could guide regional policymaking and urban planning initiatives.

In the development of the method for analysing urban sustainability factors in Uzbekistan, the Uzbek context and its unique challenges were primarily taken into consideration. While this approach ensures relevance and effectiveness in addressing local concerns, it is also essential to acknowledge its potential for wider applicability and adaptability to other settings.

Although the method employed in this study was developed specifically for Uzbekistan, with the Uzbekistan context in mind, it is versatile and can be tailored to suit various urban contexts around the globe. When adapting the method for use in other countries or regions, it is crucial to consider the specific local challenges and priorities, as well as cultural, economic, and political differences. These adaptations can be made through the incorporation of locally relevant factors and the engagement of stakeholders with a deep understanding of the area's unique circumstances.

One significant advantage of employing this method in other regions is the possibility of comparison. By utilising the same method across different urban settings, a meaningful comparison of urban sustainability factors, challenges, and solutions can be conducted. This comparative analysis can lead to the identification of patterns and trends in urban sustainability issues, facilitating the exchange of best practices and lessons learned among cities and countries.

Furthermore, the cross-regional application of this method can contribute to the development of a global understanding of urban sustainability, promoting collaboration and knowledge-sharing on an international scale. By adopting and adapting this method in various urban contexts, policymakers, practitioners, and academics can gain valuable insights into the diverse approaches to urban sustainability, ultimately fostering the implementation of more effective strategies to address the pressing global challenge of sustainable urban development.

## 6. Conclusions

The environmental, economic, sociological, and awareness components of sustainable development, as well as the subgroup of gender equality and female empowerment, are all taken into account using the comprehensive formula we established and are used in this study to assess urban sustainability in Uzbekistan. Our findings suggest that Uzbekistan is in the middle of the sustainability spectrum, showing growth in certain areas but also emphasising the need for additional development in others.

Policymakers, urban planners, and other stakeholders in Uzbekistan can benefit from the findings of this study by getting a more nuanced understanding of the state of urban sustainability today and the issues that must be resolved if the nation is to promote more sustainable development. The thorough method created in this study can be an effective tool for assessing urban sustainability in various nations and circumstances, adding to the expanding body of knowledge in this area.

Several areas still need more research, even though this study significantly contributes to our understanding of urban sustainability in Uzbekistan. Future studies can, for instance, concentrate on the possible influence of institutional, political, and technological elements on sustainable urban growth in Uzbekistan. It is recommended to use this methodology on separate regions in the country to indicate region-specific problems that need to be addressed first. At present, however, no data is available for such analysis. It would also be beneficial to test this methodology in other countries in the region to examine its applicability to other nations with similar backgrounds.

This study's conclusions have significant policy ramifications. Given the severe socioeconomic and environmental problems brought on by growing urbanisation, Uzbekistan should emphasise efforts to make its urban areas more sustainable. A few possible policy ideas are enhancing infrastructure development, encouraging sustainable transportation networks, and promoting eco-friendly urban design techniques. Additionally, promoting gender equality and female empowerment is believed to accelerate the pathway towards a higher sustainability level and due to improvements in social and economic spheres.

This research advances knowledge of urban sustainability in Uzbekistan and lays the groundwork for future studies and the formulation of relevant policies. Uzbekistan can work to create more sustainable urban environments that benefit all citizens and contribute to a more just, inclusive, and environmentally friendly future by addressing the major issues highlighted in this research, such as gender equality, environmental protection, and economic development.

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*sustainability*

*Article*

# The Convergence in the Sustainability of the Economies of the European Union Countries between 2006 and 2016

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**Abstract:** On the background of the exponential growth of the world's population, doubled by the decrease of natural resources and the continuous, accentuated degradation of the quality of the environment, with global warming as its main effect, ensuring the sustainability of economic and social processes is becoming a growing concern. At the European Union level, it is important that all member countries adhere to and implement common measures on sustainable development, which involve, inter alia, ensuring the convergence of policies and their effects at EU level. The EU through detailed SDGs presents the structure of a system of indicators structured on 17 objectives, indicators taken over, implemented, and calculated by EUROSTAT. The study proposes, based on a Composite Index of Sustainable Development of EU Countries' Economies (ISDE-EU), the analysis of the convergence of the sustainability of EU states' economies, not so much at individual level, but at cluster level, each cluster containing EU countries with similar/close ISDE-EU levels and dynamics. The results of the analysis confirm the partial existence of the beta and sigma convergence of the sustainability of EU countries' economies. Please note that, at the time when we processed data, the UK was an EU state, which is why it was included in the analysis.

**Keywords:** sustainability; sigma convergence; beta convergence; clusters; composite index

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## 1. Introduction

On the background of the exponential growth of the world's population, doubled by the decrease of natural resources and the continuous, accentuated degradation of the quality of the environment, with global warming as its main effect, ensuring the sustainability of economic and social processes becomes an increasingly important issue of concern. At EU level, it is important that all member countries adhere to and implement common measures on sustainable development, which involves, among other things, ensuring the convergence of policies and their effects at EU level [1].

The EU (European Union) through SDGs (Sustainable Development Goals) [2] presents a system of indicators structured on 17 objectives, indicators taken over, implemented, and calculated by EUROSTAT. Based on these, Turturean et al. [3] proposed the construction of the Composite Index of Sustainable Development of EU Countries' Economies (ISDE-EU) to quantify and compare the sustainability of EU economies, and which was the basis for the analysis of the beta and sigma convergence of EU economies for the period 2006–2016.

The study proposes an analysis of the convergence of the sustainability of EU states' economies grouped in clusters, each containing EU countries with similar/close ISDE-EU levels and dynamics.

The topic proposed by this article aims at combining two concepts: sustainable development, more precisely ways of measuring it, and convergence.

Concerns about the protection of the environment and the conservation of natural resources have existed since ancient times, but never in human history has it been clearer than now that they must become a desideratum of the policies of all states of the world, the most important task being held by developed economies.

In 1987, the UN (United Nations) concludes in the Report of the World Commission on Environment and Development "Our Common Future" [4]:

> *"[ ... ] the "environment" is where we all live: and "development" is what we all do in attempting to improve our lot within that abode. The two are inseparable. Further, Development issues must be seen as crucial by the political leaders who feel that their countries have reached a plateau towards which other nations must strive. Many of the development paths of the industrialized nations are clearly unsustainable. And the development decisions of these countries. Because of their great economic and political power. Will have a profound effect upon the ability of all peoples to sustain human progress for generations to come."*

This moment is a reference both for the development and popularization of the concept of sustainable development and for the creation of global policies that promote the idea of the need to adhere to a set of principles and rules that lead to achieving a common goal: the sustainable development of the world states.

The discussion on the convergence of EU states would have become useless without an external factor that would lead states to move towards a common denominator on sustainable development. This factor arose with the presentation by the UN of the report "Our Common Future" (1987) and culminated at EU level with the publication in 2001 by the Commission of European Communities (CEC) [5] of the document "A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development", which states that:

> *"Sustainable development is a global objective. The European Union has a key role in bringing about sustainable development, within Europe and also on the wider global stage, where widespread international action is required. To meet this responsibility, the EU and other signatories of the 1992 United Nations' "Rio declaration" committed themselves, at the 19th Special Session of the United Nations' General Assembly in 1997, to draw up strategies for sustainable development in time for the 2002 World Summit on Sustainable Development. This strategy forms part of the EU preparations for that summit."*

These statements will create the proper environment for a discussion on convergence of the sustainable development of EU states, and we have in mind the existence of a set of indicators, principles, and rules designed to quantify and compare the intensity with which this new concept of sustainable development is implemented at the level of economic policies of the EU member states.

The current paper tackles the beta and sigma convergence of the sustainability member states of EU 27 (EU states including United Kingdom and excluding Croatia). To reach this objective, a sustainability composite index developed by Turturean et al. [3] is used. The results obtained confirm: the existence of clusters with homogeneous states from the point of view of sustainability and the existence of both beta and sigma convergence at the level of the entire EU 27 as well as for some of the clusters.

This paper is relevant and brings contributions to the existing literature in the field of sustainability. Its first originality is represented by the use of a composite index for the analysis of similar behaviours of sustainability in the EU 27 member states, followed by the identification of five clusters in the EU 27 member states. The second originality element is the beta and sigma analysis of the sustainability convergence in the EU 27 member states. Thirdly, there is the analysis of the convergence at the level of the five clusters based on the composite index of sustainability, and in the fourth place the paper analysed the correspondence between the results obtained for the beta and sigma convergence both at the level of EU 27 and at cluster level.

The paper continues with the following structure: the Section 2 presents the literature and the research hypotheses, the Section 3 describes the Materials and Methods, the Section 4 highlights the Results, ending with the Conclusions.

## 2. Literature Review and Research Hypotheses

The term sustainable development is relatively new and was first used in 1987 at the UN level in the Report of the World Commission on Environment and Development [1], being defined as follows: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" a definition that tried to outline the idea of responsible development of society taking into account the protection of the environment with all the resources it makes available.

The continuing concern about the degradation of natural resources and their conservation is the basis for the day-to-day growth of indicators that want to quantify each type of resource. Therefore, for researchers, measuring sustainable development is an ongoing challenge. Among the pioneers who worked on the creation of a system of indicators for measuring sustainable development there is Bossel [6], who is one of the first researchers to try to define the components of such a system, broken down by territorial administrative aggregation levels.

Starting with 2002, just one year after the launch of "A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development" (2001) [3] and the establishment by Eurostat of the EU SDGs [2], the efforts of specialists have been focused on the construction of an aggregate indicator that allows the evaluation of sustainable development—Ronchi et al. [7] for Italy—but who noted that the data available at the time were poor in terms of both recording frequency and number of indicators to quantify different dimensions of sustainable development, which does not allow for statistical quality data processing. In the same year, Barrera-Roldan and Saldivar-Valdes [8] proposed a methodology for building a sustainable development index (SDI) which, in the opinion of the authors, was able to quantify both the degree of greening of urban community activities as well as their socio-economic status. Myriam Nourry [9] conducts a study on the ability to comprehensively characterize sustainable development in France using a set of eight indicators, concluding that none of the indicators provide a comprehensive picture of the phenomenon of sustainable development and highlights the fact that the use of GDP in assessing sustainable development artificially reduces the complexity of the phenomenon.

Bartelmus [10], in "Quantitative Economics: How Sustainable are our Economies?", presents a set of aggregation methods and tools, needed to build indicators to measure sustainable development. In a study published in 2014, Salvati and Carlucci [11], based on a multidimensional approach, measured the sustainable development, locally, for Italy, using a composite index using exploratory statistics and spatial analysis. In 2015, Mikulic, Kozic, and Kresic [12] make a critical analysis of measuring sustainable development in tourism using weighted indicators. In order to support the authorities in monitoring sustainable development, Tret'yakova and Osipova [13] proposed and developed a set of methodological tools that they applied to several regions in Russia.

In 2019, Turturean et al. [3] proposed to quantify the level of sustainability for EU 27 economies a composite index called the Index of Sustainable Development of EU Countries' Economies (ISDE-EU), which initially considered all indicators of sustainable development provided by EUROSTAT. It was based on the methodology provided by the OECD, Handbook on Constructing Composite Indicators: Methodology and User Guide [14].

Please note that, during the period analyzed, the UK was an EU state, which is why it was included in the analysis.

Even if in the last six years, between 2017–30 July 2022, according to Clarivate, Web of Science (WoS), there were 15,991 papers in the literature whose title comprises the word Convergence, most of them being in the field of Mathematics, and 30,439 papers which contained in the title the word Sustainability; when we refer to papers which contained both the words Convergence and Sustainability, their number reduces drastically, narrowing down to 28 papers, 27 more precisely since one repeats itself. These 27 papers, even if few in number, have a very heterogeneous structure as regards the distribution by category according to WoS.

The distribution of papers in the above mentioned WoS report by topics related to the theme of our current paper is the following:

- the Category Green sustainable Science and Technology with 9 studies;
- the Category Environmental Studies with 8 papers;
- the Category Economics with 3 studies;
- the Category Development Studies with 2 papers.

They total 22 papers, but we need to mention that their number could be even smaller since the same paper might have been included in two or even three different categories.

A large part of the papers published on the topic of Convergence and Sustainability during the period 2017–30 July 2022 tries to prove the need to introduce the concept of Sustainability and subsequently to reach a convergence in sustainability as standards of corporate management, starting from the social responsibility assumed by most of the corporations, Pazienza et al. [15]. Another category of papers attempts to determine, by means of the bibliometric analysis conducted, the correlation between convergence of innovation and sustainability. De la Vega and De Paula [16], following the bibliometric analysis conducted, coin a new term, "innovability", which should simultaneously cover the concept of innovation and that of sustainability. Another paper from the same field focuses on the creation of Local Innovative and Productive Systems (LIPS) and on the effect the innovations they produce lead to the increase in the sustainability level of socio-economic processes, giving as an example Brazil [17].

George [18] tries to demonstrate, on a case study performed at CIAL: India's Green Port, what the framework required to reach a natural convergence of sustainability is, by identifying as main factors the good governance, the social responsibility, and an adequate organisational management.

Harlow et al. [19] propose an efficient management manner of sustainable transition by projecting the "convergent political windows", which should ensure the fulfilment of the expected outcome by using "a combination between the transition management and the method of multiple flows in order to increase the transforming potential of transitional arenas".

Simo-Kengne [20] performs an ample study on 148 countries during the period 2006–2016, using panel data, concerning the relationship between the tourism growth and the environmental sustainability and concludes that beside the positive implications the tourism has on the economies of the states comprised in the analysis, there is also the estimation of a negative effect on the environmental sustainability. In this regard, the authors propose the implementation of a tourism management which should set the balance between its economic benefits and the negative impact these have on the environment.

Guidotti [21] suggests that the economic sustainability has a catalytic effect on the health state of the population, by eliminating the treatment disparities. The population's health state also beneficially influences in its turn economic growth, producing thus a positive chain reaction.

The COVID-19 pandemic and its secondary consequence, the drop in the population's mobility, has resulted in the migration of convergence towards the objectives of sustainable development (ODD) according to the 2030 Agenda of the United Nations published in 2015 [22] by means of:

- the transition to the Digital Economy, Castro et al. [23] and Camodeca and Almici [24];
- the digitalization of the educational process, especially in higher education, Deev et al. [25] and Melles et al. [26].

The Convergence and the Sustainability get new meanings in finances. Thus, Sbarcea [27] considers that the economic sustainability provides sustainability to a country on a long term regarding the main macroeconomic and financial indicators such as: Inflation rate (%), Fluctuation of exchange rate, Long-term interest rate (%), Budget Deficit (%), and Public debt (% of GDP). The adherence to the Euro zone will be ensured by setting the convergence and the stability of these indicators at standard values imposed by the EU. The example provided by the author is for Romania for the period 2006–2018.

Vilas et al. [28] ascertain for the period 1990–2018 the existence of convergence between the conventional stock exchange indices, belonging to the FTSE index family, and sustainable development. This is due to the corporate social performance (CSP), the corporate social responsibility (CSR), and the socially responsible investing (SRI). In the financial field, Lesko and Muchova [29], make an analysis of the sustainability of the convergence of the growth rate of the balance of payment (BOP) of ECE countries towards an equilibrium point (BOP) calculated as the ratio between the elasticities of the incomes of export and import demand and the increase of external demand, according to Thirlwal's theory [30]. The authors manage to prove that almost all the ECE countries have a growth rate which exceeds the value of the balance point of BOP Thirlwal. As a paradox, the convergence of the ECE region is not sustainable if one takes into account the low ratio of income elasticities and the growth of external debt.

The last category of papers aims to study the economic convergence and its influence on sustainability at international level, Juknys et al. [31]; at European level, Suciu et al. [32]; or at regional level, Di Berardino et al. [33].

The three papers are the closest ones through the methodology and objectives to what the authors of the current paper also aimed at doing. Nevertheless, none has the goal to study directly the convergence of the states/regions observed based on a sustainability composite index.

The analysis proposed by the authors in this paper is original because it directly assesses the convergence in sustainability, by means of the sustainability composite index, ISDE-EU27, built for the 27 EU countries. The above-mentioned papers start from the analysis of the economic growth convergence and end in identifying correlations or associations with economic sustainability.

Many articles use the indicator Gross Domestic Product per capita (GDP/capita) in the convergence analysis. This is a controversial indicator especially for the evaluation (measurement) of development (Stiglitz et al., (2009), pp. 23–58) [34]. In the European Union, this indicator is still used to assess economic cohesion and to allocate resources from European funds.

Studies based on the GDP/capita, which focused on convergence in the European Union, were conducted by Mankiw et al. [35], Ben-David [36], Islam [37], Smolny [38], Barro, Sall-I-Martin [39], De la Fuente [40], and Di Liberto and Symons [41].

In most cases, the presence of the convergence process was confirmed, which was highlighted especially for beta convergence. However, the lack of convergence within the studied regions (countries) in the European Union was also analyzed. On the one hand, we find the lack of beta convergence in the works of Baro, Sala-i-Martin (pp. 479–496) [39], Mankiw et al. (pp. 407–437) [35] and, on the other hand, the lack of sigma convergence in the works of Ben-David (pp. 653–679) [38] or Mello and Perrelli (pp. 643–667) [42] for the countries studied.

As mentioned above, the gross domestic product per capita indicator is used in many studies on convergence. The assessment of the development of some countries and the possible convergence is also studied by authors who used a more complex indicator, which considers not only income but also social aspects. This indicator, namely human development index (HDI) was used to measure the convergence beta of Mazumdar [43], Stutcliffe [44], and Noorbakhsh [45]. Konia and Guisan [46] tested both beta convergence and sigma convergence.

The concept of beta convergence arose from the neoclassical growth models of Solow [47] or Cass [48] and is based on the observation that as capital increases, its profitability decreases. This concept is known as the phenomenon of catching-up. Based on this phenomenon, countries with poor economies could "catch up" with the developed economies. Beta convergence is the inverse relationship between the growth rate, specific to a period of time, and the initial level of economic development. The estimation of a negative coefficient between the two variables reflects the existence of beta convergence.

Beta convergence identifies the extent to which economic growth rates are the cause of convergence identified by sigma convergence. Therefore, the existence of beta convergence for the analyzed countries is a necessary but not sufficient condition for the existence of sigma convergence [49]. Thus, there may be beta convergence, but there should be no reduction of the dispersion between the economic growth of the countries, i.e., there should be no sigma convergence. Therefore, sigma divergence can exist at the same time with both beta divergence and beta convergence [50]. These two methods of identifying convergence are complementary to Baro, Sala-i-Martin [39] but the reduction of disparities between countries is highlighted only by the sigma convergence [51,52].

Beta convergence has emerged as a possibility to assess convergence. The method was initially challenged by researchers such as Friedman [51] and Quah [52], who argued that it was not a relevant possibility to quantify the convergence of economic growth. Gradually, beta convergence has taken an increasingly important place in research, evolving from the initial form of absolute beta convergence to conditioned beta convergence.

In the specialized works [53], there are three ways to quantify the beta convergence: absolute beta convergence, group beta convergence (club), and conditional convergence. Absolute beta convergence considers the basic hypothesis of neoclassical theory, namely the existence of the catching-up phenomenon, without considering the different technological and institutional conditions of the countries included in the analysis. Group (club) beta convergence involves the analysis of the phenomenon of convergence within groups of homogeneous countries in terms of technological, institutional, and economic policy conditions. Conditional beta convergence considers absolute convergence and the determinants of economic growth in estimating the equation used in beta.

If, in 1986, Baumol [54] presented a methodology for the analysis of beta convergence, in 1990, Sala-i-Martin presented the term sigma convergence in his doctoral dissertation for the first time [55]. The concept of sigma convergence can be defined as a long-term decrease in dispersion across a group of countries or regions. Thus, if the value of the indicator by which the sigma convergence is measured decreases over time, $\sigma_t > \sigma_{t+n}$ means that we have a reduction of the dispersion at the level of the regions, which indicates the convergence of the studied phenomenon (sigma convergence was initially used for the study of economic convergence). Otherwise, if $\sigma_t < \sigma_{t+n}$, there is a divergence in the regions.

In the existing literature, empirical research on the sigma of convergence mainly uses the following indicators: coefficient of variation, standard deviation of the logarithmic variable, Gini index, and Theil Index. The presence of the sigma convergence was confirmed by the coefficient of variation in the works of de la Fuente [56], Giannetti [57], Soukiazis and Castro [58], Sala-i-Martin [59], and Yang et al. [60]. The standard deviation indicator has been used by: Fuente [56], Sa-la-i-Martin [59], Young et al. [49], Yang at al. [60]. The Gini and Theil indices were the basis for the assessment of convergence in the works belonging to Sala-i-Martin [59], Monfort [61] or Yang et al. [60].

As a consequence of these previously presented results, the authors formulate the following hypotheses:

**H1.** *At the level of the EU 27 countries there is convergence in sustainability.*

**H1.1.** *At the level of the EU 27 countries there is beta convergence in sustainability.*

**H1.2.** *At the level of the EU 27 countries there is sigma convergence in sustainability.*

Kowalski and Rybacki [62] study the convergence of innovation performance in the World Economy and reach the conclusion that there is a lack of convergence of innovative potential between countries. They also underline a discrepancy between the innovative potential of developed economies and of the emerging ones. In the same line, there is the research conducted by Kijek and Matras-Bolibok [63] and Park [64].

An important theme in the analysis of economies' sustainability is represented by the analysis of energy use from renewable resources which is found in the studies conducted by Jankiewicz [65], Butnaru et al. [66], Payne et al. [67], and Kasman et al. [68]. In the research performed by Butnaru et al. [69], the existence of the convergence of renewable energy consumption from non-conventional sources is mentioned but it is also underlined that the results are influenced by the development level of the countries analysed, by the homogeneity or heterogeneity of the states from the group as well as by the measures of economic policy taken in the states under analysis.

The study of the convergence of innovations in the renewable energy is dealt with by Bai et al. [69] in China and Kijek et al. [70] in the European countries. Kijek et al. [70] when studying the European countries prove the existence of three convergence clubs while the identified factors of the occurrence of these clubs are the differences between the human resources in science and technology, the initial expenses per capita for environmental research and development and the environment policy.

Testing the real convergence in order to attain a long-term sustainability was addressed by Suciu et al. [32], based on the data available for the countries that entered the EU between 2004–2013. In this research it is ascertained that the newly entered EU countries which have the single currency (EURO) form a homogeneous cluster of convergence, unlike the newly entered EU states which have not yet adopted the single currency (non-EURO). The adoption of the single currency is an important objective alongside the necessary steps of this approach so that the newly entered EU countries should aim for a sustainable, convergent development towards the developed countries in the EU.

As a consequence of these previously presented results, the authors formulate the following hypotheses:

**H2.** *The different evolutions of the sustainability dynamics of the EU 27 countries can be grouped by homogeneous clusters.*

**H3.** *At the level of the EU 27 countries there is convergence in sustainability.*

**H3.1.** *At the level of the EU 27 there is beta convergence in sustainability.*

**H3.2.** *AT the level of the EU 27 clusters there is sigma convergence in sustainability.*

Based on the results of the current research, the authors will attempt to establish to which extent the above-mentioned hypotheses are validated or not. Based on the validated/invalidated hypotheses actions to be taken by the European organisations/institutions will be suggested, actions able to monitor the sustainability of the economies of the member countries. Starting from the suggestions made available by this study, measures/policies can be built and implemented in order to lead to and/or to strengthen/accelerate the convergence process in sustainability of the economies of the EU states.

## 3. Materials and Methods

Figure 1 summarizes, in stages, the methodology used in this article. Subsequently, each stage will be presented in detail.

### *3.1. Stage 1: Data Collection*

The data used in this article is based on the values of an Index of Sustainable Development of EU Countries' Economies (ISDE-EU), which was originally based on *101 independent variables* structured in 17 goals and represented by the indicators in chapter Sustainable Development Indicators on the Eurostat website [71]. The ISDE-EU calculation methodology and its values are explained in detail in the article Composite Index of Sustainable Development of EU Countries' Economies (ISDE-EU) published by Turturean et al. [3] and are not covered by this article. The values of the ISDE-EU indicator for the 27 countries corresponding to the analyzed 11-year period, 2006–2016, are presented in Table 1.

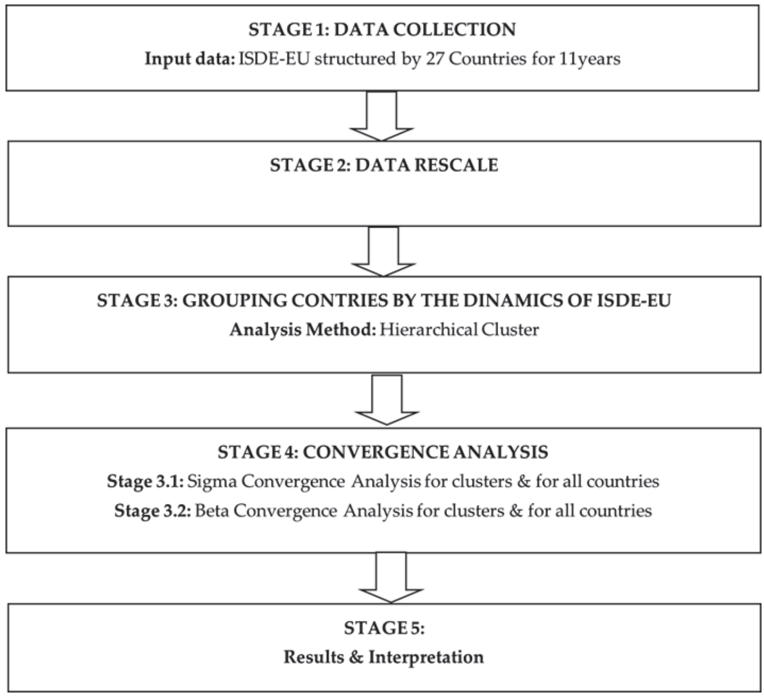



**Figure 1.** Stages of the methodology used in the analysis of the convergence in sustainability of EU countries' economies.

**Table 1.** ISDE-EU for 2006–2016 for 27 Countries, original data.

| | | **ISDE-EU** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Years** | | | | | | | | | | |
| | | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
| **Country** | AT | 0.080 | 0.100 | 0.220 | 0.150 | 0.200 | 0.150 | 0.210 | 0.240 | 0.250 | 0.250 | 0.280 |
| | BE | 0.160 | 0.150 | 0.120 | 0.140 | 0.180 | 0.180 | 0.200 | 0.190 | 0.210 | 0.210 | 0.250 |
| | BG | 0.320 | 0.430 | 0.200 | 0.210 | 0.260 | 0.180 | 0.210 | 0.240 | 0.140 | 0.190 | 0.210 |
| | CY | −0.190 | −0.170 | −0.240 | −0.270 | −0.230 | −0.240 | −0.200 | −0.190 | −0.180 | −0.130 | −0.150 |
| | CZ | −0.370 | −0.360 | −0.370 | −0.380 | −0.330 | −0.320 | −0.240 | −0.290 | −0.250 | −0.220 | −0.210 |
| | DK | 0.320 | 0.370 | 0.430 | 0.490 | 0.520 | 0.460 | 0.460 | 0.520 | 0.490 | 0.550 | 0.510 |
| | EE | −0.220 | −0.190 | −0.220 | −0.240 | −0.220 | −0.140 | −0.160 | −0.180 | −0.130 | −0.140 | −0.120 |
| | FI | 0.290 | 0.300 | 0.340 | 0.350 | 0.310 | 0.330 | 0.320 | 0.280 | 0.300 | 0.340 | 0.270 |
| | FR | −0.010 | −0.010 | −0.020 | 0.050 | 0.080 | 0.050 | 0.060 | 0.130 | 0.120 | 0.120 | 0.150 |
| | DE | 0.080 | 0.130 | 0.170 | 0.170 | 0.170 | 0.210 | 0.220 | 0.220 | 0.280 | 0.290 | 0.330 |
| | GR | −0.060 | −0.060 | −0.060 | −0.080 | −0.110 | −0.020 | 0.080 | 0.140 | 0.130 | 0.140 | 0.160 |
| | HU | −0.170 | −0.300 | −0.330 | −0.310 | −0.290 | −0.230 | −0.120 | −0.080 | −0.100 | −0.120 | −0.150 |
| | IE | −0.030 | −0.010 | 0.030 | 0.020 | 0.050 | 0.110 | 0.200 | 0.180 | 0.210 | 0.200 | 0.180 |
| | IT | −0.060 | −0.030 | −0.010 | −0.030 | 0.030 | 0.130 | 0.200 | 0.250 | 0.270 | 0.290 | 0.400 |
| | LV | 0.080 | 0.000 | 0.050 | 0.060 | −0.010 | 0.040 | −0.020 | −0.010 | −0.070 | −0.070 | −0.140 |
| | LT | 0.040 | −0.060 | −0.120 | −0.150 | 0.000 | −0.090 | −0.120 | −0.070 | −0.100 | 0.010 | 0.030 |

**Table 1.** *Cont.*

| | | ISDE-EU | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Years | | | | | | | | | | |
| | | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
| **Country** | LU | 0.260 | 0.250 | 0.290 | 0.350 | 0.330 | 0.280 | 0.290 | 0.340 | 0.360 | 0.360 | 0.420 |
| | MT | −0.490 | −0.460 | −0.440 | −0.490 | −0.400 | −0.360 | −0.330 | −0.230 | −0.250 | −0.270 | −0.290 |
| | NL | 0.100 | 0.120 | 0.120 | 0.150 | 0.160 | 0.180 | 0.180 | 0.200 | 0.220 | 0.240 | 0.290 |
| | PO | −0.080 | −0.150 | −0.230 | −0.240 | −0.220 | −0.240 | −0.220 | −0.220 | −0.190 | −0.190 | −0.150 |
| | PT | −0.140 | −0.090 | −0.060 | −0.080 | −0.050 | −0.050 | −0.070 | −0.010 | 0.030 | 0.000 | −0.010 |
| | RO | 0.050 | 0.110 | 0.010 | −0.050 | −0.060 | −0.080 | −0.030 | −0.020 | −0.010 | 0.050 | 0.030 |
| | SK | −0.310 | −0.380 | −0.390 | −0.380 | −0.320 | −0.330 | −0.320 | −0.290 | −0.230 | −0.200 | −0.230 |
| | SL | −0.240 | −0.220 | −0.180 | −0.150 | −0.120 | −0.080 | −0.010 | 0.000 | −0.020 | −0.010 | 0.010 |
| | ES | 0.040 | 0.040 | 0.100 | 0.120 | 0.150 | 0.100 | 0.150 | 0.150 | 0.200 | 0.210 | 0.230 |
| | SE | 0.360 | 0.250 | 0.320 | 0.380 | 0.380 | 0.410 | 0.440 | 0.450 | 0.460 | 0.470 | 0.520 |
| | UK | 0.170 | 0.170 | 0.200 | 0.190 | 0.220 | 0.180 | 0.210 | 0.240 | 0.230 | 0.250 | 0.260 |

Source: Adapted from Turturean et al. [3] (calculations using EUROSTAT data).

The EU countries not included in this table did not have sufficient data at the date when calculations were performed, to allow the calculation of the ISDE-EU for the entire analyzed period.

### *3.2. Stage 2: Rescaling Original Values of ISDE-EU to a Fixed 0.01–0.99 Range*

In order to increase the degree of comparability and interpretation of the original ISDE-EU values presented in Table 1, we opted for their transformation so that the range of variation is reduced to the range [0.01; 0.99], where 0.01, represents countries with very weak sustainable economy while 0.99 represents countries with very strong sustainable economy.

The relationship used to *rescale* the original data, is called min-max normalization between specific range [a; b], ISDE-EU and is of the form [72]:

$$\text{ISDE-EU}'_{c,y} = a + [(\text{ISDE-EU}_{c,y} - \text{ISDE-EU}_{min})(b - a)/(\text{ISDE-EU}_{max} - \text{ISDE-EU}_{min})] \quad (1)$$

Normalization based on an arbitrary set of values [a, b] will have the following effects on the initial data:

- the normalized values will take values from the interval [a, b] where a = 0.01 and b = 0.99, which is finite and allows us to calculate the indicators for beta and sigma convergence (e.g., logarithms);
- the influence of the outliers on the series is diminished;
- the level of homogeneity of the series increases the data becoming more compact.

The data resulting from the normalization [0.01; 0.99], based on the relation (1), are presented in Table 2.

### *3.3. Stage 3: Grouping Countries by the Dynamics of ISDE-EU*

The *27 EU countries have different levels of sustainability* of their national economies, which is why, in order to obtain groups of countries with similar values and behaviors of ISDE-EU for the period 2006–2016, we used Hierarchical Cluster Method, implemented in IBM-SPSS 20 Software (IBM, Armonk, NY, USA).

Cluster grouping of the sustainability of EU states will enable the adoption by the EU of differentiated measures or policies adjusted to the specifics of the countries forming each cluster, which should ensure the convergence to the objectives set up in the 2030 Agenda for Sustainable Development [22].

**Table 2.** ISDE-EU for 2006–2016 for 27 Countries Rescaling data to a fixed 0.01–0.99 range.

| | | **ISDEEU** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Years** | | | | | | | | | | |
| | | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
| | AT | 0.5471 | 0.5660 | 0.6790 | 0.6131 | 0.6602 | 0.6131 | 0.6696 | 0.6979 | 0.7073 | 0.7073 | 0.7356 |
| | BE | 0.6225 | 0.6131 | 0.5848 | 0.6037 | 0.6413 | 0.6413 | 0.6602 | 0.6508 | 0.6696 | 0.6696 | 0.7073 |
| | BG | 0.7733 | 0.8769 | 0.6602 | 0.6696 | 0.7167 | 0.6413 | 0.6696 | 0.6979 | 0.6037 | 0.6508 | 0.6696 |
| | CY | 0.2927 | 0.3115 | 0.2456 | 0.2173 | 0.2550 | 0.2456 | 0.2833 | 0.2927 | 0.3021 | 0.3492 | 0.3304 |
| | CZ | 0.1231 | 0.1325 | 0.1231 | 0.1137 | 0.1608 | 0.1702 | 0.2456 | 0.1985 | 0.2362 | 0.2644 | 0.2738 |
| | DK | 0.7733 | 0.8204 | 0.8769 | 0.9335 | 0.9617 | 0.9052 | 0.9052 | 0.9617 | 0.9335 | 0.9900 | 0.9523 |
| | EE | 0.2644 | 0.2927 | 0.2644 | 0.2456 | 0.2644 | 0.3398 | 0.3210 | 0.3021 | 0.3492 | 0.3398 | 0.3587 |
| | FI | 0.7450 | 0.7544 | 0.7921 | 0.8015 | 0.7638 | 0.7827 | 0.7733 | 0.7356 | 0.7544 | 0.7921 | 0.7262 |
| | FR | 0.4623 | 0.4623 | 0.4529 | 0.5188 | 0.5471 | 0.5188 | 0.5283 | 0.5942 | 0.5848 | 0.5848 | 0.6131 |
| | DE | 0.5471 | 0.5942 | 0.6319 | 0.6319 | 0.6319 | 0.6696 | 0.6790 | 0.6790 | 0.7356 | 0.7450 | 0.7827 |
| | GR | 0.4152 | 0.4152 | 0.4152 | 0.3963 | 0.3681 | 0.4529 | 0.5471 | 0.6037 | 0.5942 | 0.6037 | 0.6225 |
| | HU | 0.3115 | 0.1890 | 0.1608 | 0.1796 | 0.1985 | 0.2550 | 0.3587 | 0.3963 | 0.3775 | 0.3587 | 0.3304 |
| | IE | 0.4435 | 0.4623 | 0.5000 | 0.4906 | 0.5188 | 0.5754 | 0.6602 | 0.6413 | 0.6696 | 0.6602 | 0.6413 |
| **Country** | IT | 0.4152 | 0.4435 | 0.4623 | 0.4435 | 0.5000 | 0.5942 | 0.6602 | 0.7073 | 0.7262 | 0.7450 | 0.8487 |
| | LV | 0.5471 | 0.4717 | 0.5188 | 0.5283 | 0.4623 | 0.5094 | 0.4529 | 0.4623 | 0.4058 | 0.4058 | 0.3398 |
| | LT | 0.5094 | 0.4152 | 0.3587 | 0.3304 | 0.4717 | 0.3869 | 0.3587 | 0.4058 | 0.3775 | 0.4812 | 0.5000 |
| | LU | 0.7167 | 0.7073 | 0.7450 | 0.8015 | 0.7827 | 0.7356 | 0.7450 | 0.7921 | 0.8110 | 0.8110 | 0.8675 |
| | MT | 0.0100 | 0.0383 | 0.0571 | 0.0100 | 0.0948 | 0.1325 | 0.1608 | 0.2550 | 0.2362 | 0.2173 | 0.1985 |
| | NL | 0.5660 | 0.5848 | 0.5848 | 0.6131 | 0.6225 | 0.6413 | 0.6413 | 0.6602 | 0.6790 | 0.6979 | 0.7450 |
| | PO | 0.3963 | 0.3304 | 0.2550 | 0.2456 | 0.2644 | 0.2456 | 0.2644 | 0.2644 | 0.2927 | 0.2927 | 0.3304 |
| | PT | 0.3398 | 0.3869 | 0.4152 | 0.3963 | 0.4246 | 0.4246 | 0.4058 | 0.4623 | 0.5000 | 0.4717 | 0.4623 |
| | RO | 0.5188 | 0.5754 | 0.4812 | 0.4246 | 0.4152 | 0.3963 | 0.4435 | 0.4529 | 0.4623 | 0.5188 | 0.5000 |
| | SK | 0.1796 | 0.1137 | 0.1042 | 0.1137 | 0.1702 | 0.1608 | 0.1702 | 0.1985 | 0.2550 | 0.2833 | 0.2550 |
| | SL | 0.2456 | 0.2644 | 0.3021 | 0.3304 | 0.3587 | 0.3963 | 0.4623 | 0.4717 | 0.4529 | 0.4623 | 0.4812 |
| | ES | 0.5094 | 0.5094 | 0.5660 | 0.5848 | 0.6131 | 0.5660 | 0.6131 | 0.6131 | 0.6602 | 0.6696 | 0.6885 |
| | SE | 0.8110 | 0.7073 | 0.7733 | 0.8298 | 0.8298 | 0.8581 | 0.8863 | 0.8958 | 0.9052 | 0.9146 | 0.9617 |
| | UK | 0.6319 | 0.6319 | 0.6602 | 0.6508 | 0.6790 | 0.6413 | 0.6696 | 0.6979 | 0.6885 | 0.7073 | 0.7167 |

Source: Data calculated by authors based on data using the relation (1).

When choosing the measure of the distance between the clusters, we considered the fact that the original data were min-max normalized, resulting in a more compact data set with a diminished outlier's effect [73]. The advantages resulting from the min-max normalization will recommend, as a measure of the distances between the clusters, one of the components of the Minkovski family of measures, among which are: Manhattan Distances, Euclidean Distance, and so on [74].

The Euclidean distance is frequently used and easy to calculate, being adapted to work with data sets for which there are compact or isolated clusters [73,75].

In our analysis, we chose the Squared Euclidean Distance (SED) measure with the intention of amplifying, by squaring, the advantages of the Euclidean Distance and creating clusters with a different behavior. Additionally, the Squared Euclidean Distance (SED) is frequently used for continuous variables, to measure the distances between two indents, $x$

and $y$, belonging to two different clusters, $C_i$ and $C_j$, and is calculated as the sum of the squared differences between the values for the instances [76].

$$SED(x_i, y_j) = \sum_{\substack{i=1,\ card\ (C_i) \\ j=1,\ card\ (C_j)}} (x_i - y_j)^2 \tag{2}$$

Hierarchical Clusters Agglomeration Algorithm involves the iterative traversal of a set of steps, involving the merging of instances into sub-clusters and the sub-clusters into larger and larger clusters, respecting a set of principles related to the similarity of the instances included in them [77].

The algorithm will stop when it reaches a finite number of clusters that are different enough from each other so that they can no longer be attached to larger clusters.

Before explicitly presenting the steps, we must go through, we will have to specify that the method of calculating the distances between two clusters is the average between linkages and it was based on the *metric of the square of the Euclidean distances*, as it is described in the relation (2). This method assumes that the distance between two clusters, $C_i$ and $C_j$, is measured by averaging the distances between all pairs of instants of the form ($x$, $y$), where instant $x$ belongs to cluster $C_i$ and $y$ belongs to cluster $C_j$ [78], as you can see in Figure 2.

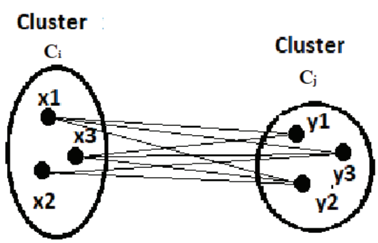



**Figure 2.** Calculation of the distance between clusters based on the average linkage method.

In relation (3) we have presented the way of calculating the distance between the pair of clusters $C_i$ and $C_j$ based on the average between linkage method [79]:

$$d(C_i, C_j) = \overline{d^2} = \frac{\sum_{k=1}^{card(C_i) \times card(C_j)} (d_k^2)}{card(C_i) \times card(C_j)} = \frac{\sum_{\substack{i\ =\ 1,\ card\ (C_i) \\ j\ =\ 1,\ card\ (C_j)}} (x_i - y_j)^2}{card(C_i) \times card(C_j)} \tag{3}$$

The application of the Hierarchical Clusters agglomeration algorithm [80] using the average between linkage method involves the iterative completion of the following steps:

1. Each instance will initially be considered a separate cluster;
2. All cluster pair distances will be evaluated based on the calculation ratio specific to the average between linkage method, relation (3), using the square metric of Euclidean distances, relation (2);
3. Construction of the matrix containing the distances between the pairs of clusters calculated in the previous step;
4. Choosing the pairs of clusters for which, in the distance matrix, we record the smallest distances;
5. Based on a similarity criterion, we attach the pairs of clusters at a distance less than a reference value;
6. Resuming the previous steps until the clusters can no longer be attached;
7. Once the goal from the previous step has been reached, the algorithm will stop and provide the last clustered structure obtained.

### 3.4. Stage 4: Convergence Analysis

#### 3.4.1. Beta Convergence Methodology

Baumol [51] was the first to develop a methodology for studying the real convergence of certain countries' economies. He relied on the estimation of a regression model that he identified graphically. The regression model he used is:

$$\frac{1}{T} ln\left(y_{i,t_0+T} - y_{i,t_0}\right) = \beta_0 + \beta_1 ln\left(y_{i,t_0}\right) + \varepsilon_{it} \tag{4}$$

where:

$T$—last recorded time period
$y_{t_0}$—the value of GDP per capita at the beginning of the period
$y_t$—the value of GDP at the end of the period
$\beta_0$—intercept
$\beta_1$—regression coefficient, an indicator that measures beta convergence.

Mankiw et al. [35] and Barro and Sala-i-Martin [81] created the methodology for estimating the beta convergence based on economic growth modeling. The study performed by Mankiw et al. [35] is based on the theoretical model of Solow [47] and Swan [82] and Barro and Sala-i-Martin [81] deduce the model of regression based on the theoretical model of Ramsey [83], Cass [48], and Koopmans [84].

$$\frac{1}{T}\log\left(\frac{y_{i,t_0+T}}{y_{i,t_0}}\right) = \beta_0 + \beta_1 \log\left(y_{i,t_0}\right) + \varepsilon_{it} \tag{5}$$

where:

$y_{i,t_0}$—represents the per capita income of the region or country $i$ in period $t$
$T$—represents the number of years for which beta convergence is estimated
$\varepsilon_{it}$—the random factor.

If $\beta_1$ is negative and statistically significant, then there is the phenomenon of beta convergence. If this parameter is positive, it will indicate a divergence phenomenon.

Based on the parameters estimated by the previous relation, the convergence rate can be calculated, which represents the time period necessary to halve the difference between the incomes at the level of the individual states to the equilibrium state. The beta convergence rate, according to Barro and Sala-i-Martin [39], is calculated as follows:

$$\beta = -\frac{1}{T} ln(1 - \beta_1 T) \tag{6}$$

This indicator expresses the rate of convergence, i.e., the annual rate at which poorer economies catch-up with the developed economies.

The main disadvantage of this method is that it considers the average annual growth rate of economic development for the period studied. During this period, the conditional average rates may not be constant or, in other words, economic growth for a country may both increase and decrease. Therefore, the slope of the regression line that estimates the absolute beta convergence indicator should not be constant. For this reason, in the literature, the estimate of the regression equation was used, that allows the determination of beta convergence, but on a panel data [85,86]. Moreover, another advantage of using panel data is that the equilibrium may not be kept constant, as in the original methodology, using fixed effects.

Barro and Sala-i-Martin [39] note that the convergence rates of economic development of countries determined using fixed effects panel data are much higher than the value of 2% around which the results of most research are located, identifying values between 12 and 20%. The possible explanation identified by them is represented by a few values recorded in time. Therefore, in estimating convergence, short-term adjustments are captured around the trend instead of determining long-term convergence.

Considering the methodology for assessing the convergence of economies, we will test the existence of the beta convergence of the sustainability of the member states of the European Union based on the sustainable development index created, ISDE.

The equation that will be estimated, to determine the beta convergence, is of the form:

$$\frac{1}{T}ln\left(\frac{ISDE_{i,t_0+T}}{ISDE_{i,t_0}}\right) = \beta_0 + \beta_1 ln\left(ISDE_{i,t_0}\right) + \varepsilon_{it} \quad (7)$$

where:

$ISDE_{i,t_0}$—the sustainable development index at the initial moment of analysis

$ISDE_{i,t_0+T}$—sustainable development index at the end of the period considered in the analysis

$\beta_0$—constant (intercept) of the regression model

$\beta_1$—the slope of the regression that quantifies the existence of beta convergence.

If $\beta_1$ is statistically negative and significant, then the countries considered in the analysis show beta convergence in sustainability; the growth rate of the sustainability of the less developed countries is higher compared to the more sustainably developed countries.

Based on the above equation, we will also estimate the convergence rate of sustainability in order to identify how less sustainably developed economies are closer to the equilibrium of sustainability. The study is performed on cross-section data. We will not address the beta estimation of absolute convergence on panel data, because we only have records for eleven years for the sustainability quantification indicator.

The beta analysis of sustainability convergence will be performed, both on all countries included in the study and on the homogeneous groups of countries in terms of sustainability identified above.

#### 3.4.2. Sigma Convergence Methodology

The sigma convergence analysis methodology provides for modelling the dynamics of ISDE-EU dispersion/concentration indicators. The most common indicators used in the *sigma convergence* analysis, found in the literature, are: the coefficient of variation, standard deviation of the logarithmic variable, Gini INDEX, and Theil INDEX.

##### Coefficient of Variation

The first indicator used in the sigma convergence analysis is the *coefficient of variation*. It has been used by authors such as de la Fuente [56], Giannetti [57], Soukiazis, Castro [58], Sala-i-Martin [59], and Yang et al. [60].

Thus, the coefficient of variation $\sigma_t$ in year $t$ can be calculated according to the formula:

$$\sigma_t = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_i - y)^2}{n}}}{y}, \quad (8)$$

where:

$y_i$—represents the value of the variable in region (country) $i$

$y$—is the average of the variable

$n$—number of regions (countries).

Considering the methodology for assessing the convergence of sustainability, we will verify the existence of the sigma of the convergence of sustainability of the member states of the European Union based on the sustainable development index created, ISDE.

The equation used to determine the sigma of sustainability convergence in this article will take the form of:

$$Sigma(CV)_{ISDE} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(ISDE_i - \overline{ISDE})^2}{n}}}{\overline{ISDE}} \quad (9)$$

where:

$ISDE_i$ represents the index of sustainable development in the country $i$,
$\overline{ISDE}$ average of the sustainable development index of the EU countries under study,
$n$ the number of countries, and $Sigma(CV)_{ISDE}$ represent the coefficient of variation.

SD of Logarithm

The second method, often used in empirical research, considers the standard deviation of the logarithmic variable, calculated according to the formula [81]:

$$\sigma_t = \sqrt{\frac{\sum_{i=1}^{n}[ln(y_i) - \overline{ln(y)}]^2}{n-1}} \quad (10)$$

To determine the sigma of the convergence of the Sustainable Development Index (ISDE), we use the equation:

$$Sigma = \sqrt{\frac{\sum_{i=1}^{n}[ln(iSDE_i) - \overline{ln(iSDE)}]^2}{n-1}} \quad (11)$$

where $iSDE_i = \frac{ISDE_i}{\overline{ISDE}}$ is the proportion of the sustainable development of country $i$, compared to the average sustainable development index of all countries (cluster or total).

This standardized index may reflect changes in the relative position of different countries [60].

Gini INDEX

The Gini concentration index was first used by Corado Gini to study the inequality (degree of concentration) of income in a population. By definition, it ranges from 0 to 1. A low value corresponds to a more equal distribution, while a high value corresponds to a more unequal distribution.

This Gini INDEX can also be used to measure convergence across countries or regions [59]. One of the Gini INDEX calculation methods is shown below.

$$Gini = \frac{1}{2n^2y}\sum_{i=1}^{N}\sum_{j=1}^{N}|y_i - y_j| \quad (12)$$

Another Gini INDEX calculation method is the trapezoid method.

$$Gini = 1 - \sum_{i=1}^{n}(Y_i + Y_{i-1})(F_i - F_{i-1}) \quad (13)$$

where:

$Y_i$ represents the value of the cumulative proportion of the study variable (e.g., Income, GDP/loc),

$F_i$ represents the value of the cumulative proportion of the number of individuals (regions, countries).

Knowing that $F_i = F_{i-1} + f_i \Rightarrow f_i = F_i - F_{i-1}$, then we can rewrite the above formula as follows:

$$Gini = 1 - \sum_{i=1}^{n}(Y_i + Y_{i-1}) \cdot f_i \quad (14)$$

To simplify the calculation of Gini INDEX for the sustainable development index, in our article, we condition that $\mathrm{ISDE_{i-1}} < \mathrm{ISDE_i}$ (the values of sustainable development indices are ordered in ascending order), and we obtain:

$$Gini = 1 - \sum_{i=1}^{n}(ISDE_i + ISDE_{i-1}) \cdot f_i \quad (15)$$

Theil Index

The fourth indicator used to measure the convergence of the sustainable development index is Theil INDEX [59].

By definition, it varies between zero and infinity. Theil INDEX is, together with Gini INDEX, part of the family of concentration/diversification indicators that can measure the degree of inequality between various entities. The general formula is:

$$Theil = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{y_i}{y}\cdot ln\left(\frac{y_i}{y}\right)\right] \quad (16)$$

In our analysis, in order to measure the convergence of the sustainable development index between states, we used the formula:

$$Theil = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{ISDE_i}{\overline{ISDE}}\cdot ln\left(\frac{ISDE_i}{\overline{ISDE}}\right)\right] \quad (17)$$

The existence of the convergence sigma implies a decreasing evolution/a negative trend of the dynamics of the indicators used, hence the need to verify the significance of the slope of the existing trend and the significance of the regression model:

$$IND_t = \beta_0 + \beta_1 t + \varepsilon_t \quad (18)$$

where: $IND_t$—represents any of the indicators used in the sigma convergence analysis: coefficient of variation, standard deviation of the logarithmic variable, Gini INDEX and Theil INDEX corresponding to the time period $t$.

## 4. Results

### 4.1. Results of Grouping Countries by the Dynamics of ISDE-EU

Following the clustering of EU countries, except Croatia (EU 27), based on the values recorded for ISDE-EU interval analyzed, we obtained the following groups/clusters of countries with a higher level of homogeneity in terms of ISDE-EU values and its dynamics over time.

The five clusters are shown in both Figure 3 and Table 3 below. It is observed that there are two clusters with more than five countries and three clusters with a maximum of three countries. The different evolutions of the sustainability dynamics of EU 27 countries were grouped by homogeneous clusters, following the application of the cluster methodology; therefore, the H2 hypothesis is valid.

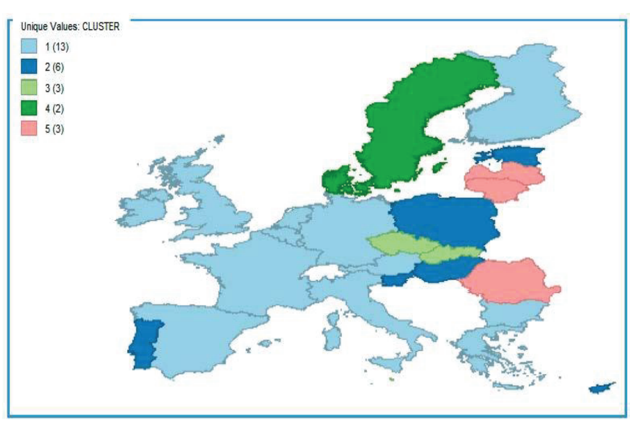



**Figure 3.** Result of the grouping of EU 27 countries 2017 (excluding Croatia) based on ISDE-EU using the Hierarchical Clusters method.

**Table 3.** Grouping of EU 27 countries 2017 (excluding Croatia) * based on ISDE-EU using the Hierarchical Clusters method.

| Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 |
|---|---|---|---|---|
| Austria | Cyprus | Czechia | Denmark | Latvia |
| Belgium | Estonia | Malta | Sweden | Lithuania |
| Bulgaria | Hungary | Slovakia | | Romania |
| Finland | Poland | | | |
| France | Portugal | | | |
| Germany | Slovenia | | | |
| Greece | | | | |
| Ireland | | | | |
| Italy | | | | |
| Luxembourg | | | | |
| Netherlands | | | | |
| Spain | | | | |
| United Kingdom | | | | |

* According to the situation in 2017, from which Croatia was excluded due to lack of data. Grouping obtained by authors based on ISDE-EU and the clustering method according to the presented methodology.

### *4.2. Beta Convergence Analysis Results*

The period covered by the study is determined by the availability of indicators for quantifying sustainable development based on which the sustainable development index of the 27 member countries of the European Union 2006–2016 was calculated.

Table 4 shows both the estimated beta convergence indicators for each country cluster, but also for all countries, as well as the beta convergence rate.

**Table 4.** Beta Convergence indicator values across the 5 clusters and across the EU 27.

| | $\hat{\beta}_0$ (*) | $\hat{\beta}_1$ (*) | $\beta$ (**) |
|---|---|---|---|
| Cluster 1 | −0.2293 (0.017) | −0.0783 (0.000) | −0.0565 |
| Cluster 2 | −0.1288 (0.068) | −0.1247 * (0.045) | −0.0785 |
| Cluster 3 | −0.1037 (0.060) | −0.0817 (0.025) | −0.0583 |
| Cluster 4 | N.A. | N.A. | 0 |
| Cluster 5 | −0.4163 (−0.132) | −0.6208 (0.137) | −0.1871 |
| All | −0.0239 * (0.004) | −0.0556 * (0.000) | −0.0434 |

(*) $\hat{\beta}_0$ and $\hat{\beta}_1$ represent the estimated parameters of the regression model according to Equation (7); (**) $\beta$—convergence rate. In parentheses are presented the *p*-value corresponding to the Student's *t* test for testing the significance of the regression parameter for 5% significance level.

The analysis of all countries from the point of view of the beta convergence of the sustainability index in the period 2006–2016 highlights the existence of a negative link between the average annual growth rate of the sustainable development index and the sustainable development index. This element is highlighted in Figure 4.

The graphical representation of the average annual growth rate of the sustainability index in the period 2006–2016 and the sustainable development index for all member states of the EU 27, highlights the existence of an inverse linear link.

The estimation of the beta convergence indicator for all countries considered in the study and presented in Table 4, confirms the existence of the beta convergence of sustainability. The convergence rate of countries' sustainability is about 4.34%. This value is mainly found in determining the convergence beta of economic growth [87].

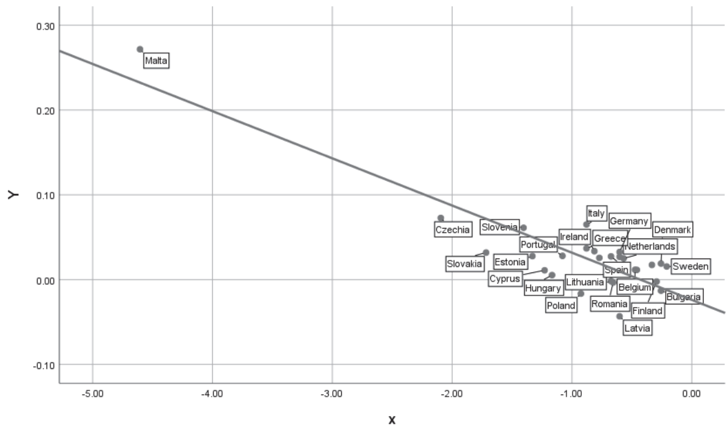



**Figure 4.** Beta-convergence of the sustainability of the countries of the EU 27 in the period 2006–2016.

A more detailed analysis of the sustainability beta convergence of the member states of the EU 27 is further carried out on the clusters of homogeneous countries in terms of sustainability, previously determined.

Cluster one includes Austria, Belgium, Bulgaria, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Spain, and the United Kingdom. The graphical representation of the average growth rate of the sustainable development index according to the sustainable development index, namely Figure 5, highlights the existence of an inverse linear link specific to the existence of the convergence beta. The estimated $\hat{\beta}_1$ parameter is negative and statistically significant, which confirms the existence of beta convergence. Therefore, the countries that are included in cluster 1 are characterized by the beta sustainability convergence, i.e., the less sustainable developed countries tend to recover, on average, 5.65% annually the difference up to the steady state of the sustainability of cluster 1, according to the beta convergence rate shown in Table 4.

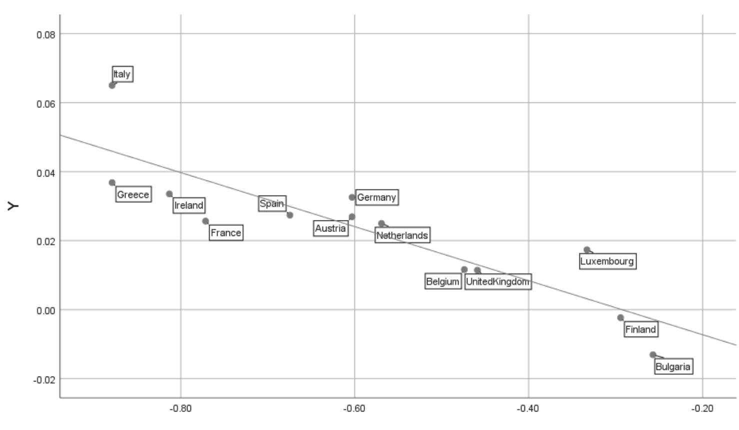



**Figure 5.** Beta-convergence of sustainability of cluster 1 countries, in the period 2006–2016.

The second cluster includes the countries of Cyprus, Estonia, Hungary, Poland, Portugal, and Slovenia. The negative slope of the scatterplot determined based on the average growth rate of the sustainable development index, highlights the existence of an inverse linear link corresponding to the existence of beta convergence (Figure 6). The existence of the beta convergence of the sustainability of the countries in cluster 2 is also supported by the estimated parameter $\beta_1$ (−0.1247), which is statistically negative and significant. The convergence rate of sustainability is 7.85%, the highest value for the five clusters.

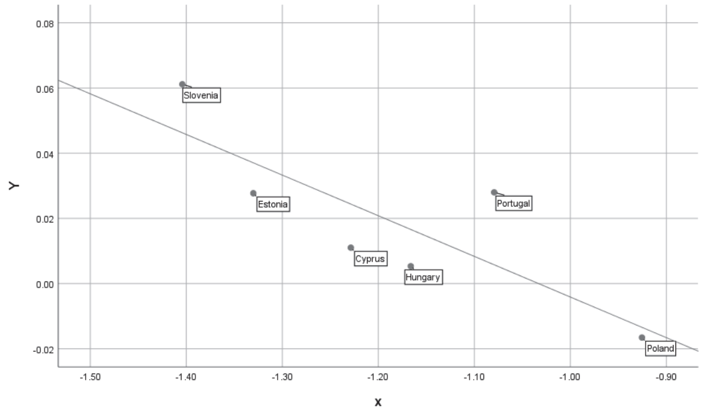



**Figure 6.** Beta-convergence of the sustainability of cluster 2 countries in the period 2006–2016.

We also note that in the analysis period 2006–2016, Poland has an average negative annual growth rate, which suggests the divergence of the sustainability index, the value of their sustainability index registering, on average, a decrease.

Cluster three, shown in Figure 7, comprises three countries, the Czech Republic, Malta, and Slovakia, a small sample to estimate a regression model to identify the beta sustainability convergence. The existence of the beta convergence of the sustainability of the countries in cluster 3 is, however, supported by the parameter $\hat{\beta}_1$ estimated (−0.1247) which is negative and statistically significant. The convergence rate of sustainability is 5.83%, close to that of the first cluster.

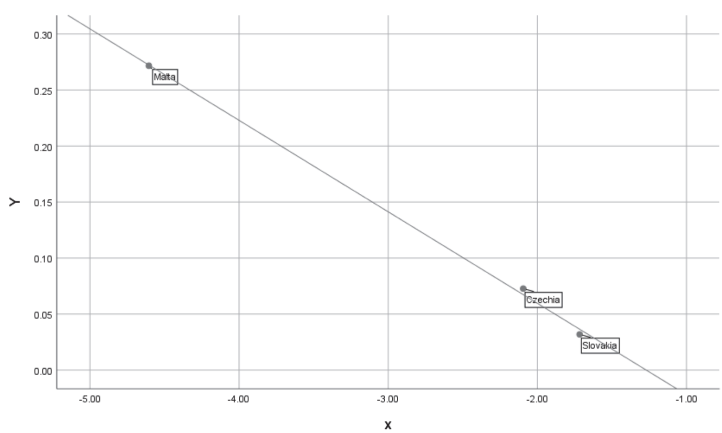



**Figure 7.** Beta-convergence of the sustainability of cluster 3 countries in the period 2006–2016.

Denmark and Sweden are the countries that are part of cluster 4. We cannot perform a regression analysis in this cluster.

The last cluster, represented in Figure 8, includes Latvia, Lithuania, and Romania. The estimated regression coefficient, $\hat{\beta}_1$ is negative (−0.6208), but not statistically significant. We also note that in the analysis period 2006–2016, all three countries have an average negative annual growth rate, which suggests the divergence of the sustainability index, the value of their sustainability index registering, on average, a decrease.

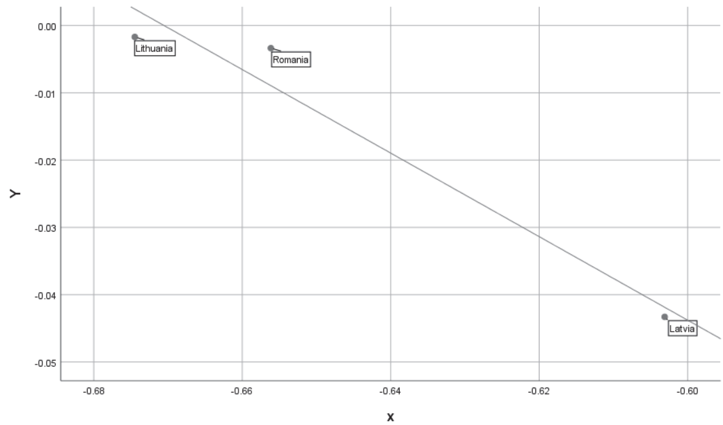



**Figure 8.** Beta-convergence of the sustainability of cluster 5 countries in the period 2006–2016.

### *4.3. The Results of the Sigma Convergence Analysis*

The analysis of ISDE convergence in EU 27 countries with the help of beta convergence has the disadvantage that beta convergence focuses only on the analysis of average values for the period studied. Sigma convergence, on the other hand, can measure the degree of convergence or divergence at each moment in time, in the study period.

#### 4.3.1. Sigma Convergence in the EU 27

Table A1 in the Appendix A shows the convergence sigma indicators, the coefficient of variation (Sigma CV), the standard deviation of ln (ISDE), Sigma (ISDE), the Gini concentration index (Gini INDEX), and the Theil concentration index (Theil INDEX), for the studied EU 27 countries.

We further aim to highlight the downward evolution of these sigma convergence indicators, an evolution that would confirm the existence of convergence at the ISDE level in the studied EU countries.

Figure 9 shows that both the sigma convergence coefficients Sigma CV and Sigma (ISDE) and the concentration indices Gini INDEX and Theil INDEX have a downward trend in the period 2006–2016 for all EU 27 countries studied.

All these indicators show that ISDE, for the different EU 27 countries, are converging at a certain speed. However, this rate is relatively low, which confirms previous results of beta-convergence. At the same time, there is an increase in sigma convergence indicators (indicating a divergence) starting in 2006 and culminating in 2009, when EU 27 countries were already affected by the financial crisis and recession. Since 2010, there has been a sustainable convergence of ISDEs in EU 27 countries.

The presence of the decreasing trend for the evolution of the four indicators measuring sigma convergence is not sufficient, considering the relatively short study period (2006–2016) of 11 years and the rather low speed of convergence.

For this reason, in addition to estimating the trend equation, trend tests of these convergent sigma indicators in Figure 9 were also performed. Linear trend patterns and significance levels were summarized in Table 5.

We can see that the time series for Sigma CV and Sigma have negative and significant trends, which indicates a real convergence. The trend slope for Sigma CV is $b_{1(SigmaCV)} = -0.012$ and for Sigma is $b_{1(Sigma)} = -0.045$, both parameters being statistically significant. This convergence is also supported by the so-called indicators of inequality or concentration, namely Gini INDEX and Theil INDEX. Additionally, these two indicators have a downward trend with negative and statistically significant trends, respectively $b_{1(Gini)} = -0.006$, $b_{1(Theil)} = -0.007$.

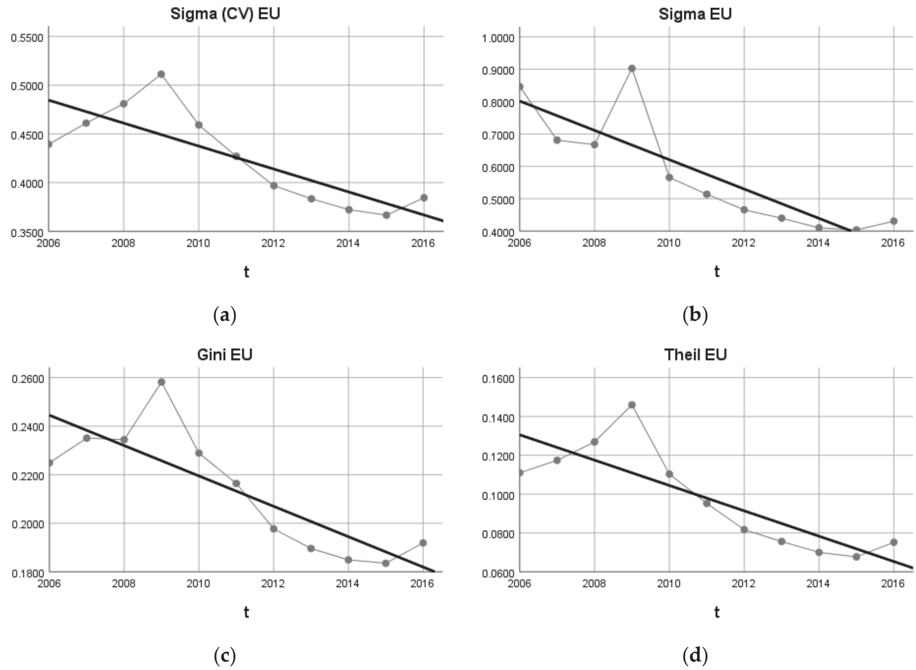



**Figure 9.** Sigma Convergence indicators in the EU 27 countries studied, 2006–2016. (**a**) Coefficient of variation (Sigma CV); (**b**) Standard deviation (Sigma); (**c**) Gini concentration index (Gini INDEX); (**d**) Theil concentration index (Theil INDEX).

**Table 5.** Testing the significance of the sigma convergence trend in the period 2006–2016 in the EU 27.

| | **Constant** | $\mathbf{b_1}$ | $\mathbf{b_1}$ **Stdz** | **R Sq.** |
|---|---|---|---|---|
| Sigma CV | 24,124<br>(0.003) | −0.012<br>(0.003) | −0.804<br>(0.003) | 0.647<br>(0.003) |
| Sigma | 91,715<br>(0.001) | −0.045<br>(0.001) | −0.851<br>(0.001) | 0.723<br>(0.001) |
| Gini | 12,797<br>(0.001) | −0.006<br>(0.002) | −0.828<br>(0.002) | 0.686<br>(0.002) |
| Theil | 13,222<br>(0.001) | −0.007<br>(0.002) | −0.828<br>(0.002) | 0.686<br>(0.002) |

Figure 9 shows that the trends of the four sigma convergence indicators are similar (the slope of the trend models is approximately the same). The same can be seen based on the third column in Table 5, which estimates the regression coefficients of the standardized beta coefficients of the convergence sigma indicators. These estimates have values between (−0.804 and −0.851), which are relatively close.

### 4.3.2. Sigma Convergence in Each Cluster

For a more detailed presentation of the sigma convergence of sustainability of the studied EU member states, we further perform an analysis on clusters of homogeneous countries in terms of sustainability, clusters that have been previously determined.

Thus, the first cluster, the graphical representation of the sigma convergence indicators in Figure 10 highlights the existence of a negative trend for all these indicators. The four graphs in Figure 10 were obtained based on the data recorded in the Appendix, respectively Table A2.

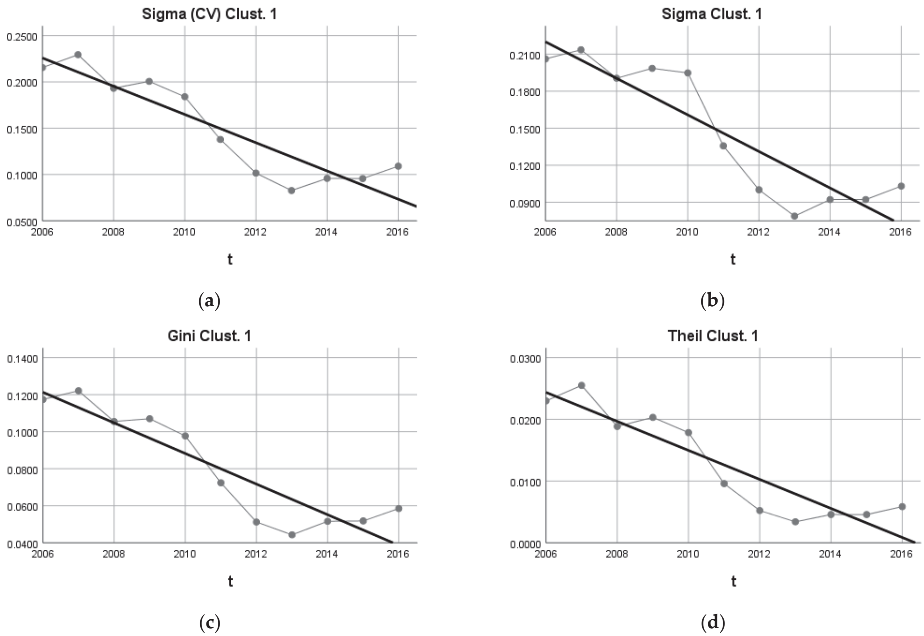



**Figure 10.** Sigma Convergence indicators in Cluster 1 countries, 2006–2016. (**a**) Coefficient of variation (Sigma CV); (**b**) Standard deviation (Sigma); (**c**) Gini concentration index (Gini INDEX); (**d**) Theil concentration index (Theil INDEX).

It is also observed here, in cluster 1 (Figure 10), that there is a sigma convergence, as in the case of the analysis of all EU 27 countries. Thus, for the countries: Austria, Belgium, Bulgaria, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Spain, and United Kingdom, which were grouped in the first cluster according to ISDE, there are decreases of the four calculated indicators for sigma convergence, in the period 2006–2016, and linear trend models approximate these downward evolutions with greater accuracy.

If we compare the values in Table 6 with those in Table 5, we find that for the four sigma convergence indicators the trend models are better for cluster 1 (R Square are significantly higher) and the regression coefficients of standardized variables (standardized beta coefficients) of the sigma convergence indicators also have higher negative values for cluster 1.

**Table 6.** Testing the significance of the sigma convergence trend in the period 2006–2016 in Cluster 1 of the EU 27.

| | **Constant** | **$b_1$** | **$b_1$ Stdz** | **R Sq.** |
|---|---|---|---|---|
| Sigma CV | 30,830<br>(0.000) | −0.015<br>(0.000) | −0.912<br>(0.000) | 0.832<br>(0.000) |
| Sigma | 29,931<br>(0.000) | −0.015<br>(0.000) | −0.902<br>(0.000) | 0.814<br>(0.000) |
| Gini | 16,704<br>(0.000) | −0.008<br>(0.000) | −0.909<br>(0.000) | 0.827<br>(0.000) |
| Theil | 4741<br>(0.000) | −0.002<br>(0.000) | −0.917<br>(0.000) | 0.841<br>(0.000) |

We see in this cluster only developed countries in Western Europe (except Bulgaria) that joined the EU before 2000. This may be one of the reasons why the level of the sigma convergence is more pronounced.

In the second cluster, the four sigma convergence indicators have a negative trend, with the highest slope, compared to the five clusters and the group of all EU 27 countries. In this cluster we find the countries: Cyprus, Estonia, Hungary, Poland, Portugal, and Slovenia. Figure 11 contains the second cluster convergence sigma indicators, calculated based on Table A3 from the Appendix A.

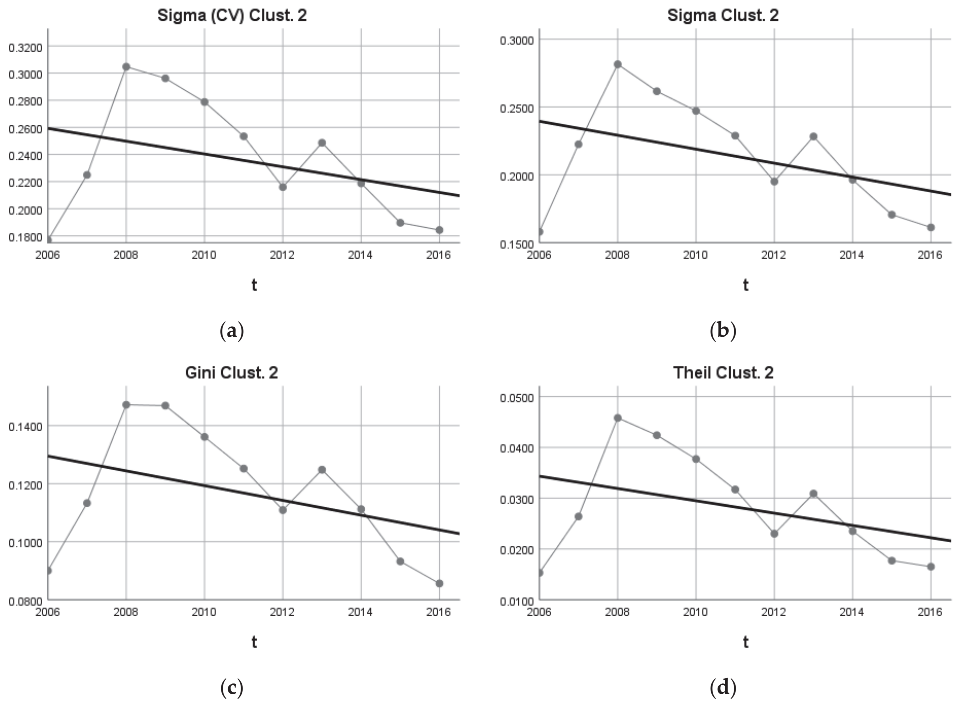



**Figure 11.** Sigma convergence indicators in Cluster 2 countries, 2006–2016. (**a**) Coefficient of variation (Sigma CV); (**b**) Standard deviation (Sigma); (**c**) Gini concentration index (Gini INDEX); (**d**) Theil concentration index (Theil INDEX).

Figure 11, which shows the sigma convergence indicators for the countries in cluster 2, indicates that the values for the years 2006 to 2016 have a rather low downward trend and the variability is high, so there are many increases and decreases during the period studied, respectively 2006–2016.

The values in Table 7 in columns 4 and 5, for the four sigma convergence indicators, mark the existence of a decreasing trend, but this is not statistically significant.

**Table 7.** Testing the significance of the sigma convergence trend in the period 2006–2016 in Cluster 2 of the EU 27.

| | **Constant** | **$b_1$** | **$b_1$ Stdz** | **R Sq.** |
|---|---|---|---|---|
| Sigma CV | 9733<br>(0.277) | −0.005<br>(0.288) | −0.352<br>(0.288) | 0.124<br>(0.288) |
| Sigma | 10,559<br>(0.196) | −0.005<br>(0.204) | −0.415<br>(0.204) | 0.172<br>(0.204) |
| Gini | 5232<br>(0.225) | −0.003<br>(0.235) | −0.391<br>(0.235) | 0.153<br>(0.235) |
| Theil | 2467<br>(0.236) | −0.001<br>(0.241) | −0.386<br>(0.241) | 0.149<br>(0.241) |

For the third cluster we find, in Figure 12, the evolution of the sigma convergence indicators. The evolution is downward for this third cluster, which has only three countries, namely the Czech Republic, Malta, and Slovakia.

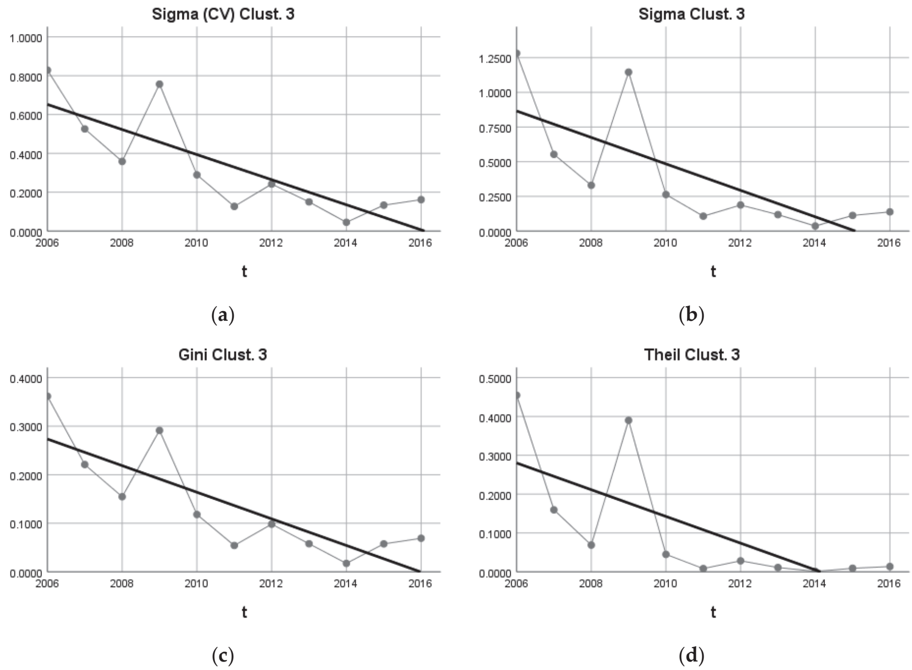



**Figure 12.** Sigma convergence indicators in Cluster 3 countries, 2006–2016. (**a**) Coefficient of variation (Sigma CV); (**b**) Standard deviation (Sigma); (**c**) Gini concentration index (Gini INDEX); (**d**) Theil concentration index (Theil INDEX).

The linear trend models for the four sigma convergence indicators, related to cluster 3, were estimated and summarized in Table 8, based on the data in Table A4, in the Appendix A. It is observed that the parameters of the trend models are significant. Therefore, we can say that there is significant sigma convergence at the level of the third cluster.

**Table 8.** Testing the significance of the sigma convergence trend in the period 2006–2016 in Cluster 3 of the EU 27.

| | Constant | $b_1$ | $b_1$ Stdz | R Sq. |
|---|---|---|---|---|
| Sigma CV | 130,229<br>(0.003) | −0.065<br>(0.003) | −0.809<br>(0.003) | 0.655<br>(0.003) |
| Sigma | 192,212<br>(0.010) | −0.095<br>(0.011) | −0.731<br>(0.011) | 0.534<br>(0.011) |
| Gini | 55,251<br>(0.002) | −0.027<br>(0.002) | −0.824<br>(0.002) | 0.678<br>(0.002) |
| Theil | 69,311<br>(0.016) | −0.034<br>(0.016) | −0.703<br>(0.016) | 0.494<br>(0.016) |

The convergence sigma indicators, related to the fourth cluster, can be found in Figure 13. The evolution of these indicators, during the period 2006–2016, shows a slightly upward trend. Thus, for the countries in cluster 4, namely Denmark and Sweden, there is sigma convergence, from the ISDE point of view.

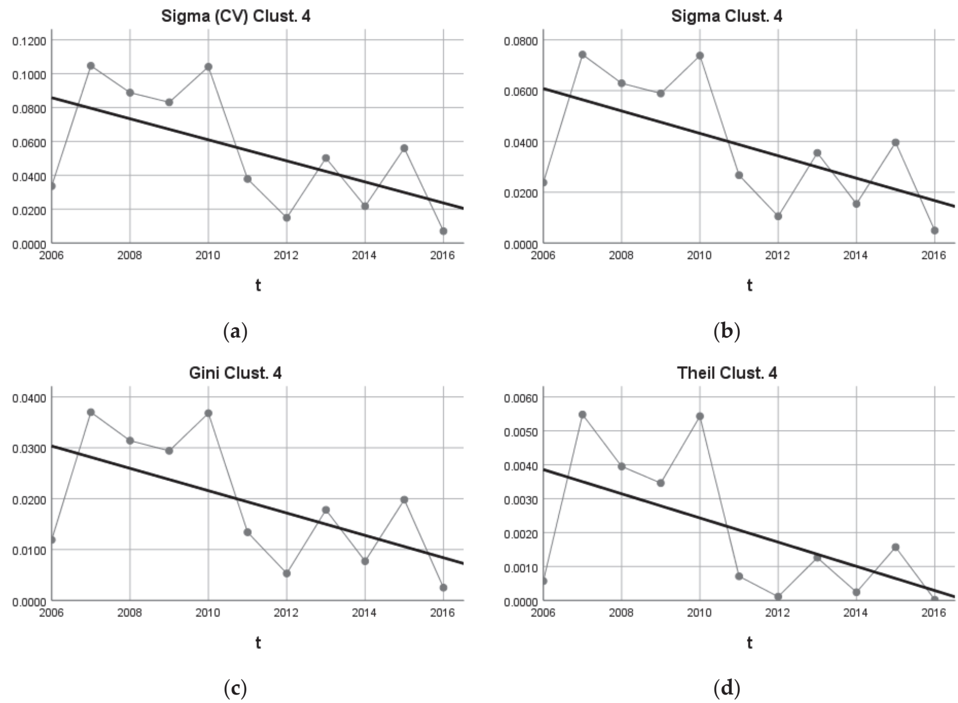



**Figure 13.** Sigma convergence indicators in Cluster 4 countries, 2006–2016. (**a**) Coefficient of variation (Sigma CV); (**b**) Standard deviation (Sigma); (**c**) Gini concentration index (Gini INDEX); (**d**) Theil concentration index (Theil INDEX).

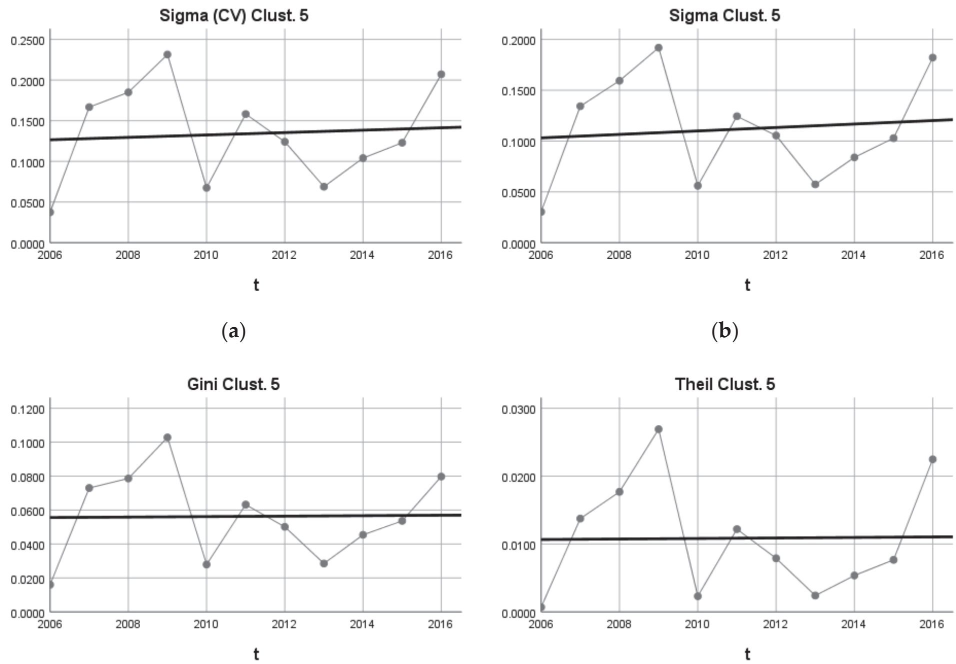
It should be noted, however, that the downward trend for sigma convergence indicators is not a significant trend. If we look at the results in Table 9 (results obtained based on the data in Table A5, in the Appendix A) we find that the parameters of the trend model, for each of the four sigma convergence indicators, are not statistically significant. Therefore, in cluster 4 we cannot specify whether there is convergence or divergence.

**Table 9.** Testing the significance of the sigma convergence trend in the period 2006–2016 in Cluster 4 of the EU 27.

| | Constant | $b_1$ | $b_1$ Stdz | R Sq. |
|---|---|---|---|---|
| Sigma CV | 12,561<br>(0.060) | −0.006<br>(0.061) | −0.581<br>(0.061) | 0.337<br>(0.061) |
| Sigma | 8915<br>(0.060) | −0.004<br>(0.061) | −0.581<br>(0.061) | 0.338<br>(0.061) |
| Gini | 4436<br>(0.060) | −0.002<br>(0.061) | −0.581<br>(0.061) | 0.337<br>(0.061) |
| Theil | 0.719<br>(0.073) | $-3.57 \times 10^{-4}$<br>(0.074) | −0.559<br>(0.074) | 0.313<br>(0.074) |

Finally, for cluster 5, the evolutions of the convergence sigma indicators in Figure 14 are presented. This cluster consists of Latvia, Lithuania, and Romania, Eastern European countries that joined the EU after 2004.

Figure 14 shows that the values for the years 2006 to 2016 have a slightly upward trend.




(**a**) (**b**) (**c**) (**d**)

**Figure 14.** Sigma Convergence indicators in Cluster 5 countries, 2006–2016. (**a**) Coefficient of variation (Sigma CV); (**b**) Standard deviation (Sigma); (**c**) Gini concentration index (Gini INDEX); (**d**) Theil concentration index (Theil INDEX).

The values in Table 10 (results obtained from the data in Table A6, Appendix A), in columns 4 and 5 for the four sigma convergence indicators, are among the lowest, in absolute terms, compared to the other clusters. There is a divergence, but this is not statistically significant.

**Table 10.** Testing the significance of the sigma convergence trend in the period 2006–2016 in Cluster 5 of the EU 27.

| | Constant | $b_1$ | $b_1$ Stdz | R Sq. |
|---|---|---|---|---|
| Sigma CV | −2830<br>(0.825) | 0.001<br>(0.817) | 0.079<br>(0.817) | 0.006<br>(0.817) |
| Sigma | −3311<br>(0.762) | 0.002<br>(0.754) | 0.107<br>(0.754) | 0.011<br>(0.754) |
| Gini | −0.216<br>(0.968) | 0.000<br>(0.960) | 0.017<br>(0.960) | 0.000<br>(0.960) |
| Theil | −0.066<br>(0.971) | 0.000<br>(0.966) | 0.015<br>(0.966) | 0.000<br>(0.966) |

## 5. Conclusions

Table 11 summarizes the research results. Their cumulative analysis shows that, at the level of all analysed states (total EU 27), the simultaneous existence of both beta and sigma convergence in sustainability is validated.

**Table 11.** Summary of the presence and statistical significance of beta and sigma convergence in the EU 27 and the five clusters.

| Clusters/Total EU 27 | Total EU 27 | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 |
|---|---|---|---|---|---|---|
| | | | **Beta Convergence** | | | |
| Regression Slope ($\beta_1$) (Positive/Negative) | N | N | N | N | N/A | N |
| Statistical significance (Yes/No) | Y | Y | Y | Y | N/A | N |
| Convergence/Divergence (C/D) | C | C | C | C | N/A | C |
| | | | **Sigma Convergence** | | | |
| Regression Slope ($\beta_1$) (Positive/Negative) | N | N | N | N | N | P |
| Statistical significance (Yes/No) | Y | Y | N | Y | N | N |
| Convergence/Divergence (C/D) * | C | C | C/n * | C | C/n * | D |
| | | | **Beta and Sigma Convergence match** | | | |
| **Concordance between β and σ Convergence (YES/NO)** | **Y** | **Y** | **Y** | **Y** | **N/A** | **N** |
| **Convergence/Divergence (C/D)** | **C** | **C** | **C** | **C** | **N/A** | **C/D** |

Note: *—"C/n" means convergence, but not statistically significant.

In conclusion, summarizing the research results, we can state the following:

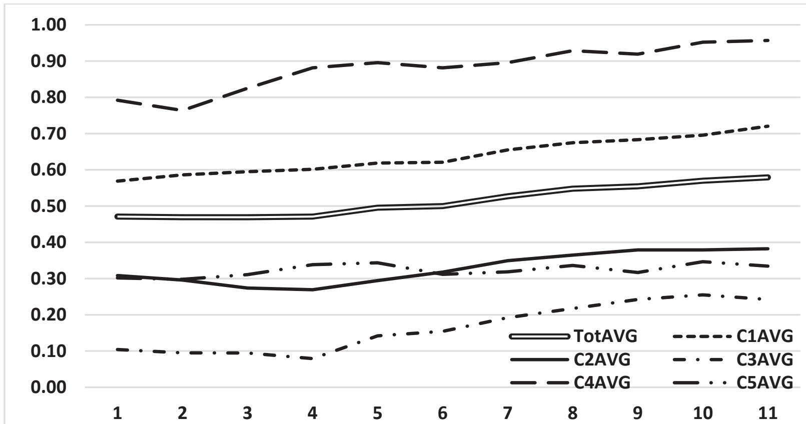
At the level of the EU 27 countries one can notice that the hypotheses H1.1 (there is beta convergence at sustainability level) and H1.2 (there is sigma convergence at sustainability level) are validated because the regression slopes ($\beta_1$) are negative and statistically significant. Since there is consistency between beta and sigma convergence, we can therefore state that the hypothesis H1 is validated.

- **Cluster 1**, consisting of 16 EU countries, mostly belonging to W and SW Europe, is characterized by an average level of ISDE-EU, which is on an upward trend, above the European average, and a degree of dispersion of ISDE-EU values, located on a decreasing trend, below the degree of dispersion characteristic of the analysed EU countries, Figure 15a,b.

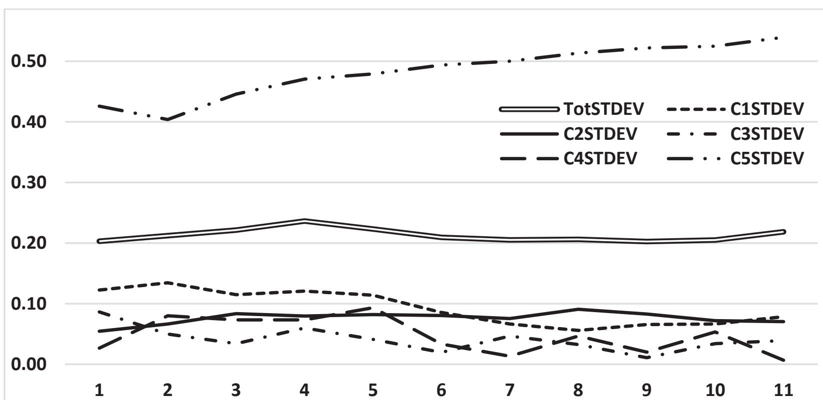
For this cluster, the existence of beta and sigma convergence regarding the sustainability of national economies is confirmed, Table 11.

At the level of this cluster, hypotheses H3.1 (there is beta sustainability convergence at cluster level) and H3.2 (there is sigma sustainability convergence at cluster level), while the concordance between beta and sigma convergence determines the validation of H3 hypothesis.

- **Cluster 2**, made up of six EU countries, most of them in N-E Europe, is characterized by an average level of ISDE-EU, located on an upward trend, slightly below the European average and a degree of dispersion of ISDE-EU values, located on a slightly upward trend, below the degree of dispersion characteristic of the analyzed EU countries, Figure 15a,b. For this cluster, the existence of beta convergence in sustainability of the member states is confirmed while sigma convergence in sustainability is uncertain, according to Table 11, because the estimated value of the right slope, although negative, is not significant, as Tables 7 and 11 show. At the level of this cluster, the H3.1 hypothesis is validated. The H3.2 hypothesis cannot be totally validated because, even if there is a negative regression slope, it is not statistically significant. In regard of the concordance between the beta and sigma convergence, this exists and would determine the validation of the H3 hypothesis, provided that the sigma convergence is not statistically significant.




(**a**)




(**b**)

**Figure 15.** (**a**) Dynamics of averages between 2006 and 2016; (**b**) Dynamics of standard deviations between 2006 and 2016.

- **Cluster 3** consisting of three EU countries, mostly located in the central area of Europe, is characterized by the lowest average level of ISDE-EU, which is on an upward trend, well below the European average but also by a degree of dispersion of values ISDE-EU, which is on a downward trend, the lowest, below the degree of dispersion characteristic of the analyzed EU countries (Figure 15a,b). For this cluster, the existence of beta and sigma convergence in the sustainability of national economies is validated. An additional remark is that two of the three states—the Czech Republic and Slovakia—together formed a single state before 1993, and this is probably why this cluster, although it has the lowest level of ISDE-EU average, is still the most homogeneous cluster in the five studied. For this cluster, the H3.1 and H3.2 hypotheses are validated and the concordance between beta and sigma convergence determines the validation of the H3 hypothesis.

- **Cluster 4** consists of only two countries—Denmark and Sweden—and from a statistical point of view it is almost impossible to estimate the convergence in sustainability of national economies. Regarding sigma convergence in sustainability, although the estimates of the straight slope are negative, they are not significant, making its assessment uncertain. Cluster 4 is characterized by the highest ISDE-EU average, which is on an upward trend, far exceeding the European average and a low degree of dispersion for the values recorded for ISDE-EU, which is on a strong downward trend compared to the values recorded for all EU countries. Despite the small volume of cluster 4 which makes it impossible to assess convergence in sustainability, it should be noted that it is a leading cluster in terms of sustainability at EU level. At the level of this cluster, neither H3.1, H3.2 or consequently H3 hypotheses are validated.
- **Cluster 5**, consisting of three countries, located in E and N-E Europe, is characterized by an average level of ISDE-EU, located on an upward trend, slightly below the European average and a degree of dispersion of ISDE-EU values, located on a strong upward trend, far above the degree of dispersion characteristic of the analyzed EU countries, as it is shown in Figure 15a,b. According to Table 10, for this cluster the existence of beta and sigma convergence cannot be confirmed or refuted because the estimated slopes for the models are statistically insignificant, both for beta and for sigma convergence (Tables 10 and 11). Even though cluster 5 is characterized by an average of ISDE-EU level close to that of the EU, it is the most heterogeneous, which does not allow a meaningful assessment of convergence in its sustainability. As a negative aspect of this cluster, we notice that the slope of the standard deviations is increasing strongly, which suggests that, within this cluster, there are sustainability behaviors that tend to differ more and more one from another.

In conclusion, we can say that, at EU level, it was found that there is both beta and sigma convergence in sustainability of the economies of its member states, which is also validated at the level of the analyzed clusters. For clusters containing the largest share of EU states, which is cluster 1 (16 countries) and cluster 3, including three countries, both beta and sigma convergence sustainability is validated. For cluster 2, consisting of six EU countries, only beta convergence in sustainability is validated, the existence of sigma convergence in sustainability being uncertain. Due to its small size, cluster 4, although it cannot be assessed in terms of beta and sigma convergence in sustainability, is undeniably a leading cluster in terms of the sustainability of national economies at EU level and beyond.

The "problem" cluster is cluster 5 and not necessarily in terms of the average level of ISDE-EU and its corresponding trend, but in terms of heterogeneity. This heterogeneity can be attributed to the fact that, imposing in the grouping process a maximum number of 5 clusters, it is possible that in this cluster were allocated countries for which the ISDE-EU component in the associated period was not found in any of the four clusters formed, this cluster being the "victim" of a "residual effect" of clustering on clusters. This requires a closer analysis of the ISDE-EU evolutions for the observed period 2006–2016 corresponding to the 3 states that make up cluster 5 as presented in Figure 16.

Figure 16 shows that there is a state, Lithuania, which has a discordant evolution compared to the other two member states, Romania and Latvia, which, although slightly different, are on a trend forward convergence. Lithuania has a negative evolution towards the two states, moving away from the evolutions of the two states. It is possible that the inclusion of this state in cluster 5 represents the residual effect of the clustering algorithm.

For this cluster, none of the hypotheses H3.1, H3.2, and consequently H3 are validated.

The analyses performed in this study aimed at validating the hypotheses presented in chapter 2, literature review and research hypotheses.

In order to sum up the validation or invalidation of the hypotheses we must mention that the hypotheses H1 (existence of convergence of the entire EU 27 region), H1.1. (existence of beta convergence at the entire EU 27 level), H1.2 (existence of sigma convergence at the level of EU 27), and H2 (the different evolutions of the sustainability dynamics for the EU 27 countries can be grouped by homogeneous clusters) have been entirely validated.

The hypotheses H3 (existence of convergence at cluster level), H3.1 (existence of beta convergence at cluster level) and H3.2 (existence of sigma convergence at cluster level) have been fully validated for clusters 1 and 3, partially for cluster 2, and have been invalidated for clusters 4 and 5.

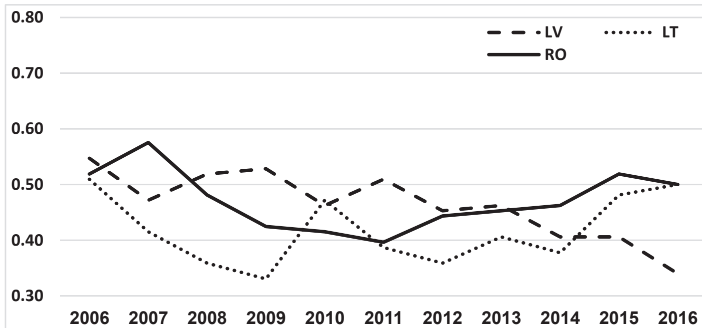



**Figure 16.** ISDE-EU dynamics for cluster 3 countries between 2006 and 2016.

Thus, according to the specificity of each cluster, measures/policies to support/encourage the transition process to sustainably convergent economies can be customised in compliance with the objectives set up in the 2030 Agenda for Sustainable Development [22].

Future research trends should include extensive methods of convergence analysis as well as spatial models of beta convergence or conditional beta convergence. New variables to determine a more performant sustainability index could also be introduced, which would highlight the long-term effects of sustainability.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Sigma convergence at the level of EU 27 countries.

| Anul | Sigma CV | Sigma SD Log ISDE | Gini Index | Theil Index |
|---|---|---|---|---|
| 2006 | 0.4393 | 0.8464 | 0.2249 | 0.1110 |
| 2007 | 0.4611 | 0.6807 | 0.2351 | 0.1174 |
| 2008 | 0.4809 | 0.6670 | 0.2344 | 0.1269 |
| 2009 | 0.5113 | 0.9026 | 0.2582 | 0.1460 |
| 2010 | 0.4592 | 0.5656 | 0.2289 | 0.1103 |
| 2011 | 0.4270 | 0.5137 | 0.2164 | 0.0952 |
| 2012 | 0.3968 | 0.4656 | 0.1977 | 0.0817 |
| 2013 | 0.3834 | 0.4398 | 0.1896 | 0.0756 |
| 2014 | 0.3722 | 0.4098 | 0.1849 | 0.0700 |
| 2015 | 0.3666 | 0.4033 | 0.1835 | 0.0677 |
| 2016 | 0.3845 | 0.4307 | 0.1919 | 0.0752 |

**Table A2.** Sigma convergence in Cluster 1 countries.

| Anul | Sigma CV | Sigma SD Log ISDE | Gini Index | Theil Index |
|---|---|---|---|---|
| 2006 | 0.2155 | 0.2061 | 0.1174 | 0.02299 |
| 2007 | 0.2294 | 0.2135 | 0.1221 | 0.02550 |
| 2008 | 0.1932 | 0.1905 | 0.1055 | 0.01885 |
| 2009 | 0.2006 | 0.1985 | 0.1070 | 0.02032 |
| 2010 | 0.1840 | 0.1948 | 0.0977 | 0.01785 |
| 2011 | 0.1378 | 0.1357 | 0.0724 | 0.00959 |
| 2012 | 0.1015 | 0.1001 | 0.0512 | 0.00522 |
| 2013 | 0.0827 | 0.0788 | 0.0443 | 0.00340 |
| 2014 | 0.0958 | 0.0922 | 0.0516 | 0.00458 |
| 2015 | 0.0956 | 0.0922 | 0.0518 | 0.00457 |
| 2016 | 0.1090 | 0.1031 | 0.0585 | 0.00586 |

**Table A3.** Sigma convergence in Cluster 2 countries.

| Anul | Sigma CV | Sigma SD Log ISDE | Gini Index | Theil Index |
|---|---|---|---|---|
| 2006 | 0.1768 | 0.1580 | 0.0900 | 0.0153 |
| 2007 | 0.2249 | 0.2225 | 0.1133 | 0.0264 |
| 2008 | 0.3047 | 0.2815 | 0.1472 | 0.0458 |
| 2009 | 0.2961 | 0.2616 | 0.1469 | 0.0424 |
| 2010 | 0.2787 | 0.2471 | 0.1361 | 0.0377 |
| 2011 | 0.2534 | 0.2289 | 0.1252 | 0.0317 |
| 2012 | 0.2159 | 0.1950 | 0.1109 | 0.0230 |
| 2013 | 0.2486 | 0.2283 | 0.1248 | 0.0309 |
| 2014 | 0.2187 | 0.1963 | 0.1112 | 0.0235 |
| 2015 | 0.1896 | 0.1706 | 0.0932 | 0.0177 |
| 2016 | 0.1843 | 0.1612 | 0.0856 | 0.0165 |

**Table A4.** Sigma convergence in Cluster 3 countries.

| Anul | Sigma CV | Sigma SD Log ISDE | Gini Index | Theil Index |
|---|---|---|---|---|
| 2006 | 0.8286 | 1.2818 | 0.3616 | 0.45459 |
| 2007 | 0.5259 | 0.5529 | 0.2209 | 0.15948 |
| 2008 | 0.3584 | 0.3298 | 0.1546 | 0.06882 |
| 2009 | 0.7565 | 1.1458 | 0.2912 | 0.38998 |
| 2010 | 0.2894 | 0.2634 | 0.1180 | 0.04478 |
| 2011 | 0.1270 | 0.1071 | 0.0542 | 0.00823 |
| 2012 | 0.2419 | 0.1877 | 0.0981 | 0.02821 |
| 2013 | 0.1502 | 0.1182 | 0.0578 | 0.01100 |
| 2014 | 0.0449 | 0.0362 | 0.0173 | 0.00100 |
| 2015 | 0.1332 | 0.1123 | 0.0575 | 0.00906 |
| 2016 | 0.1618 | 0.1381 | 0.0691 | 0.01346 |

**Table A5.** Sigma convergence in Cluster 4 countries.

| Anul | Sigma CV | Sigma SD Log ISDE | Gini Index | Theil Index |
|---|---|---|---|---|
| 2006 | 0.0336 | 0.0238 | 0.0119 | 0.00057 |
| 2007 | 0.1047 | 0.0742 | 0.0370 | 0.00548 |
| 2008 | 0.0888 | 0.0629 | 0.0314 | 0.00395 |
| 2009 | 0.0831 | 0.0589 | 0.0294 | 0.00346 |
| 2010 | 0.1041 | 0.0738 | 0.0368 | 0.00543 |
| 2011 | 0.0378 | 0.0267 | 0.0134 | 0.00071 |
| 2012 | 0.0149 | 0.0105 | 0.0053 | 0.00011 |
| 2013 | 0.0502 | 0.0355 | 0.0178 | 0.00126 |
| 2014 | 0.0217 | 0.0154 | 0.0077 | 0.00024 |
| 2015 | 0.0560 | 0.0396 | 0.0198 | 0.00157 |
| 2016 | 0.0070 | 0.0049 | 0.0025 | 0.00002 |

**Table A6.** Sigma convergence in Cluster 5 countries.

| Anul | Sigma CV | Sigma SD Log ISDE | Gini Index | Theil Index |
|---|---|---|---|---|
| 2006 | 0.0374 | 0.0303 | 0.0160 | 0.00069 |
| 2007 | 0.1667 | 0.1343 | 0.0730 | 0.01374 |
| 2008 | 0.1849 | 0.1593 | 0.0786 | 0.01768 |
| 2009 | 0.2314 | 0.1918 | 0.1028 | 0.02691 |
| 2010 | 0.0674 | 0.0560 | 0.0279 | 0.00230 |
| 2011 | 0.1582 | 0.1244 | 0.0632 | 0.01219 |
| 2012 | 0.1241 | 0.1054 | 0.0501 | 0.00789 |
| 2013 | 0.0688 | 0.0573 | 0.0285 | 0.00240 |
| 2014 | 0.1040 | 0.0839 | 0.0454 | 0.00536 |
| 2015 | 0.1229 | 0.1028 | 0.0536 | 0.00766 |
| 2016 | 0.2071 | 0.1821 | 0.0797 | 0.02247 |

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# Economic Dependence Relationship and the Coordinated & Sustainable Development among the Provinces in the Yellow River Economic Belt of China

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**Abstract:** This study uses the mutual information method to study economic dependence among the provinces in the Yellow River Economic Belt, constructs the core dependence structure through the maximum spanning tree method, and uses the rolling window method to observe the changes in the dependence structure from a dynamic point of view. It has been found that there are extensive economic links among the nine provinces in the Yellow River Economic Belt, but that the degree of economic dependence varies greatly in different time periods. When economic development and the capital market are overheated, the interregional dependence is stronger, while the dependence decreases when economic development is in a state of contraction or when the total demand is relatively reduced. In addition, the phenomenon of geographical clustering of economic dependence is not obvious among provinces in the Yellow River Economic Belt. Most of the provinces maintain strong economic dependence with the economically developed provinces, and the economically developed provinces also maintain strong economic ties with one another. Finally, the implementation of the Yellow River Economic Belt strategy strengthens the economic links between the less developed provinces and the other provinces in the region, and promotes coordinated and sustainable development in the region.

**Keywords:** economic dependence; regional coordinated and sustainable development; mutual information; Yellow River Economic Belt

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## 1. Introduction

At present, with the deepening of economic globalization and trade liberalization, economic exchanges, capital flow, and population flow among different countries and regions around the world are becoming more frequent and convenient. Even though there are signs of trade protectionism in some countries at present, the degree of economic dependence among various economies will continue to deepen on the whole. This is because extensive economic dependence can make the allocation of capital, production resources, and labor more reasonable and efficient [1]. The current research on regional links is mainly divided into the following three aspects: The first is from the perspective of infrastructure networks; this is mainly divided into the transportation infrastructure and communication infrastructure networks. Through the close connection of infrastructure networks, the relationships between various regions are strengthened [2,3]. The second aspect of research is from the perspective of enterprise organization—for instance, multinational enterprises, headquarters and branches, enterprise ownership, changes in industrial spatial network structures, etc.,—to investigate the resulting changes in regional economic relationships [4–7]. The third aspect is from the perspective of population flow, capital flow, and information communication, to study whether these flows will bring changes in the degree of interregional economic dependence [8–12]. While interregional economic dependence relationships are mainly manifested in the interactions between economic entities within the region(s) [13], the school of relational geography further points out that the study of economic geography should focus on the impact of the interactions between regional economic entities on regional economic development [14].

With the extensive deployment of capital, production resources, labor, etc., interregional economic dependence has been strengthened, and the urbanization process and the formation of large urban agglomerations will also have a positive effect on the efficient economic development of the region(s) [15]. At present, some urban agglomerations have been formed or are being constructed around the world, such as the Northeast Atlantic coastal urban agglomerations in the United States, the Pacific coastal urban agglomerations in Japan, and the British urban agglomerations in the United Kingdom. After more than 40 years of reform and opening-up, China's urbanization level and degree of economic development have been greatly improved. In order to adapt to the new development mode of the region, China's urban agglomerations must be developed. In order to meet the needs of urbanization, the Chinese government is now speeding up the construction of urban agglomerations and regional development belts. On regional economic dependence and regional economic coordination and sustainable development, it is pointed out by the Development Research Center of the State Council of China in "China's Regional Coordinated Development Strategy" that the coordinated development of regional economy includes several aspects; the main points are increasing the economic driving effect of rich areas on the less developed regions, and promoting regional integration. From the above understanding of the coordinated development of regional economies, it can be seen that the coordinated development of regional economies should include interaction between regions and coordinated development among various economic units, and the existing literature finds that close regional economic dependence will affect the sustainable development levels of each city [16].

With the deepening construction of urban agglomerations and regional economic development belts, the coordinated development of various regions has been widely considered. Studies have shown that efficient and coordinated industrial and economic layouts will promote regional development [17]. Furthermore, in terms of the regional coordinated development of urban agglomerations, existing studies have conducted extensive research on the following aspects: the degree of regional coordinated development [18–20]; the influencing factors in the development process of urban agglomerations, and the relevant definitions of urban agglomerations [21–27]; and the formation and development mechanisms of regional dependent structures [28–32].

In recent years, the Chinese government has proposed focusing on building important economic belts and development poles in the Yangtze River Basin, the Yellow River Basin, and the coastal areas, in order to increase economic ties and cooperation between provinces and cities in the above areas, and form a new and more dynamic regional development pattern. Under this background, the Yellow River Basin High-Quality Development Economic Belt, with ecological protection and sustainable regional development, has emerged. This paper takes the nine provinces in the Yellow River Basin as the study object, calculates the degree of economic dependence among the above provinces in this region, constructs the core structure of the economic links, and compares their changes in the past six years. Most importantly, the relevant conclusions of this study provide some important reference directions for the coordinated and sustainable development of the Yellow River Economic Belt in the future, which is more conducive to promoting coordination and cooperation among the provinces in this region. At present, the research on China's regional economic dependence and regional coordination and sustainable development initiatives mainly focuses on the Yangtze River Economic Belt. It has been found that there is a high correlation between the strength of economic connection and sustainable development in the Yangtze River Economic Belt [33]. Zheng and Xiang found that the degree of economic dependence and the level of economic growth showed the same trend; that is, the less a region is connected with others, the lower its level of economic growth. Based on the 11 provinces in China's Yangtze River Economic Belt, they found that Guizhou and Yunnan, which are the most underdeveloped provinces of the west, are highly dependent on the economic development of the more developed provinces. Their results show that the development of economic integration can rapidly promote the economic growth of underdeveloped areas, and that regional integration is an important way to break through the unbalanced development [34]. However, due to the relatively recent establishment of the Yellow River Economic Belt, there are few studies on economic interdependence among the provinces in this region. Therefore, this paper takes the Yellow River Economic Belt as the analysis background in order to study interdependence among the provinces in the region.

Mutual information is a kind of relative entropy, which measures the interdependence of two variables by the information they share. Mutual information can measure not only the linear dependence but also the nonlinear dependence between variables; at the same time, the mutual information method is data-driven, does not rely on specific models, and has a wide range of applicability [35,36]. At present, the theory and method of mutual information has been widely used in the study of economic dependence; for example, Kharrazi et al. used mutual information to build a global oil trade network from 1998 to 2012, and found that mutual information can help researchers track the changes in dependence between trading partners, and provide references for policy evaluation [37]. Wang X.D. et al. used mutual information to study the financial contagion effect of the major global stock markets during the 2008 financial crisis, and found that mutual information can effectively investigate the interdependence of, and changes to, various stock markets during different periods of the financial crisis [38]. Wu X.B. et al. used mutual information and other methods to study the regional dependence of China's stock market, and constructed the regional dependence network of the stock market [39]. Mohti et al. used mutual information and DFA methods to study the nonlinear dependence and efficiency of stock markets [40]. Viegas et al. used mutual information and other methods to quantify the distance between the economic system, such as business, and the effective market allocation of Japan, so as to study the efficiency level of economic activities in the region [41]. Through the above research, it can be seen that mutual information is an effective method for studying economic dependence and building the dependence network, but the application of mutual information theory is relatively less applicable to the economic interdependence of regions and sub-regional provinces.

This article examines the economic interdependence of nine provinces in the Yellow River Economic Belt over the past six years, as well as the core structure and dynamic changes of their interdependence, and through the comparison of the average interdependence of the provinces over the past six years, the sustainable development of the Yellow River Economic Belt is investigated. We mainly consider the following issues:

(1) Analysis of the economic interdependence of the nine provinces in the Yellow River Economic Belt over the past six years.
(2) The core structure of, and dynamic changes to, economic interdependence among the nine provinces of the Yellow River Economic Belt over the past six years.
(3) Whether the development strategy of the Yellow River Economic Belt will contribute to the sustainable development of the region's economy.

The rest of this paper is organized as follows: Section 2 introduces the methods. Section 3 introduces the data used in this study. Section 4 displays the empirical results and some analyses. Section 5 displays the conclusion of this paper. The research methodology infographic of this study is shown in Figure 1.

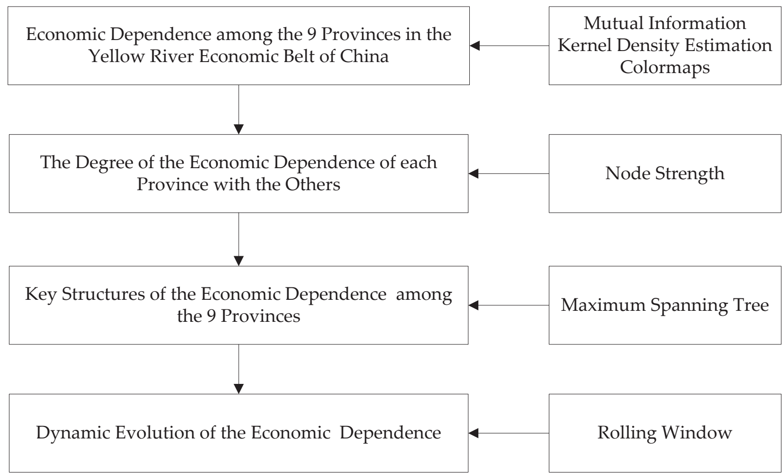



**Figure 1.** Research methodology infographic.

## 2. Methods

In this study, mutual information and kernel density estimation are used to calculate the economic interdependence of provinces in the Yellow River Economic Belt. In previous studies on the coordinated development and economic dependence of urban agglomerations, methods such as spatial econometric modelling, regional dependence structure, and network risk propagation were applied to describe the dependence of each node in urban agglomerations or urban development clusters [42–45]. Compared with the above methods, mutual information and kernel density estimation have the following advantages: First of all, the traditional econometric-model-based study of regional economic interdependence is mainly applied in the linear condition, but some studies have proved that the economic time series often show nonlinear characteristics, and mutual information can be used to calculate the interdependence of variables under both linear and nonlinear conditions [46–50]. In addition, the econometric models calculating the dependence relationship often need to set the parameters of the model in advance, and the setting of parameters will affect the final estimation results, while mutual information is model-free, therefore it is not necessary to set the model in advance. Finally, a large number of studies need to make assumptions about the distribution of samples. For example, in most cases, it is assumed that the samples obey normal distribution, but in reality, the samples tend to show peaked and thick-tailed distribution. Therefore, this paper uses the kernel density estimation method to calculate the mutual information between variables, which does not depend on specific assumptions of data distribution.

### *2.1. Mutual Information*

The definition of information entropy was established by Shannon in 1940s, and it has been considered that information entropy can be used to measure the uncertainty of an event. According to the definition given by Shannon, the entropy of a discrete random variable $X$ can be expressed as:

$$H(X) = -\sum_{x\in\chi} p(x)\log p(x) \tag{1}$$

where $\chi$ is the set of all states of the random variable $X$, $p(x)$ is the probability of $x$, and the base of the logarithm is commonly chosen as 2; the unit is the bit.

For the two random variables $X$ and $Y$, the joint entropy between the two variables could be defined as:

$$H(X,Y) = -\sum_{x\in X}\sum_{y\in Y} p(x,y)\log p(x,y) \tag{2}$$

where $p(x,y)$ is the joint probability of $x$ and $y$.

The definition of MI between $X$ and $Y$ is given in Formula (3) [51]:

$$MI(X,Y) = \sum_{x\in X}\sum_{y\in Y} p(x,y)\log\frac{p(x,y)}{p(x)p(y)} \tag{3}$$

According to Formulas (1) and (2), MI could be rewritten as Formula (4) [52]:

$$MI(X,Y) = H(X) + H(Y) - H(X,Y) \tag{4}$$

MI measures the information that one variable discloses about another [53]. It can be seen from Formula (4) that, in a mathematical sense, the mutual information value of two variables can be expressed as the sum of the entropy of the two variables and the difference between the joint entropy of the two variables. Theoretically speaking, the mutual information of two variables represents, when the information contained in one of the two variables is fully known, the degree by which the known information of known variable reduces the uncertainty of the other variable; alternatively, it can be understood as the degree by which the known information of one variable increases the information of the other variable. The mutual information between two variables can be understood as the amount of information shared by two variables; that is, if one of the two variables is known, and the uncertainty of the other variable can be greatly reduced as a result, then it can be considered that the known variable contains a lot of information about the other variable.

### 2.2. Kernel Density Estimation

Let $U = \{u_1, u_2, \ldots, u_N\}$ be a $d$-dimensional real variable, and the kernel density of its probability density function is estimated by Formula (5):

$$\hat{f}(u_j) = \frac{1}{Nh^d}\sum_{i=1}^{n} K(\frac{u_j - u_i}{h}) \tag{5}$$

where $h$ is the window parameter, also known as bandwidth, and $K(\cdot)$ is the $d$-dimensional kernel function. Then, under the Gaussian kernel function, Formula (5) is transformed into (6):

$$\hat{p}(\boldsymbol{u}_j) = \frac{1}{Nh^d}\sum_{i=1}^{n}\frac{1}{\sqrt{(2\pi)^d|S|}}\exp(-\frac{(\boldsymbol{u}_j-\boldsymbol{u}_i)^T S^{-1}(\boldsymbol{u}_j-\boldsymbol{u}_i)}{2h^2}) \tag{6}$$

where $S$ is the determinant of its covariance matrix.

The choice of bandwidth has a great influence on the estimation effect. According to the authors of [41], this paper selects the optimal bandwidth, as shown in Formula (7):

$$h = (\frac{4}{d+2})^{1/(d+4)} N^{-1/(d+4)} \tag{7}$$

The probability density of samples can be obtained by kernel density estimation, and then the entropy formula can be obtained as follows:

$$H(\boldsymbol{U}) = -\frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(\boldsymbol{u}_t) \tag{8}$$

Combined with Formulas (4) and (8), we can obtain the final formula with which to calculate the mutual information value of the two variables, as shown in Formula (9):

$$I(X,Y) = -\frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(x_t) - \frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(y_t) + \frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(x_t, y_t) \quad (9)$$

The basis and premise of empirical research is to estimate the probability density and distribution of the observed samples. At present, a large number of studies are based on assumptions, such as the assumption that the observed samples will obey normal distribution. Under this assumption, the parameters in the samples are estimated. However, a large number of economic time series are not strictly subject to a single probability distribution, so the previous assumption that the samples will obey a certain distribution will lead to inaccurate parameter estimation, which will in turn lead to bias in the results. In order to overcome this problem, this paper uses the kernel density estimation method, which is a nonparametric estimation method.

## 3. Data

This paper selects China's regional stock price index as the research object, which reflects the overall performance of listed companies in different regions of China's A-share market, depicts the development characteristics of regional economies, and is an important indicator by which to measure the development of regions. In China, the listed companies in a region often reflect the main economic development characteristics and industrial structure of a province or a city, and they can reflect not only the economic and capital development level and potential, but also the business environment, policy support, and infrastructure construction—which may be called "soft power"—in one region. In addition, it has been proven by research that regional economic interconnection manifests as the interaction between regional economic entities—which may take the form of business connection, capital circulation, etc., [13]—and the daily trading data of China's regional stock price index can reflect the economic development of one region [39].

Although there are many factors affecting stock prices and the co-variation among them, this paper does not use a single stock price dataset, but rather a comprehensive index, which can reflect regional development after calculation and adjustment. In addition, this paper calculates the dependence relationships among the regional indices in each of the six years from 2015 to 2020, and finds common conclusions, which may also help to avoid inaccuracies in the calculation results caused by changes to the stock market during a certain period. The data selected in this paper come from the Wind Economic Database, and the time range of the data is from 5 January 2015 to 31 December 2020—a total of 6 years of indexed daily closing prices. The numbers and index names are listed in Table 1.

**Table 1.** The numbers, names and the codes of the nine regional indices.

| No. | Index Name | Code | No. | Index Name | Code |
|---|---|---|---|---|---|
| 1 | Gansu Index | CN6004 | 6 | Shandong Index | CN6021 |
| 2 | Henan Index | CN6010 | 7 | Shanxi Index | CN6022 |
| 3 | Inner Mongolia Index | CN6018 | 8 | Shaanxi Index | CN6023 |
| 4 | Ningxia Index | CN6019 | 9 | Sichuan Index | CN6025 |
| 5 | Qinghai Index | CN6020 | | | |

In accordance with previous literature, this paper calculates the logarithmic return of each index according to Formula (10):

$$R(t) = \ln P(t) - \ln P(t-1) \quad (10)$$

where $p(t)$ and $p(t-1)$ are the daily closing prices of the regional index on dates $t$ and $t-1$, respectively, and $R(t)$ is the logarithmic return of the regional index on date $t$. Table 2 shows the descriptive statistical results of the logarithmic rate of return of the nine provinces. It can be seen that the time series after the difference are stable, and none of them obey Gaussian distribution.

**Table 2.** Statistical characteristics of the nine regional indices.

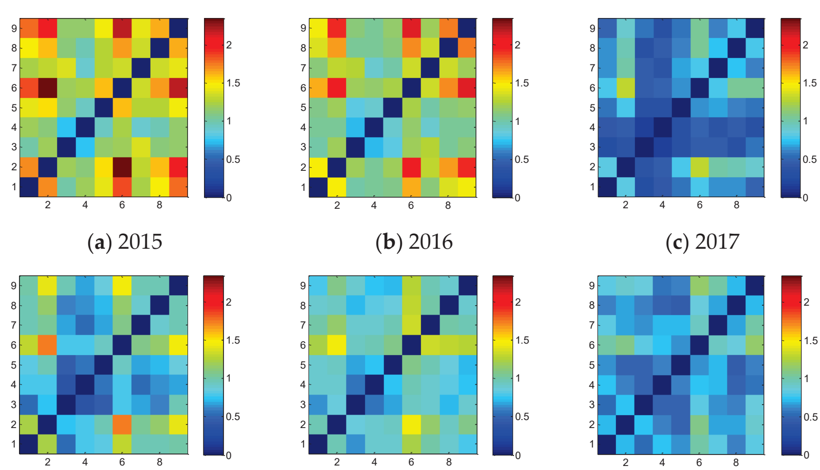
| No. | Mean | Std. Dev. | Skewness | Kurtosis | ADF Statistic | Jarque–Bera Statistic |
|---|---|---|---|---|---|---|
| 1 | $-8.31 \times 10^{-5}$ | 0.0198 | −1.0759 | 7.0631 | −34.4492 *** | 1286.827 *** |
| 2 | $3.33 \times 10^{-4}$ | 0.0179 | −1.0290 | 7.3840 | −35.6237 *** | 1427.818 *** |
| 3 | $3.18 \times 10^{-4}$ | 0.0178 | −0.7248 | 6.8397 | −37.6013 *** | 1025.385 *** |
| 4 | $-1.82 \times 10^{-4}$ | 0.0187 | −0.8611 | 6.2893 | −34.2632 *** | 839.1872 *** |
| 5 | $-2.38 \times 10^{-4}$ | 0.0204 | −0.8815 | 6.5795 | −35.6890 *** | 969.1649 *** |
| 6 | $3.25 \times 10^{-4}$ | 0.0176 | −1.0764 | 7.7921 | −35.3815 *** | 1680.070 *** |
| 7 | $4.91 \times 10^{-6}$ | 0.0186 | −1.1569 | 9.0852 | −35.3596 *** | 2580.079 *** |
| 8 | $4.08 \times 10^{-4}$ | 0.0206 | −0.7889 | 6.7558 | −34.6022 *** | 1010.246 *** |
| 9 | $5.54 \times 10^{-4}$ | 0.0188 | −1.0312 | 7.3076 | −34.4032 *** | 1388.468 *** |

Note: *** means statistical significance at the 1% level.

## 4. Empirical Analysis

### *4.1. Mutual Information among the Regional Indices*

Figure 2 shows the mutual information values of the economic interdependence of the nine provinces in each of the past six years. In order to visually observe the changes in economic interdependence in different years, this study uses thermal maps to display the results, in which the abscissa and ordinate represent the numbers of the nine provinces as indexed in Table 1. In order to achieve a better contrast effect, the value ranges of these six thermal maps are all adjusted to 0–2.348, because the maximum mutual information value among provinces over the six years is 2.3472 between Henan (No. 2) and Shandong (No. 6) in 2015.



(**a**) 2015 (**b**) 2016 (**c**) 2017

(**d**) 2018 (**e**) 2019 (**f**) 2020

**Figure 2.** Colormaps of the MI among the nine provinces in each of the six years.

From Figure 2, it can be observed that economic interdependence exists, but at different strengths in different years. Over the six years from 2015 to 2020, the economic interdependence of the nine provinces in the Yellow River Economic Belt has changed greatly, and this change can be clearly observed in the thermal maps in Figure 2. First of all, in 2015 and 2016, the economic dependence among the nine provinces was strong, with the average MI reaching 1.3830 and 1.2730, respectively—among which Henan (No. 2), Shandong (No. 6) and Sichuan (No. 9) showed particularly high economic interdependence, especially in 2015, when the interdependence of Henan (No. 2) and Shandong (No. 6) was the largest among all regional indices in all six years. The strong economic interdependence of the provinces in 2015 and 2016 is related to the overheated Chinese economy and the massive bubble in China's capital market at that time. In 2015, China's capital market was highly volatile; as a barometer of the economy, the stock market began to fall off in June that year, and this fluctuation continued until 2016. The overheating of economic development and the capital market naturally increased the exchange of economic activities and the flow of funds, thus intensifying the economic ties between regions. Since then, China has introduced a number of policies and measures to stabilize the economy and the capital market. Therefore, from the thermal maps in Figure 2, it can be seen that the economic interdependence of the nine provinces was greatly reduced in 2017, and from the results in Table 3, we can see that the economic interdependence of the provinces in 2017 was only 0.6204, which is the lowest value among the six years involved in this study, and only half of that in 2016.

**Table 3.** Average MI in each of the six years.

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|
| Average MI | 1.3830 | 1.2730 | 0.6204 | 0.9004 | 0.9425 | 0.7209 |

Table 3 shows the average MI of each year, and these values can be used to compare the overall situation of economic interdependence among the nine provinces over the six years. From the results displayed in Table 3, it can be seen that with the introduction and deepening of the Yellow River Economic Belt strategy, the average interdependence of the provinces in 2018 and 2019 was improved to a certain extent, and the average mutual information value in 2019 was 0.9425, which is 50% higher than that in 2017. Some studies have shown that the economic interdependence of provinces in some regions is closely related to the sustainable development levels of the region in question. The economic interdependence of provinces in the region promotes overall sustainable development level of the region [16,33]. This also shows that the introduction of the Yellow River Economic Belt policy will promote the sustainable development of the economy of the this region. However, in 2020, this value dropped to 0.7209, which is only 76.49% of that in 2019. This was due to the reduction of social demand and the closure of regions caused by COVID-19, which restricted the business activities of entities in different provinces, resulting in a huge reduction in the economic interdependence of the nine provinces.

Based on the above analysis, the following conclusions can be drawn: The economic interdependence of the provinces in the Yellow River Economic Belt changed with their economic development. In overheated stages of economic development—such as in 2015 and 2016—the interdependence was relatively strong, while in shrinking stages of economic development, or in a relatively declining stage of total demand—such as in 2017 and 2020, respectively—the interdependence is relatively weak.

This study then analyzes the strength of each node (NS) of the nine regional indices' dependence networks over the past six years. The node strength reflects the sum of the mutual information values between each regional index and other indices during a certain period, as shown in Formula (11):

$$NS_i = \sum w_{ij} \tag{11}$$

where $w_{ij}$ is the mutual information value between node $i$ and node $j$.

Figure 3 shows the strength of each node of the nine regional indices' networks at different periods. The abscissa in the figure represents the regional index number in Table 1, while the ordinate represents the strength value of the nodes (NS). Table 4 shows the standard deviation of the regional index node strength of the nine provinces in each year, which is used to reflect the differences in node strength among provinces in the Yellow River Economic Belt in each year.

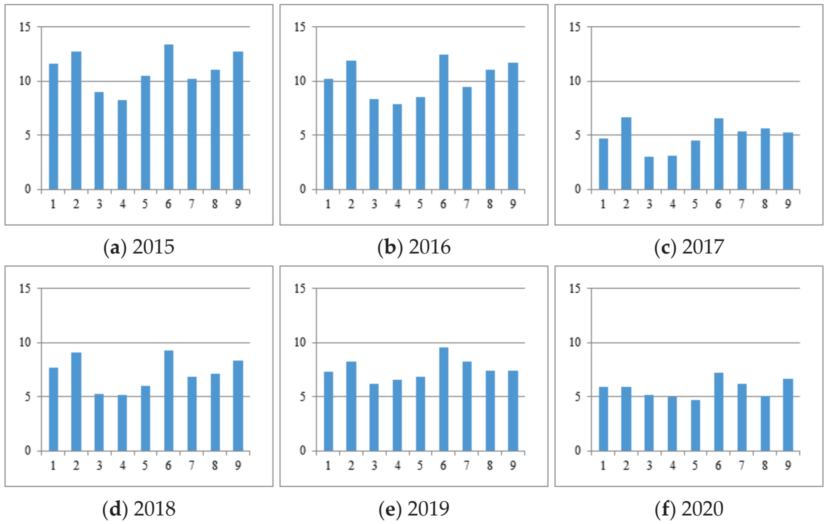



**Figure 3.** The NS value of the nine regional indices in each of the six years.

It can be seen from the results in Figure 3 that the node strength of Inner Mongolia (No. 3), Ningxia (No. 4), and Qinghai (No. 5) is the smallest in almost all of the six years, while the node strength of Henan (No. 2), Shandong (No. 6), and Sichuan (No. 9) is the largest in almost all of the years, which indicates that the interdependence of Inner Mongolia, Ningxia, Qinghai and the other provinces is weak, while the interdependence of Henan, Shandong, Sichuan and the other provinces is strong, which also echoes some of the conclusions from Figure 2. This result is consistent with the conclusion of the authors of [34]; that is, that the level of regional economic development is related to the degree of economic closure of the region. When the economic development of a region is more closed, the level of economic development of the region is worse. In this study, Inner Mongolia (No. 3), Ningxia (No. 4), and Qinghai (No. 5) are located in the western region of China, and their economic development levels are relatively low. Meanwhile, Shandong (No. 6) is the only eastern coastal province in the Yellow River Economic Belt, with strong economic foundations and huge development potential, while Henan (No. 2) and Sichuan (No. 9) are the provinces with the greatest economic potential in the central and western regions of China, respectively. It can be seen that the provinces with better economic development conditions and greater development potential have larger node strength and have stronger economic interdependence with other provinces, while the provinces with poor economic development levels have relatively closed economic development.

**Table 4.** Standard deviations of the NS in each of the six years.

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|
| S. D. of NS | 1.6554 | 1.6026 | 1.2371 | 1.4366 | 0.9717 | 0.8044 |

In addition, from the results in Table 4, it can be seen that from 2015 to 2020, the standard deviation of the node strength of each province in the Yellow River Economic Belt shows a downward trend on the whole, which indicates that economic dependence in the provinces is developing towards a balanced trend on the whole. Furthermore, the gap between the node strengths of Inner Mongolia (No. 3), Ningxia (No. 4), and Qinghai (No. 5) on the one hand, and that of Henan (No. 2), Shandong (No. 6), and Sichuan

(No. 9) on the other, is gradually narrowing, which also shows that the implementation of the Yellow River Economic Belt strategy has promoted coordinated development in the region, especially in terms of the economic ties between the economically underdeveloped provinces and the other provinces in this region.

Based on the above analysis, we can see that the economic interdependence of the nine provinces in the Yellow River Economic Belt was quite different during different periods. In 2015 and 2016, with the overheated Chinese economy and the massive bubble in China's capital market, the interdependence was stronger. After the market was adjusted and resumed in 2017, the interdependence relationship between 2018 and 2019 was steadily raised. At the same time, the degree of economic interdependence between different provinces is not the same, among which the economically developed provinces—such as Henan (No. 2), Shandong (No. 6), and Sichuan (No. 9)—have stronger node strength, while the less economically developed areas—such as Inner Mongolia (No. 3), and Ningxia (No. 9)—are relatively weak. However, with the deepening of Yellow River Economic Belt strategy, the economic interdependence of the provinces in the region is gradually becoming more and more balanced, and the economic dependence of the less developed provinces on other provinces has been strengthened.

### *4.2. Maximum Spanning Tree*

The MST is one of the spanning trees of a network with the maximum total edge weights. It can be used to help to disentangle the network and to visualize its key structures [54]. Figure 4 shows the MSTs in each of the six years, and the numbers represent the numbers of the nine provinces, as shown in Table 1. It can be seen that the structures of the trees are different.

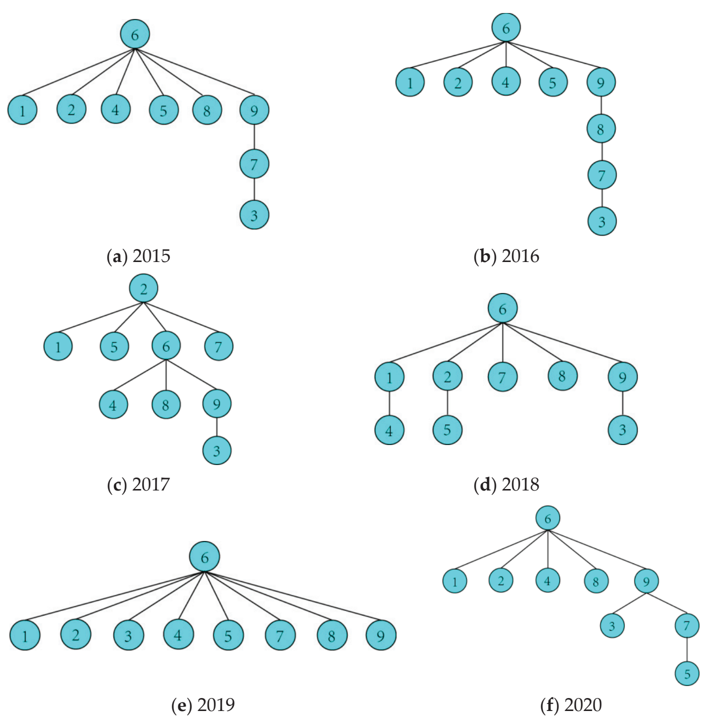



**Figure 4.** Maximum spanning trees (MSTs) of the nine provinces in each of the six years.

From Figure 4, we can observe that the No. 6 node always has the largest number of edges, followed by nodes No. 2 and No. 9, which also echoes the conclusions of

Section 4.1: that is, that Henan (No. 2), Shandong (No. 6), and Sichuan (No. 9) have strong economic ties with many provinces in the Yellow River Economic Belt. This proves once again the relationship between the level of economic development and the degree of closeness of development [34]. As provinces with higher levels of economic development, Henan (No. 2), Shandong (No. 6), and Sichuan (No. 9) not only have greater node strength (as shown in Figure 3), but also are at the core of the results of economic interdependence.

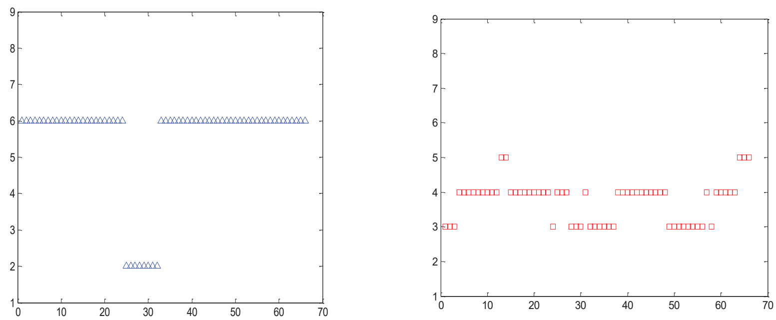
By analyzing the results of Figure 4, we can also draw another two interesting observations: First, that Shandong (No. 6), as the strongest economic province in the Yellow River Economic Belt—which is in third place in the Chinese mainland's total GDP rankings as of 2019—maintains strong economic ties with other provinces, especially in 2019, when Shandong had the strongest link with all of the other eight provinces. Secondly, that Shandong, as a province in the lower reaches of the Yellow River, is only adjacent to Henan in the Yellow River Economic Belt; from this point of view, the geographical clustering phenomenon—that is, strong interdependence between neighboring provinces or regions—is not obvious in the Yellow River Economic Belt, while each province appears more inclined to maintain strong links with the more economically developed provinces, such as Henan (No. 2), Shandong (No. 6), and Sichuan (No. 9). In addition, at some points, the economic interdependence of the provinces reflects a certain geographical clustering phenomenon—such as with Inner Mongolia (No. 3) and Shanxi (No. 7) in 2015 and 2016; Shanxi (No. 7) and Shaanxi (No. 8), and Shaanxi (No. 8) and Sichuan (No. 9), in 2016; Henan (No. 2) and Shanxi (No. 7) in 2017; and Gansu (No. 1) and Ningxia (No. 4) in 2018.

Based on the above analysis, we can gather that the economic interdependence of the nine provinces in the Yellow River Economic Belt does not strictly follow the geographical clustering phenomenon, whereby the neighboring provinces would maintain relatively close economic ties. On the contrary, the provinces prefer to maintain close economic interdependence with the more developed provinces—especially with Shandong Province, which is located in the eastern region.

### *4.3. Dynamic Evolution of Interependence*

The previous analysis of the economic interdependence network and the core structure of the nine provinces in the Yellow River Economic Belt during the six years was a static analysis. This section will use the rolling window method to explore the dynamic relationships and structures of the economic interdependence of the provinces in the Yellow River Economic Belt. In this study, the width of the rolling window is set as 150 trading days, and the sliding distance of each window is set as 20 trading days. The reason for this setting of the window width and sliding distance is that it can not only guarantee the number of samples required for each window, but also guarantee that each slide is equivalent to one month, as well as guaranteeing a sufficient contrast effect. All samples are divided into 66 windows in total.

Figure 5 shows the provinces with the highest and lowest node strength in each rolling window. The abscissa represents the position of each window, while the ordinate represents the nine regional indices shown in Table 1. It can be seen from the figure that over the 66 windows, the greatest node strength is concentrated in two provinces—namely, Henan (No. 2) and Shandong (No. 6)—while the weakest node strength is concentrated in three provinces—namely, Inner Mongolia (No. 3), Ningxia (No. 4), and Qinghai (No. 5)—which is consistent with the results of previous static analyses.



(**a**) The greatest node strength (**b**) The weakest node strength

**Figure 5.** The regional indices with the greatest and weakest node strengths.

Table 5 shows, in each of the 66 sliding windows, with which one a certain region maintains the strongest dependence relationship—in other words, which region is most closely related to the window in question. For example, if the maximum weight of region A connects to region B, then we add 1 to the position of matrix (A,B), and the initial value of position (A,B) is 0. It can be seein in Table 4 that the table is not symmetric, because the maximum weight edge of region A may connect to region B, while the maximum weight edge of region B may connect to another region, such as region C, which leads to asymmetry.

**Table 5.** Total numbers of the strongest edges between the indices in rolling windows.

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Sum |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 13 | 0 | 0 | 0 | 48 | 0 | 0 | 5 | 66 |
| 2 | 0 | 0 | 0 | 0 | 0 | 66 | 0 | 0 | 0 | 66 |
| 3 | 0 | 6 | 0 | 0 | 0 | 8 | 23 | 0 | 29 | 66 |
| 4 | 15 | 6 | 0 | 0 | 0 | 35 | 4 | 4 | 2 | 66 |
| 5 | 0 | 29 | 0 | 0 | 0 | 26 | 8 | 1 | 2 | 66 |
| 6 | 0 | 38 | 0 | 0 | 0 | 0 | 4 | 1 | 23 | 66 |
| 7 | 0 | 17 | 9 | 0 | 0 | 22 | 0 | 6 | 12 | 66 |
| 8 | 0 | 6 | 0 | 0 | 0 | 46 | 0 | 0 | 14 | 66 |
| 9 | 0 | 0 | 0 | 0 | 0 | 66 | 0 | 0 | 0 | 66 |
| Sum | 15 | 115 | 9 | 0 | 0 | 317 | 39 | 12 | 87 | |

It can be seen from the table that the largest numbers among the top three provinces are Henan, Shandong, and Sichuan—of which Shandong has the largest weight edge 317 times, Henan 115 times, and Sichuan 87 times—and this ranking is consistent with the GDP of the three provinces among the Chinese mainland provinces. In addition, we can find that the region Shandong (No. 6) has the largest weight edge 317 times; among them, Henan (No. 2) and Sichuan (No. 9) each give the maximum weight edge to Shandong (No. 6) 66 times, while Shandong also gives Henan and Sichuan the maximum weight edge 38 and 23 times, respectively. It can be seen that among the nine provinces in the Yellow River Economic Belt, these three provinces with the best economic and social development maintain a strong economic dependence on one another, and other provinces also maintain the strongest ties with the above three provinces. In addition, Inner Mongolia, Ningxia, and Qinghai have the smallest number of largest weight edges from other provinces, and Ningxia and Qinghai do not have the largest weight edges from any other provinces, indicating that no provinces actively maintain the strongest economic interdependence with these two provinces. From the above results, it can be seen that the provinces with poor economic development are more willing to maintain a strong economic dependence on the provinces with more developed economies, or it can be explained that the provinces with poor economic development are more dependent on the better developed economic provinces in matters of economic development, and the economic integration construction of the Yellow River Economic Belt can quickly enhance the economic growth of these provinces, so as to realize the economic growth and the balanced development of the whole region.

## 5. Conclusions

This paper focuses on the economic interdependence and the coordinated and sustainable development of the nine provinces in the Yellow River Economic Belt, and the changes to the economic interdependence structure over the past six years.

The research conclusions of this paper mainly include the following:

Firstly, there are extensive economic links between the provinces in the Yellow River Economic Belt, but the degree of economic interdependence varies greatly during different periods. When the economic development or the capital market is overheated, the interdependence of the provinces is stronger, while the interdependence decreases when the economic development is in a state of contraction or the total demand is relatively reduced. This shows that economic development and capital market operation have significant impacts on regional economic interdependence.

Secondly, the geographical clustering phenomenon of economic dependence is not obvious among provinces in the Yellow River Economic Belt. Most provinces maintain strong economic dependence on economically developed provinces, while economically underdeveloped provinces tend to be on the edge of the interdependence structure. In addition, the economically developed provinces also maintain strong economic ties with one another.

Finally, the implementation of the Yellow River Economic Belt strategy promotes coordinated and sustainable development in this region, especially the economic links between the less developed provinces and other provinces.

However there are still some limitations to this study. This paper studies economic interdependence and its core structure among the nine provinces in the Yellow River Economic Belt, but does not make a detailed analysis of the mechanisms of the dependence relationships or the core structure, which would be helpful in better explaining regional economic interdependence, and will be paid more attention in future research. Combined with the conclusions obtained in this paper, some suggestions could be drawn for the future development of the Yellow River Economic Belt. The most important thing is to pay attention to the economic driving role of the developed provinces, and at the same time pay more attention to the economic stability of the developed provinces, so as to prevent financial risks or economic bubbles from spreading to other provinces through the economic interdependence structure.

**Author Contributions:** X.W., and X.H. proposed the research framework together. X.W. collected the data, finished the computation, and wrote the paper. X.H. provided some important guidance and advice during the process of this research. Both authors have read and agreed to the published version of the manuscript.

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# The Environment in the Lead: A Scorecard System to Assess Adaptation Measures and Score Ecosystem Services at the Street Level

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**Abstract:** Currently, there is no method available that can systematically score the available ecosystem services in streets or street segments in suburban districts. In this study, different climate adaptation measures and their ecosystem services were categorized into green, blue, and grey categories and weight was given to each category based on their impact on the microclimate. This study took place in the Hillesluis district in the city of Rotterdam and the Paddepoel district in the city of Groningen. In Rotterdam, 21 streets, composed of 42 street segments, were assessed. In Groningen, 17 streets, composed of 45 street segments, were assessed. The available ecosystem services of each street segment were scored from 0–100. The scorecard method that was developed and tested during this study provided insight in the variation of available ecosystem services of streets and street segments. Individual street scores were very low in the city of Rotterdam and ranged between 3 and 50, with the average score for the street segments of 29. In Groningen, the scores were considerably higher with a range between 23 and 70, with an average score of 47 per street segment. The presence of larger green trees, front yards, and façade gardens in the green category are the most distinctive variable, while adaptation measures in the blue category were absent in both cities. The scorecard proved to be very useful in the adaptation labeling of street segments and entire streets. After assessing a neighborhood, the least adaptive streets can be identified relatively easy. Based on the score a label can be given between A+++ and G. The scorecard informs residents and decision makers about which streets are most adaptive and which streets have an adaptation potential. The method can easily be duplicated and used by local governments and community groups to have better insight in the level of climate adaptation of their street. Labels for entire streets can be used to create awareness and encourage residents to take action and expand the number of climate adaptation measures in their street.

**Keywords:** climate adaptation; scorecard; ecosystem services; microclimate; street segment

## 1. Introduction

Human-induced climate change is causing dangerous and widespread disruption in nature and is affecting the lives of billions of people around the world, despite efforts to reduce the risks. The people and ecosystems least able to cope are being hardest hit, according to scientists in the latest Intergovernmental Panel on Climate Change report [1]. For cities, some aspects of climate change may be amplified, including heat, flooding from heavy precipitation events, and sea level rise in coastal cities [2]. The world has recorded the hottest decade on record (2010–2020) with 2019 being the second warmest year on record [3]. Implementing nature-based solutions on a larger scale would increase climate resilience and contribute to multiple Green Deal objectives. Blue green (as opposed to grey) infrastructures are "no regret" solutions and provide environmental, social, and economic benefits and help build climate resilience [4]. According to the European Environment Agency, cities have the potential to become a major driving force for a green and just recovery after the COVID-19 pandemic [5]. The challenge is now how to integrate these measures in our cities and to assume directive roles in their implementation [6].

In 2018, an estimated 55.3% of the world's population lived in urban settlements. By 2030, urban areas are projected to house 60% of people globally [7]. All these people will be directly affected by the impacts of climate change. One of the solutions that has been suggested to make cities more resilient is the urban green infrastructure (UGI) [8]. Urban green and blue spaces and green infrastructure are very effective to combat the effects of climate change and to tackle water and heat risks. A common method to evaluate such contributions is to measure the ecosystem services (ES) provided by the vegetation or water bodies present in urban green and blue spaces (UGBS) that constitute the UGI [9]. Examples of urban ecosystem services are air purification, carbon storage, noise reduction, run-off retention, cooling, and recreation [10].

Urban communities are the most affected by changes in the microclimate as a result of climate change. There are examples resilience scorecards that help communities to become resilient [11], or scorecards that aim to assess disaster resilience on the city scale, such as the he United Nations Office for Disaster Risk Reduction (UNDRR) Scorecard [12], or scorecards with sets of indicators that assist communities to perform a self-evaluation, such as the Resilience Performance Scorecard [13]. Labdaoui et al. developed the Street Walkability and Thermal Comfort index (SWTCI) [14], which includes shade.

Most cities do know, on a city scale, which neighborhoods have less trees, are densely populated, have less parks, and are less green, or in which neighborhoods lush front yards and an abundance of urban green spots are present. At the level of the street, cities in general do not have much insight regarding which climate adaptation measures are present. In a changing climate that more often causes heat waves, for example, it would be crucial to know in which street the climate adaptation measures are present and are more or less ready for the impacts of climate change, and which streets are not. In the streets that do not have climate adaptive measures, local government should invest in the implementation of climate adaptation measures.

An instrument such as a scorecard that assesses the climate adaptive measures at the street level and attaches climate adaptation labels to street segments and streets, is accurate and is easy to use by residents and communities to self-assess streets and neighborhoods, would be very valuable to identify the least adaptive streets and raise awareness about climate adaptation among the members of the community. In the literature, no such scorecard or instrument was found that systematically assess the presence of climate adaptation measures at street segments or entire streets. This paper therefore proposes a new method to assess climate adaptation measures at the street level, which has been proven to be very successful in scoring measures and labeling streets after testing in two districts in two different Dutch cities. With this method, we hope to equip communities and local government units with a new method to assess climate adapttationmeasures in their locality.

## 2. Methods

To be able to compare streets in different districts, street segments were chosen as units of comparison. Streets are composed of one or more street segments and street segments are used in the virtual street audit of front yards [15] or in streetscapes studies [8,16], or in studies related to crime behavior [17] or walking speed [18]. A street segment is typically defined as the portion of a public or private street, between its intersections with two other public or private streets [19] (see Figure 1).

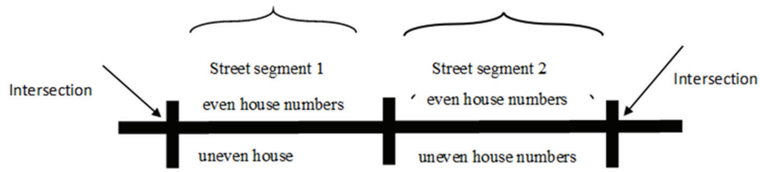


**Figure 1.** Street segment.

For this study, two different urban districts in the cities of Groningen and Rotterdam were selected by the civil servants of the two cities that were involved in the project "Citizen participation in climate adaptation". The two districts were selected based on the fact that the districts are considered as particularly vulnerable to climate change [19]. In order to make the assessment comparable, observations of specific street features and measures both in the street and the housing units at both sides of the street were included in the assessment, and observations were converted into a 100 m street length value. Google street view was used in the field to measure the length of the street segment, then a conversion factor was determined for each street, e.g., divide by 1.2 for a street length of 120 m, and the values were converted into a score for a length of 100 m of street length. In order to be able to score the microclimate adaptation facilities or measures at street level, a literature review was undertaken and a selection of scoreable adaptation facilities or measures was identified. These were divided into three main categories—the green, blue, and grey categories. Each category is a combination of a number of scorable measures at street level. Field visits were undertaken to the two cities for ocular inspection and assessment of the selected streets. In order to make the results of the assessments and the ocular inspection unambiguous, a reference card was made for easy reference. The QR code on the reference card can be opened with a mobile phone and opens an excel file, where the observations can be directly tabulated in excel.

### *2.1. Scoring and Labelling*

The scorable adaptation measures at the street level were calculated per street segment. In total, a street segment could be awarded a score of 100 points (Figure 2). The scores of 1–100 for each street segment were divided into 10 climate adaptation labels with different colors. The presence of many adaptation measures translated into a high score and corresponded with a dark green color. Street segments with few or no adaptation measures translated into a low score and the corresponding color was dark red. A deduction of score points was applied in the grey category. The scoring was composed of three categories, and each category contained one or more measures. For each category, weight was given. The highest weight was given to measures that were most common with the highest chance to be present in a street, and at the same time provided a combination of ecosystem services. Large urban trees and (green) front yards were the most common and provide shade, coolness, and increase infiltration capacity, among other ecosystem services. After testing different measures with different weights totaling 100 points, it was decided to do a full test in two districts with the measures and weights presented in Table 1, divided over three categories.

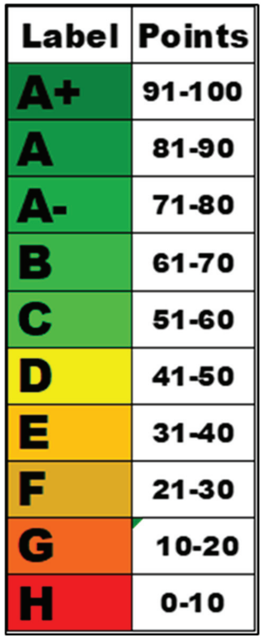


**Figure 2.** Climate adaptation labels.

**Table 1.** Climate adaptation measures and weight.

| Category | Measure | Maximum Score |
|---|---|---|
| Green category | Urban trees | +40 |
| Green category | Green walls | +4 |
| Green category | Façade gardens/front yards | +16 |
| Green category | Green strips | +13 |
| Green category | Climate adaptive roofs | +2 |
| Green category | Green parking spaces | +2 |
| Blue category | Rain barrels | +1 |
| Blue category | Permeable pavement | +3 |
| Blue category | Bioswale | +6 |
| Blue category | Surface water | +6 |
| Grey category | Shaded areas, natural or artificial | +2 |
| Grey category | Additional grey parking spaces | −2 to +2 |
| Grey category | Unpaved surfaces | +2 |
| Grey category | Soil sealed driving lanes | + 1 or −1 per lane |

As awareness among community members was an important objective of the scorecard, reference cards were designed that showed examples of the measure, complementary to the excel file, and supported the researcher in the field while doing the assessment in the field. The front and the back of the reference card are presented in Figures 3 and 4.


**Figure 3.** Reference card, front.


**Figure 4.** Reference card, back.

### *2.2. Green Category Climate Adaptation Facilities and Measures*

The green measures are the combined value of the following adaptation facilities or measures, namely trees, green walls, façade gardens, green strips, climate-adaptive roofs, and green parking spaces.

#### 2.2.1. Urban Trees

Urban trees represent a large portion of the urban tree canopy and provide a significant amount of ecosystem services for mitigation of the negative environmental impact [20]. The World Health Organization has described in detail the beneficial aspect of urban green spaces [21], such as reduced exposure to air pollution and a reduction of the heat island effect. Trees planted along streets and roads may dampen noise and air pollution levels in residential houses and mitigate the adverse health effects of proximity to busy roads. Wang showed that [22] in the urban green infrastructure, the outdoor human thermal comfort and indoor environment improves [23].

The trees category is divided into three subcategories, namely 0–10 m, 10–15 m, and above 15 m, so as to make the indicator trees scorable. The average floor height in the Netherlands is between 2.4–2.6 according to article 4.28 of the National Building Code [24]. Including the floor material itself, average floor is about 3 m high. A tree with a height that is just slightly higher than the height of a typical Dutch single-family dwelling, up to 10 m in height, will be tagged as a category 1 tree, with a value of 2. A tree between 10–15 m in height will be tagged as a category 2 tree, with a value of 3, and very tall and older trees that are above 15 m in height will be tagged as a category 3 tree, with a value of 4. The categorization of trees into different categories of 0–10 m, 10–15 m, and above 15 m was chosen so that the three categories could easily be assessed through ocular observation. This categorization was not presented in other studies, but proved to be very efficient for easy analysis. The number of trees on both sides of the street segment was counted, categorized, and tabulated. The maximum score for the urban trees measure was set at 40.

#### 2.2.2. Green Walls

Wall shrubs and climbing plants provide significant thermoregulation around brick walls and appear to be a feasible green wall system for retrofitting existing housing stock in temperate climates [25]. Green wall installation can simultaneously provide multiple benefits such as noise reduction, contribute to urban ecosystems, pollutant removal, and cooling. The green wall had potential to mitigate daytime air temperature in the cooler seasons in all of the investigated climate zones, except in Csb, where a slight increase was found. Such a decrease could be as high as ~5 °C and it might be decisive for mitigating UHI in some cities [26]. Because of the thermal resistance effect of green walls, the temperature reduction at the pedestrian level of the canyon center was 1.16 °C in the flat street canyon, such as residential areas, in a situation where streets are composed of mainly green walls [27]. Streets that do not have green walls represent a value of 0. Streets that are composed of 1–25% green roofs represent a value of 2, 25–50% a value of 2, 51–75% a value of 3, and 76–100% a value of 4.

#### 2.2.3. Façade Gardens/Front Yards

Paving over of front yards (soil sealing) reduces the environmental and social benefits of front yards and trees. Front yards in private residence play an important role in the soil sealing problem of cities worldwide [15]. The impervious cover of front yards contributes to the problems of the urban heat island effect and urban floods, and makes urban neighborhoods less pleasant. Private gardens play an important role as urban green space and can improve microclimate and address the impacts of climate change—specifically the urban heat island (UHI) effect. Paving over front yards, thus soil sealing, reduces the environmental benefit of front yards. Residential (front) yards comprise a considerable portion of land and green space in the suburbs of cities. A recent study in Rotterdam shows that in an older district, most front yards are soil sealed [18]. The European commission formulated a green infrastructure (GI) strategy to enhance Europe's natural capital [28]. Ecosystem-based approaches are strategies and measures that harness the adaptive forces of nature [29]. Cities are encouraging private citizens more and more to involve citizens, municipalities, and other stakeholders in replacing pavements with vegetation [30]. Cities even provide grants and subsidies to citizens for unhardening private gardens, such as in the city of Rotterdam, which has a subsidy of €10 per $m^2$ for realized green space, to €500 per $m^3$ water storage up to €1500 [31]. Unsealed urban gardens provide patches of natural surfaces that help reduce run-off, reducing the likelihood of urban flooding and replenishing groundwater by allowing rainwater to infiltrate. Small changes households make to their gardens over an extended period of time can add up to major environmental impacts. Adding more paved areas to gardens increases the risk of urban flooding: rainfall cannot seep into the ground and, instead, water runs off the paved surfaces into storm water and sewage systems [32]. It contributes to the development of "sponge cities", where cities are designed as sponges and are designed to absorb and capture rainwater for reducing flooding worldwide [33]. Cities should also invest in nature-based solutions to tackle water and heat risks [34]. In addition to this, urban gardens as a form of urban greenspace are an important resource for the psychosocial restoration of urban dwellers [35], and private gardens are important in terms of the ecological value of cities in complementing public green areas [36]. Not all houses are constructed with (space for) front yards. In order to reduce the temperature and heat stress during a heat wave, residents in Rotterdam are encouraged by the local government to create façade gardens and green facades, which have proven to be effective tools [26]. An example of this is the thousand façade gardens initiative in Rotterdam [37]. Street segments that do not have any façade gardens or front yards are given no points. Streets that have façade gardens in 1–50% of the houses in the street segment represent 5 points, streets with façade gardens in 50–100% of the houses represent 6 points. Houses that have front yards in 1–25% of the housing units represent a value of 10 points, 25–50% represent 12 points, 50–75% represent 14 points, and 75–100% represent 16 points.

#### 2.2.4. Green Strips

Green strips constitute similar benefits as front yards. Green strips could be larger in size than front yards. Green strips are often provided as a beautification project or as a place for dogs in densely populated urban areas. In order to provide water storage or to increase the infiltration capacity, green strips should be placed lower than street level. Street segments that have green strips of max 25 sqm represent a value of 9 points, 25–100 m represent a value of 11 points, and more than 100 sqm represent a value of 13 points.

#### 2.2.5. Climate-Adaptive Roofs

The presence of climate-adaptive roofs can be established by using Google Maps (satellite view). Examples of climate-adaptive roofs are green roofs, roofs with a high albedo (highly reflective roofs, which absorb less heat [38], and blue roofs. Green roofs can easily be recognized on Google Maps, because from above plants/grass and other greenery can be spotted. A high albedo roof is easy to spot because it is often bright white. Houses in the street segment that do have climate-adaptive roofs in 1–50% of the houses represent 1 point, and if more than 50% of the houses in the have climate-adaptive roof, they represent a value of 2.

#### 2.2.6. Green Parking Spaces

Green parking spaces differ from regular parking spaces because they allow the water to infiltrate, and they contribute significantly to reducing runoff [39]. If the parking lots are made of porous paving materials, between the tiles of parking spots, there are often patches of grass [40]. Houses in the street segment that do have green parking spaces in 1–50% of the houses represent 1 point, and if more than 50% of the houses have green parking spaces, they represent a value of 2.

### *2.3. Blue Category Climate-Adaptation Facilities and Measures*

#### 2.3.1. Rain Barrels

Rain barrels or rainwater tanks store water and relieve some stress on the sewage system during heavy precipitation. Rain barrels delay the time that it takes for water to flow into the system. Water from a roof connected to a rain barrel does not flow immediately into the sewage system, and rainwater harvesting can be used as a remedial measure and can help in flood reduction [41]. If one or more rain barrels are present in the street segment, the segment represents a value of 1.

#### 2.3.2. Permeable Pavement

Water-permeable pavements are porous or are laid to allow voids, have an open structure, or are made of partially pervious materials. They allow water to pass through or around them into the soil. This has various advantages: rainwater can infiltrate into the ground, groundwater is replenished, and sewerage systems are relieved [40]. If there is permeable pavement in the street, on the sidewalk, or both, they represent a value of 1, 2, or 3, respectively.

#### 2.3.3. Bioswale

A bioswale is an adaptive measure that has the ability to store water during heavy rain and it redirects surface water to groundwater. It also aids in infiltration and often looks aesthetically pleasing [40,42]. If a bioswale is located within 50 m of the street segment, it represents a value of 6.

#### 2.3.4. Surface Water

Surface water nearby functions as natural water storage. If the surface water is located nearby and is lower than the street level, water can be channeled into the surface water with natural gravity. If the surface water is located within 50 m of the street segment, it represents a value of 6.

### *2.4. Grey Category Climate-Adaptation Facilities and Measures*

#### 2.4.1. Shaded Areas (Canopy)

Bonus points can be earned for shaded areas. Shade is beneficial for heat stress relief [43]. Shade may be provided through canopy, natural shadows from trees, or by artificial shadow facilities. If natural canopy is present or there is artificial shade provision, it represents a value of 1 or 2 respectively.

#### 2.4.2. Unpaved Surfaces

If unpaved areas are present, they provide an additional storage capacity for precipitation and may provide cooling facilities through natural vegetation. If unpaved surfaces are located lower than the street level, they represent a value of 2.

#### 2.4.3. Grey Parking Spaces

Paved surfaces, especially parking lots, occupy a significant proportion of the horizontal surface area in cities. The low albedo of many of these parking lots contributes to the urban heat island (UHI) and affects the local microclimate around them. Parking spaces heat up during the day and contribute to a higher temperature. At night, these warm surfaces contribute to the urban heat island effect [44]. If the cars are parked on the driving lane, without additional parking places, the street segments represent a value of 2. If additional designated parking places are present, the segments represent a deduction of 2 points.

#### 2.4.4. Driving Lane

Impermeable "grey" driving lanes with a low permeability similarly to the grey parking spaces occupy a significant proportion of the horizontal surface area in cities. The low albedo of many of these driving lanes contributes to the urban heat island (UHI) and affects the local microclimate around them. Driving lanes heat up during the day and contribute to a higher temperature. At night, these warm surfaces contribute to the urban heat island effect [44]. For sustainable urban development, permeable pavement promotes urban water management [40]. If the street segment is a car free street, without soil sealed driving lanes, it represents a value of 2. For each soil sealed driving lane, one point will be deducted.

## 3. Results

Two districts in two Dutch cities were selected as the pilot area, namely the Hillesluis district in the city of Rotterdam and the Paddepoel district in the city of Groningen (Figure 5). The cities are located at a distance of 245 km with the same level of development. The two districts were both living labs in the project Citizen Participation in climate adaptation. Both neighborhoods were selected by officers from the local government because they can both be characterized as vulnerable to the effects of climate change and are also socio-economic vulnerable areas. The Paddepoel district was also chosen by the IMPETUS project as a pilot area to conduct measurements. The two cities differ from each other in both size, location, and population characteristics. Rotterdam is an important port city and the second largest city in the Netherlands with a population of around 655,000, located in the Randstad urban area in the Western part of the country. The Hillesluis district is located at the South Bank of the river Maas, which cuts the city in half. In Hillesluis, blue-collar workers that were employed in the port, before containerization created a lot of unemployment, used to live. Since the 1970s, migration changed the population district. Today, Hillesluis has a number of socio-economic problems and city data show that the area is vulnerable to the effects of climate change because the neighborhood is densely populated and lacks green spaces. The city of Groningen is much smaller and is the seventh largest city, and is located in the Northern part of the country. The city of Groningen is the capital of the Province of Groningen, which is characterized by less densely populated neighborhoods. Both neighborhoods consist of about 50% social housing units, 25% private landlords, and 25% owner-occupied. The Paddepoel district was constructed in 1950–1980 with mostly single-family dwellings, while Hillesluis was constructed in 1920–1930, and the area is characterized by multifamily dwellings.

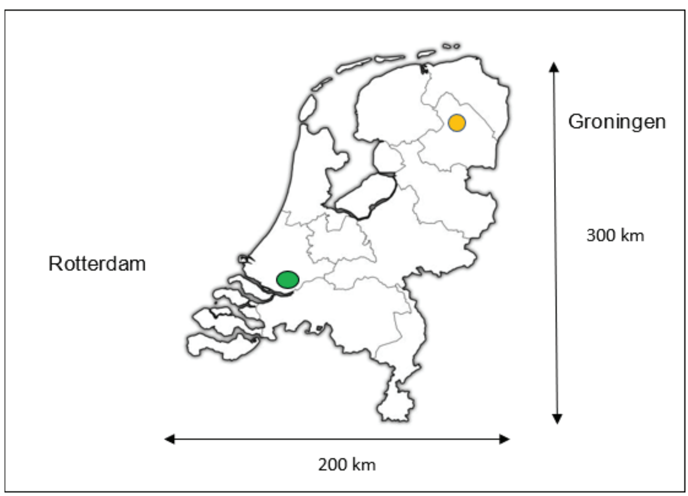


**Figure 5.** Location of case studies.

### *3.1. Rotterdam, Hillesluis District*

The Hillesluis district is located on the southern part of the city of Rotterdam and has a population of around 12,050 residents with a population density of 14,433 [45] residents per square kilometer in 2020. The district is characterized by small streets and a high population density. The narrow streets are alternated by green spaces. The district was constructed between 1920 and 1930 for workers in the port of Rotterdam. Renovation projects have replaced some of the older apartment blocks with newer housing units, but around 70 % of the housing stock date back before 1945.

The districts consists mostly of multifamily dwellings and are predominantly social housing (47%) or rental units (27%), with 25% owner-occupied. The population is relatively younger and lower educated compared with other parts of the city with a lower average household income. Around 73% of the population has a non-Western background. About half of the households (47%) are single-person households [46].

In the Hillesluis district, 21 streets were assessed with a total of 42 street segments. The scores per street segment were categorized and a corresponding label (Figure 2) was given to each street segment and is visualized in Figure 6. The span of the distribution ranges between the lowest score of 3, which corresponds with the lowest climate-adaptiveness label H, and the highest score of 63, which corresponds with climate-adaptiveness label B. The average segment score in Paddepoel was 42, which corresponds to label climate-adaptiveness label D in Table 2.

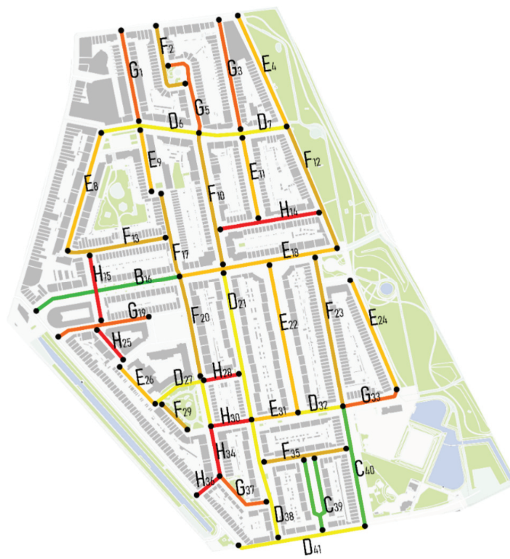


**Figure 6.** Visualization of labels for the Hillesluis district.

### *3.2. Hillesluis District Green Category Climate Adaptation Facilities and Measures*

In total, 21 streets in the Hillesluis district were assessed with a total of 42 street segments. The scores of the green category of each street segment are presented in Table 3.

The assessment of the streets shows that all streets in the Hillesluis district had trees, except for three street segments. Just four street segments in the Hillesluis district scored the highest score for trees. The average score for trees was 20, which is half of the maximum score of 40. When we look at the green walls score, just five street segments fall in the lowest 1–25% green walls category.

In the façade garden/front yard category, nine street segments did not have any façade garden and/or front yard. Out of the remaining 43 street segments, 20 segments fell into the category of 1–50% façade garden and two street segments fell into the category of 50–100% façade garden. In 10 street segments, front yards were present, although six fell in the lowest category of 1–25% front yard and only four street segments fell in the category 50–75% green front yards.

**Table 2.** Scores per segment in the Hillesluis district.

| Name of the Street | Segment 1 | Segment 2 | Segment 3 | Segment 4 | Total Score |
|---|---|---|---|---|---|
| Imobilialaan | 51 | | | | 51 |
| Imobiliastraat | 24 | | | | 24 |
| Zeeuwsestraat | 3 | | | | 3 |
| Vlasakkerstraat | 10 | 37 | 42 | 14 | 103 |
| Drentsestraat | 48 | 7 | | | 55 |
| Riederstraat | 35 | | | | 35 |
| Overijsselsestraat | 27 | 50 | 7 | 20 | 104 |
| Utrechtsestraat | 20 | | | | 20 |
| Hollandsestraat | 6 | 4 | 37 | 28 | 75 |
| Donkerslootstraat | 24 | 52 | | | 76 |
| Riederlaan | 63 | 37 | | | 100 |
| Zaadakkerstraat | 5 | | | | 5 |
| Westerbeekstraat | 28 | 45 | 43 | | 116 |
| Friesestraat | 24 | | | | 24 |
| Brabantsestraat | 32 | | | | 32 |
| Breeweg | 50 | | | | 50 |
| Beijerlandsestraat | 45 | 41 | | | 86 |
| West-Varkenoordseweg | 36 | 29 | 33 | | 98 |
| Beukelaarsstraat | 12 | 39 | | | 51 |
| Blokweg | 28 | 17 | | | 45 |
| Beverstraat | 13 | 38 | 24 | | 75 |
| Total number of segments: | 42 | | | | |
| Total score: | 1228 | | | | |
| Average segment score: | 29 | | | | |

### 3.3. Hillesluis District Blue Category

The scores of the blue category of each street segment are presented in Table 5. No rain barrels were observed in the Hillesluis district at all, and no permeable pavement in the street or sidewalk was observed. No bioswales were present either. Just three street segments had surface water within 50 m distance away from the street segment. Only three street segments scored 6 points out of a total of a maximum of 16 points.

### 3.4. Hillesluis District Grey Category

The scores of the grey category of each street segment are presented in Table 6. Most of the street segments had shaded areas from trees (one point), but none of the streets had artificial shaded areas (two points). Only 9 segments out of 42 segments did not have any shade at all.

In none of the streets were open unpaved (green) areas observed that were located lower than the level of the paved areas so as to provide infiltration capacity. Neither were unpaved areas observed that were located higher than street level.

In all 42 street segments, designated parking spaces were present (deduction of two points), contributing to urban heat stress.

In 26 street segments, one driving lane was present while in 16 street segments, two way driving lanes were present (deduction of one point per driving lane).

None of the streets scored the maximum 7 points. In total, 18 street segments scored two deduction points, 20 streets scored three deduction points, and 4 street segments scored four deduction points.

### 3.5. Total Score Hillesluis District

When we look closer at the total score of the individual street segments in the Hillesluis district, it can be seen that the maximum score is 58 in Westerbeekstraat, segment 2, and the lowest score in Zaadakkerstraat, segment 1 (see Table 7).

**Table 3.** Hillesluis district green category results per street segment.

| | | Points | Beverstraat Segment 1 | Beverstraat Segment 2 | Beverstraat Segment 3 | Blokweg Segment 1 | Blokweg Segment 2 | Beukelaarsstraat Segment 1 | Beukelaarsstraat Segment 2 | West-Varkenoordseweg Segment 1 | West-Varkenoordseweg Segment 2 | West-Varkenoordseweg Segment 3 | Beijerlandsestraat Segment 1 | Beijerlandsestraat Segment 2 | Breeweg Segment 1 | Brabantse Straat Segment 1 | Friesestraat Segment 1 | Westerbeek Segment 1 | Westerbeek Segment 2 | Westerbeek Segment 3 | Zaadakkerstraat Segment 1 | Riederlaan Segment 1 | Riederlaan Segment 2 | Donkerslootstraat Segment 1 | Donkerslootstraat Segment 2 | Hollandsestraat Segment 1 | Hollandsestraat Segment 2 | Hollandsestraat Segment 3 | Hollandsestraat Segment 4 | Utrechtsestraat Segment 1 | Overijsselsestraat Segment 1 | Overijsselsestraat Segment 2 | Overijsselsestraat Segment 3 | Overijsselsestraat Segment 4 | Riederstraat Segment 1 | Drentsestraat Segment 1 | Drentsestraat Segment 2 | Vlasakkerstraat Segment 1 | Vlasakkerstraat Segment 2 | Vlasakkerstraat Segment 3 | Vlasakkerstraat Segment 4 | Zeeuwsestraat Segment 1 | Imobiliastraat Segment 1 | Imobilialaan Segment 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Trees per 100 m street length** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No trees | + | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 | | | | 0 | | | | | 0 | | |
| Tree height 0–10 m | + | 2 | | 30 | 2 | 10 | 20 | 14 | | | | 6 | 16 | | | 12 | 2 | 24 | 10 | 10 | | | | 4 | 2 | | 4 | | 10 | 2 | | 10 | | | | | | 6 | | | 6 | | 2 | 12 |
| Tree height 10–15 m | + | 3 | | | | | | | 3 | | | | 24 | 33 | 24 | 3 | 21 | | | | | 15 | 3 | 21 | 36 | 6 | | 3 | | 6 | 30 | 9 | | 6 | 42 | 32 | | | 3 | 8 | | | 9 | |
| Tree height 15+ meter, | + | 4 | 8 | | 24 | 4 | | | 36 | 40 | 28 | 28 | | | 28 | 12 | 8 | 15 | 63 | 16 | 4 | 92 | 72 | 28 | 16 | 4 | | 24 | | 12 | | 8 | | | | 4 | | | 12 | 8 | | | 4 | 64 |
| Streetlength | | | 228 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| factor | | | 2,3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Maximum of 40 points** | | 40 | 5 | 31 | 22 | 11 | 15 | 8 | 31 | 21 | 14 | 18 | 31 | 33 | 40 | 19 | 21 | 20 | 33 | 22 | 3 | 40 | 34 | 27 | 31 | 10 | 7 | 33 | 17 | 11 | 20 | 40 | 0 | 8 | 19 | 40 | 0 | 9 | 22 | 27 | 7 | 0 | 12 | 40 |
| **Green wall** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No green wall | + | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1–25% of walls | + | 1 | | | | 1 | 0 | 1 | | | | | | | | | | | | | | 1 | 1 | | | | | 1 | | | | | | | | | | | | | | | | |
| 25–50% of walls | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 50–75% of walls | + | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 75–100% of walls | + | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Facade garden/front yard** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No facade garden/no front yard | + | 0 | | 0 | | | | | | | | | | | 0 | | | | | | | | | 0 | | 0 | 0 | | 0 | | | 0 | | 0 | | 0 | | | | | | | | |
| 1–50% facade garden | + | 5 | | | 5 | 5 | 5 | | | 5 | 5 | 5 | 5 | | | 5 | 5 | | | | 5 | | 5 | | 5 | | | 5 | | 5 | | | | | 5 | | | 5 | 5 | 5 | 5 | 5 | | |
| 50–100% facade garden | + | 6 | | | | | | 6 | | | | | | | | | | | | | | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 1–25% green front yard | + | 10 | 10 | | | | | | 10 | | | | | 10 | | | | 10 | | | | | | | | | | | | | 10 | | 10 | | | | 10 | | | | | | | |
| 25–50% green front yard | + | 12 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 50–75% green front yard | + | 14 | | | | | | | | | | | | | | | | | 14 | 14 | | | | | | | | | | | | | | | | | | | | | | | 14 | 14 |
| 75–100% green front yard | + | 16 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Green strips** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No green strip | + | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | 0 | | | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | | 0 | 0 | | 0 | | | | 0 | 0 | | | 0 | 0 | 0 | 0 |
| Green strip (1 $m^2$–25 $m^2$) | + | 9 | | 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 9 | | | | | | | | | |
| Green strip (25 $m^2$–100 $m^2$) | + | 11 | | | | | | | | | | | 11 | | | 11 | | | | | | | | | | | | | | | | | | 11 | | 11 | | | | | | | | |
| Green strip (>100 $m^2$) | + | 13 | | | | 13 | | | | 13 | 13 | 13 | | | 13 | | | | 13 | | | | | | | 13 | | | 13 | | | 13 | | | | | | | 13 | 13 | | | | |

**Table 3.** *Cont.*

**Table 4.** *Cont.*

| | | Points | Beverstraat Segment 1 | Beverstraat Segment 2 | Beverstraat Segment 3 | Blokweg Segment 1 | Blokweg Segment 2 | Beukelaarsstraat Segment 1 | Beukelaarsstraat Segment 2 | West-Varkenoordseweg Segment 1 | West-Varkenoordseweg Segment 2 | West-Varkenoordseweg Segment 3 | Beijerlandsestraat Segment 1 | Beijerlandsestraat Segment 2 | Breeweg Segment 1 | Brabantse Straat Segment 1 | Friesestraat Segment 1 | Westerbeek Segment 1 | Westerbeek Segment 2 | Westerbeek Segment 3 | Zaadakkerstraat Segment 1 | Riederlaan Segment 1 | Riederlaan Segment 2 | Donkerslootstraat Segment 1 | Donkerslootstraat Segment 2 | Hollandsestraat Segment 1 | Hollandsestraat Segment 2 | Hollandsestraat Segment 3 | Hollandsestraat Segment 4 | Utrechtsestraat Segment 1 | Overijsselsestraat Segment 1 | Overijsselsestraat Segment 2 | Overijsselsestraat Segment 3 | Overijsselsestraat Segment 4 | Riederstraat Segment 1 | Drentsestraat Segment 1 | Drentsestraat Segment 2 | Vlasakkerstraat Segment 1 | Vlasakkerstraat Segment 2 | Vlasakkerstraat Segment 3 | Vlasakkerstraat Segment 4 | Zeeuwsestraat Segment 1 | Imobiliastraat Segment 1 | Imobilialaan Segment 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Climate adaptive roofs** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No climate adaptive roofs | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Adaptive roofs 1–50% | + | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Adaptive roofs 50–100% | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Green parking lots** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No green parking lots | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1–50% green parking | + | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 50–100% green parking | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Max possible points** | | **77** | **15** | **40** | **27** | **30** | **20** | **15** | **41** | **39** | **32** | **36** | **47** | **43** | **53** | **35** | **26** | **30** | **60** | **36** | **8** | **47** | **40** | **27** | **36** | **23** | **7** | **39** | **30** | **16** | **30** | **53** | **10** | **19** | **33** | **51** | **10** | **14** | **40** | **45** | **12** | **5** | **26** | **54** |

**Table 5.** Hillesluis district blue category scores per street segment.

| | Points | Beverstraat Segment 1 | Beverstraat Segment 2 | Beverstraat Segment 3 | Blokweg Segment 1 | Blokweg Segment 2 | Beukelaarsstraat Segment 1 | Beukelaarsstraat Segment 2 | West-Varkenoordseweg segment 1 | West-Varkenoordseweg segment 2 | West-Varkenoordseweg segment 3 | Beijerlandsestraat Segment 1 | Beijerlandsestraat Segment 2 | Breeweg Segment 1 | Brabantse Straat Segment 1 | Friesestraat Segment 1 | Westerbeek Segment 1 | Westerbeek Segment 2 | Westerbeek Segment 3 | Zaadakkerstraat Segment 1 | Riederlaan Segment 1 | Riederlaan Segment 2 | Donkerslootstraat Segment 1 | Donkerslootstraat Segment 2 | Hollandsestraat Segment 1 | Hollandsestraat Segment 2 | Hollandsestraat Segment 3 | Hollandsestraat Segment 4 | Utrechtsestraat Segment 1 | Overijsselsestraat Segment 1 | Overijsselsestraat Segment 2 | Overijsselsestraat Segment 3 | Overijsselsestraat Segment 4 | Riederstraat Segment 1 | Drentsestraat Segment 1 | Drentsestraat Segment 2 | Vlasakkerstraat Segment 1 | Vlasakkerstraat Segment 2 | Vlasakkerstraat Segment 3 | Vlasakkerstraat Segment 4 | Zeeuwsestraat Segment 1 | Imobiliastraat Segment 1 | Imobilialaan Segment 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Blue category** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Rain barrels present** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No rain barrels | + 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 or more rain barrels | + 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Permeable pavement (street or sidewalk)** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No permeable pavement in the street | + 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Permeable pavement sidewalk | + 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Permeable pavement street | + 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Permeable pavement sidewalk and street | + 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Bioswale** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| There is no bioswale nearby | + 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A biowale can be found within 50 m of the street | + 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Surface water** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| There is no surface water nearby | + 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 |
| Surface water can be found within 50 m of the street | + 6 | | | | | | | | | | | | | | | | | | | | 6 | | | 6 | | | | | 6 | | | | | | | | | | | 6 | | | |
| **Max possible points (Blue category)** | **16** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **6** | **0** | **0** | **6** | **0** | **0** | **0** | **0** | **6** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **6** | **0** | **0** | **0** |

**Table 6.** Hillesluis district grey category scores per street segment.

| Bonus and Deduction | | Points | Beverstraat Segment 1 | Beverstraat Segment 2 | Beverstraat Segment 3 | Blokweg Segment 1 | Blokweg Segment 2 | Beukelaarsstraat Segment 1 | Beukelaarsstraat Segment 2 | West-Varkenoordseweg segment 1 | West-Varkenoordseweg segment 2 | West-Varkenoordseweg segment 3 | Beijerlandsestraat Segment 1 | Beijerlandsestraat Segment 2 | Breeweg Segment 1 | Brabantse Straat Segment 1 | Friesestraat Segment 1 | Westerbeek Segment 1 | Westerbeek Segment 2 | Westerbeek Segment 3 | Zaadakkerstraat Segment 1 | Riederlaan Segment 1 | Riederlaan Segment 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Shaded areas (canopy)** | | | | | | | | | | | | | | | | | | | | | | | |
| No shaded areas present | + | 0 | | | | | 0 | 0 | | | | | | | | 0 | | | | | 0 | | |
| Shades from trees (canopy) | + | 1 | 1 | 1 | 1 | 1 | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | | 1 | 1 |
| Artifical shade provision | + | 2 | | | | | | | | | | | | | | | | | | | | | |
| Total value | | | 1 | 1 | 1 | 1 | | | 1 | 1 | 11 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | | 1 | 1 |
| **If present, unpaved surface located lower than paved surface** | | | | | | | | | | | | | | | | | | | | | | | |
| Unpaved surface is located higher than paved surface | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unpaved surface is located lower than paved surface | + | 2 | | | | | | | | | | | | | | | | | | | | | |
| Total value | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Parking spaces** | | | | | | | | | | | | | | | | | | | | | | | |
| Cars are parked in the street (no designated parking spaces) | | 0 | | | | | | | | | | | | | | | | | | | | | |
| Car free street | + | 2 | | | | | | | | | | | | | | | | | | | | | |
| Designated parking spaces are present | – | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 |
| | | 2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 |
| **Driving lanes** | | | | | | | | | | | | | | | | | | | | | | | |
| Car free street | + | 1 | | | | | | | | | | | | | | | | | | | | | |
| 1 point deduction per driving lane | – | −1 | −1 | −1 | −2 | −1 | −1 | −1 | −1 | −2 | −2 | −2 | −1 | −1 | −2 | −1 | −1 | −1 | −1 | −1 | −1 | −1 | −2 |
| | | 1 | −1 | −1 | −2 | −1 | −1 | −1 | −1 | −2 | −2 | −2 | −1 | −1 | −2 | −1 | −1 | −1 | −1 | −1 | −1 | −1 | −2 |
| **Max possible points (Grey category)** | | **7** | **−2** | **−2** | **−3** | **−2** | **−3** | **−3** | **−2** | **−3** | **−4** | **−3** | **−2** | **−2** | **−3** | **−3** | **−2** | **−2** | **−2** | **−2** | **−3** | **−2** | **−3** |

| Bonus and Deduction | | Points | Donkerslootstraat Segment 1 | Donkerslootstraat Segment 2 | Hollandsestraat Segment 1 | Hollandsestraat Segment 2 | Hollandsestraat Segment 3 | Hollandsestraat Segment 4 | Utrechtsestraat Segment 1 | Overijsselsestraat Segment 1 | Overijsselsestraat Segment 2 | Overijsselsestraat Segment 3 | Overijsselsestraat Segment 4 | Riederstraat Segment 1 | Drentsestraat Segment 1 | Drentsestraat Segment 2 | Vlasakkerstraat Segment 1 | Vlasakkerstraat Segment 2 | Vlasakkerstraat Segment 3 | Vlasakkerstraat Segment 4 | Zeeuwsestraat Segment 1 | Imobiliastraat Segment 1 | Imobilialaan Segment 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Shaded areas (canopy)** | | | | | | | | | | | | | | | | | | | | | | | |
| No shaded areas present | + | 0 | | | | | | | | | | | | | 0 | 0 | 0 | | | 0 | 0 | | |
| Shades from trees (canopy) | + | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | | | | 1 | 1 | | | 1 | 1 |
| Artifical shade provision | + | 2 | | | | | | | | | | | | | | | | | | | | | |
| Total value | | | 1 | 1 | | | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | | | | 1 | 1 | | | 1 | 1 |
| **If present, unpaved surface located lower than paved surface** | | | | | | | | | | | | | | | | | | | | | | | |
| Unpaved surface is located higher than paved surface | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unpaved surface is located lower than paved surface | + | 2 | | | | | | | | | | | | | | | | | | | | | |
| Total value | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Parking spaces** | | | | | | | | | | | | | | | | | | | | | | | |
| Cars are parked in the street (no designated parking spaces) | | 0 | | | | | | | | | | | | | | | | | | | 0 | | |
| Car free street | + | 2 | | | | | | | | | | | | | | | | | | | | | |
| Designated parking spaces are present | – | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | | −2 | −2 |
| | | 2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | 0 | −2 | −2 |
| **Driving lanes** | | | | | | | | | | | | | | | | | | | | | | | |
| Car free street | + | 1 | | | | | | | | | | | | | | | | | | | | | |
| 1 point deduction per driving lane | – | −1 | −2 | −2 | −2 | −1 | −1 | −1 | −1 | −2 | −2 | −1 | −1 | −1 | −1 | −1 | −2 | −2 | −2 | −2 | −2 | −1 | −2 |
| | | 1 | −2 | −2 | −2 | −1 | −1 | −1 | −1 | −2 | −2 | −1 | −1 | −1 | −1 | −1 | −2 | −2 | −2 | −2 | −2 | −1 | −2 |
| **Max possible points (Grey category)** | | **7** | **−3** | **−3** | **−4** | **−3** | **−2** | **−2** | **−2** | **−3** | **−3** | **−3** | **−2** | **−2** | **−3** | **−3** | **−4** | **−3** | **−3** | **−4** | **−2** | **−2** | **−3** |

**Table 6.** *Cont.*

**Table 7.** Total score street segments in the Hillesluis district.

| | Points | Beverstraat Segment 1 | Beverstraat Segment 2 | Beverstraat Segment 3 | Blokweg Segment 1 | Blokweg Segment 2 | Beukelaarsstraat Segment 1 | Beukelaarsstraat Segment 2 | West-Varkenoordseweg Segment 1 | West-Varkenoordseweg Segment 2 | West-Varkenoordseweg Segment 3 | Beijerlandsestraat Segment 1 | Beijerlandsestraat Segment 2 | Breeweg Segment 1 | Brabantse Straat Segment 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total score** | 100 | 13 | 38 | 24 | 28 | 17 | 12 | 39 | 36 | 39 | 33 | 45 | 41 | 50 | 32 |

| | Friesestraat Segment 1 | Westerbeek Segment 1 | Westerbeek Segment 2 | Westerbeek Segment 3 | Zaadakkerstraat Segment 1 | Riederlaan Segment 1 | Riederlaan Segment 2 | Donkerslootstraat Segment 1 | Donkerslootstraat Segment 2 | Hollandsestraat Segment 1 | Hollandsestraat Segment 2 | Hollandsestraat Segment 3 | Hollandsestraat Segment 4 | Utrechtsestraat Segment 1 | Overijsselsestraat Segment 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total score** | 24 | 28 | 58 | 34 | 5 | 51 | 37 | 24 | 39 | 19 | 4 | 37 | 28 | 20 | 27 |

| | Overijsselsestraat Segment 2 | Overijsselsestraat Segment 3 | Overijsselsestraat Segment 4 | Riederstraat Segment 1 | Drentsestraat Segment 1 | Drentsestraat Segment 2 | Vlasakkerstraat Segment 1 | Vlasakkerstraat Segment 2 | Vlasakkerstraat Segment 3 | Vlasakkerstraat Segment 4 | Zeeuwsestraat Segment 1 | Imobiliastraat Segment 1 | Imobilialaan Segment 1 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total score** | 50 | 7 | 17 | 31 | 48 | 7 | 10 | 37 | 42 | 14 | 3 | 24 | 51 | 29 |

The highest score in the Hillesluis district was observed in Westerbeekstraat, segment 2 (Figures 7 and 8). Westerbeekstraat segment 2, scored 58 points for trees, which is just below the maximum of 40 points, as well as zero points for green walls, fourteen points for green front yards (75–100%), zero points for green strips, zero points for climate adaptive roofs, and zero points for green parking lots. In the blue category, Westerbeekstraat, segment 2, does not score any points for the presence of rain barrels, permeable streets or pavements, or nearby surface water. In the grey category, Westebeekstraat, segment 2, scored one point for shadows from canopy, zero points for green areas, and a deduction of two points for the presence of (soil-sealed) parking spaces and a deduction of 1 point for a (soil-sealed) driving lane.

**Figure 7.** Westerbeekstraat [47].

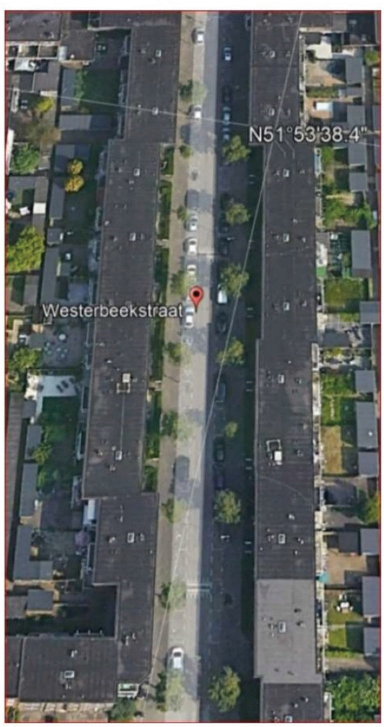


**Figure 8.** Westerbeekstraat [47].

The lowest score in the Hillesluis district, of three points, was Zeeuwsestraat, but as this street was very short, about 35 m, with only four housing units, the next street with the lowest score will be discussed here. The street with the second lowest score, of five points, was observed in Zaadakkerstraat (Figures 9 and 10).

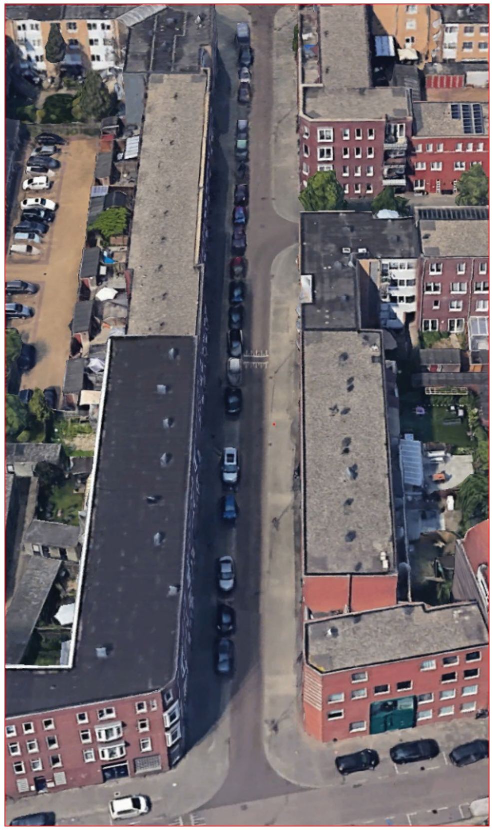

**Figure 9.** Zaadakkerstraat [48].

Zaadakkerstraat scored just three points for trees. Zero points for green walls, five points for façade gardens (1–50%), zero points for green strips, zero points for climate adaptive roofs, and zero points for green parking lots.

In the blue category, Zaadakkerstraat did not score any points for the presence of rain barrels, permeable streets or pavements, or nearby surface water.

In the grey category, Zaadakkerstraat scored zero points for shadows from canopy, zero points for green areas, and a deduction of two points for the presence of (soil-sealed) parking spaces and a deduction of one point for one (soil-sealed) driving lane.

**Figure 10.** Zaadakkerstraat [48].

*3.6. Groningen, Paddepoel North District*

The Paddepoel North district is located in the northern part of the city of Groningen and had a population of about 6000 persons in 2020 and a population density of 9009 residents per square kilometer [49]. The district is characterized by 30% single family dwellings and 70 % multifamily dwellings [49]. The district is characterized by single family dwellings with front yards, typical Dutch row houses, and green and multifamily dwellings of up to typically four floors with green lawns. Most of the district was constructed between 1950–1980 and a small portion of the housing units were constructed in the recent years of 2010–2020 [50].

About half of the total housing stock is owned by a social housing corporation (53%), a quarter is owner occupied, and (25%) and a quarter of the housing stock is rented out by private owners (22%) [50]. Around 22% of the population has a non-Western background. About 70% of the households are single-person households [49].

In the Paddepoel North district, 21 streets were assessed with a total of 45 street segments. The average score per segment was 47. The results of the segments are presented in Table 8. The scores per street segment were categorized and a corresponding label (Figure 2) was given to each street segment and was visualized in a map.

In the Paddepoel district, 17 streets were assessed with a total of 45 street segments. The results of the assessment are presented in Map 2.

The span of the distribution ranged between the lowest score of 22, which corresponds with climate adaptiveness label F, and the highest score of 70, which corresponds with climate adaptiveness label B. The average segment score in Paddepoel is 47, which corresponds with label climate adaptiveness label D. The total scores for each segment are presented in Table 8 and are visualized in Figure 11.

**Table 8.** Scores per segment Paddepoel North district.

| Name of the Street | Segment 1 | Segment 2 | Segment 3 | Segment 4 | Total Score |
|---|---|---|---|---|---|
| Morgensterlaan | 69 | 70 | | | 139 |
| Mercuriusstraat | 61 | | | | 61 |
| Kometenstraat | 51 | 25 | | | 76 |
| Capellastraat | 22 | 23 | | | 45 |
| Wegalaan | 46 | 50 | 64 | | 160 |
| Siriusstraat | 36 | 36 | 47 | | 119 |
| Spicastraat | 28 | 51 | | | 79 |
| Poolsterlaan | 59 | 66 | 61 | | 186 |
| Plutolaan | 46 | 40 | 66 | | 152 |
| Venuslaan | 40 | 62 | 60 | 29 | 191 |
| Regulusstraat | 53 | 51 | | | 104 |
| Jupiterstraat | 63 | 37 | 35 | | 135 |
| Avondsterlaan | 55 | 51 | 46 | | 152 |
| Planetenlaan | 64 | 68 | 64 | | 196 |
| Neptunusstraat | 22 | 32 | 25 | | 79 |
| Uranusstraat | 43 | 25 | 35 | | 103 |
| Marsstraat | 58 | 33 | 42 | | 133 |
| Number of segments: | 45 | | | | |
| Total score: | 2110 | | | | |
| Average segment score: | 47 | | | | |

**Figure 11.** 2 Visualization of labels the Paddepoel North district.

### 3.7. *Paddepoel District Green Category*

In total, 17 streets were assessed in the Paddepoel North district, with a total of 45 street segments. The scores of the green category of each street segment are presented in Table 9.

The assessment of the streets show that all streets in the Paddepoel North district had trees, except for one street segment, Capellastraat segment 2. Eleven street segments in the

Paddepoel North district scored the highest score for trees. The Paddepoel North district scored on average 26 points, which is about 65% of the maximum score of 40. When we look at the green walls score, just two street segments fell in the lowest 1–25% green walls category.

In the façade garden/front yard category, one street segment had a 1–50% score for the façade garden. All other streets in the Paddepoel North district had front yards; 22 out of 45 street segments had a 75–100% score for front yards, indicating that the front yard potential was fully used.

### *3.8. Paddepoel District Blue Category*

The scores of the blue category of each street segment are presented in Table 10. One rain barrel was observed in Kometenstraat, segment 2. No permeable pavement in the street or sidewalk was observed. No bioswales were present as well. Nine street segments had surface water within 50 m away from the street segment. Eight street segments scored six points out of a total of maximum 16 points, and one street segment scored seven 7 points.

### *3.9. Paddepoel District Grey Category*

The scores of the grey category of each street segment are presented in Table 11. Most of the street segments had shaded areas from trees (one point), but none of the streets had artificial shaded areas (two points). Only 7 segments out of 45 segments did not have any shade at all.

In only two street were segments of open unpaved (green) areas observed, which were located lower than the level of the paved areas to provide infiltration capacity. No unpaved areas were observed that located higher than the street level.

In only nine street segments were designated parking spaces present (deduction of two points), contributing to urban heat stress. While in the other 36 street segments, no parking lots were observed in the street itself. In all 45 street segments, two driving lanes were observed (deduction of one point per driving lane).

None of the streets scored the maximum of seven points. In total, 32 street segments scored 1 deduction point, 6 streets scored 2 deduction points, and 5 street segments scored 3 deduction points.

### *3.10. Total Score Paddepoel District*

When we looked closer at the total score of the individual street segments in the Paddepoel North district, we could see that the maximum score was 70, for Morgensterlaan, segment 2, and the lowest score was in Capellastraat, segment 1 (see Table 12).

**Table 9.** Paddepoel North district green category results per street segment.

| Green category | | Score | Marsstraat Segment 1 | Marsstraat Segment 2 | Marsstraat Segment 3 | Uranus Straat Segment 1 | Uranus Straat Segment 2 | Uranus Straat Segment 3 | Neptunusstraat Segment 1 | Neptunusstraat Segment 2 | Neptunusstraat Segment 3 | Planetenlaan Segement 1 | Planetenlaan Segement 2 | Planetenlaan Segement 3 | Avondsterlaan Segement 1 | Avondsterlaan Segement 2 | Avondsterlaan Segement 3 | Jupiterstraat Segment 1 | Jupiterstraat Segment 2 | Jupiterstraat Segment 3 | Regulusstraat Segment 1 | Regulusstraat Segment 2 | Venuslaan Segment 1 | Venuslaan Segment 2 | Venuslaan Segment 3 | Venuslaan Segment 4 | Plutolaan Segment 1 | Plutolaan Segment 2 | Plutolaan Segment 3 | Poolsterlaan Segment 1 | Poolsterlaan Segment 2 | Poolsterlaan Segment 3 | Spicastraat Segment 1 | Spicastraat Segment 2 | Siriusstraat Segment 1 | Siriusstraat Segment 2 | Siriusstraat Segment 3 | Wegalaan Segment 1 | Wegalaan Segment 2 | Wegalaan Segment 3 | Capellastraat Segment 1 | Capellastraat Segment 2 | Kometenstraat Segment 1 | Kometenstraat Segment 2 | Mercuriusstraat Segment 1 | Morgensterlaan Segment 1 | Morgensterlaan Segment 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Trees** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No trees | + | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 | | | | | |
| Tree height 0–10 m | + | 2 | 20 | 20 | 22 | | | 28 | | 14 | 14 | | 20 | 10 | | | | 20 | 18 | 22 | | | | 6 | 10 | 2 | 2 | 20 | 18 | 2 | | 10 | 6 | 14 | 6 | | 4 | 26 | 6 | | | | | | | | 2 |
| Tree height 10–15 m | + | 3 | 3 | 3 | 9 | 33 | 12 | | | | | 21 | 9 | 9 | 6 | 3 | 9 | 9 | 9 | 30 | 40 | 40 | | 3 | 30 | | 24 | | | 3 | 45 | | | 12 | 18 | 24 | 21 | 6 | 18 | 36 | 9 | | | 3 | 46 | 3 | |
| Tree height 15+ m, | + | 4 | 20 | | | | | | 12 | 8 | | 24 | 20 | 20 | 24 | 16 | 12 | 8 | | | | | 12 | 32 | | 4 | | | 32 | 28 | 4 | 48 | | 4 | | | | 4 | 32 | 8 | | | | | | 40 | 44 |
| **Maximum of 40 points** | | 40 | 38 | 20 | 27 | 28 | 10 | 24 | 10 | 19 | 12 | 40 | 40 | 34 | 27 | 17 | 16 | 34 | 24 | 40 | 40 | 40 | 15 | 36 | 36 | 6 | 22 | 17 | 40 | 31 | 40 | 40 | 5 | 27 | 21 | 21 | 22 | 31 | 40 | 40 | 9 | 0 | 36 | 3 | 40 | 34 | 35 |
| **Green wall** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No green wall | + | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1–25% of walls | + | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | 1 | | | | | | | | |
| 25–50% of walls | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 50–75% of walls | + | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 75–100% of walls | + | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Facade garden/front yard** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No facade garden/no front yard | + | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1–50% facade garden | + | 5 | | | | | | | | | | | | | | | | | | | | | | | | 5 | | | | | | | | | | | | | | | | | | | | | |
| 50–100% facade garden | + | 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1–25% green front yard | + | 10 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 10 | | | | | | | 10 | | | | | | | | |
| 25–50% green front yard | + | 12 | | | | | | | | | | | | | | | 12 | | | | | 12 | | | 12 | | | | | | | | 12 | 12 | | | 12 | | | 12 | | 12 | | | | | |
| 50–75% green front yard | + | 14 | 14 | 14 | | | | 14 | 14 | | | | | | | | | | 14 | | 14 | | 14 | 14 | | | 14 | 14 | | | 14 | | | | | | | | | | 14 | | | | | | |
| 75–100% green front yard | + | 16 | | | 16 | 16 | 16 | | | 16 | 16 | 16 | 16 | 16 | 16 | 16 | | 16 | | 16 | | | | | | | | | 16 | 16 | | | | | 16 | 16 | | 16 | | | | | 16 | 16 | 16 | 16 | 16 |
| **Green strips** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No green strip | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | | 0 | 0 | 0 | 0 | | | | | | | | | | | | | 0 | 0 | | 0 | 0 | | 0 | | 0 | 0 | 0 | | |
| Green strip (1 $m^2$–25 $m^2$) | + | 9 | | | | | | | | | | 9 | | | | | | 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Green strip (25 $m^2$–100 $m^2$) | + | 11 | | | | | | | | | | | 13 | 13 | 13 | 13 | 13 | | | | | | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | | | 13 | | | 13 | | 13 | | | | 13 | 13 |
| Green strip (>100 $m^2$) | + | 13 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Climate adaptive roofs** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No climate adaptive roofs | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| Adaptive roofs 1–50% | + | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | 1 | 1 |
| Adaptive roofs 50–100% | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**Table 9.** *Cont.*

| | | Score | Marsstraat Segment 1 | Marsstraat Segment 2 | Marsstraat Segment 3 | Uranus Straat Segment 1 | Uranus Straat Segment 2 | Uranus Straat Segment 3 | Neptunusstraat Segment 1 | Neptunusstraat Segment 2 | Neptunusstraat Segment 3 | Planetenlaan Segement 1 | Planetenlaan Segement 2 | Planetenlaan Segement 3 | Avondsterlaan Segement 1 | Avondsterlaan Segement 2 | Avondsterlaan Segement 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Green parking lots** | | | | | | | | | | | | | | | | | |
| No green parking lots | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1–50% green parking | + | 1 | | | | | | | | | | | | | | | |
| 50–100% green parking | + | 2 | | | | | | | | | | | | | | | |
| **Max possible points (Green Category)** | | 77 | 53 | 34 | 43 | 44 | 26 | 38 | 24 | 35 | 28 | 65 | 69 | 63 | 56 | 46 | 41 |

| | Jupiterstraat Segment 1 | Jupiterstraat Segment 2 | Jupiterstraat Segment 3 | Regulusstraat Segment 1 | Regulusstraat Segment 2 | Venuslaan Segment 1 | Venuslaan Segment 2 | Venuslaan Segment 3 | Venuslaan Segment 4 | Plutolaan Segment 1 | Plutolaan Segment 2 | Plutolaan Segment 3 | Poolsterlaan Segment 1 | Poolsterlaan Segment 2 | Poolsterlaan Segment 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Green parking lots** | | | | | | | | | | | | | | | |
| No green parking lots | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 1–50% green parking | | | | | | | | | | | | | | | 1 |
| 50–100% green parking | | | | | | | | | | | | | | | |
| **Max possible points (Green Category)** | 59 | 38 | 56 | 54 | 52 | 42 | 63 | 62 | 24 | 49 | 44 | 69 | 60 | 67 | 64 |

| | Spicastraat Segment 1 | Spicastraat Segment 2 | Siriusstraat Segment 1 | Siriusstraat Segment 2 | Siriusstraat Segment 3 | Wegalaan Segment 1 | Wegalaan Segment 2 | Wegalaan Segment 3 | Capellastraat Segment 1 | Capellastraat Segment 2 | Kometenstraat Segment 1 | Kometenstraat Segment 2 | Mercuriusstraat Segment 1 | Morgensterlaan Segment 1 | Morgensterlaan Segment 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Green parking lots** | | | | | | | | | | | | | | | |
| No green parking lots | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1–50% green parking | | | | | | | | | | | | | | | |
| 50–100% green parking | | | | | | | | | | | | | | | |
| **Max possible points (Green Category)** | 30 | 52 | 37 | 37 | 48 | 47 | 51 | 65 | 23 | 25 | 52 | 19 | 56 | 64 | 65 |

**Table 10.** Paddepoel North district blue category scores per street segment.

| Blue category | Score | Marsstraat Segment 1 | Marsstraat Segment 2 | Marsstraat Segment 3 | Uranus Straat Segment 1 | Uranus Straat Segment 2 | Uranus Straat Segment 3 | Neptunusstraat Segment 1 | Neptunusstraat Segment 2 | Neptunusstraat Segment 3 | Planetenlaan Segement 1 | Planetenlaan Segement 2 | Planetenlaan Segement 3 | Avondsterlaan Segement 1 | Avondsterlaan Segement 2 | Avondsterlaan Segement 3 | Jupiterstraat Segment 1 | Jupiterstraat Segment 2 | Jupiterstraat Segment 3 | Regulusstraat Segment 1 | Regulusstraat Segment 2 | Venuslaan Segment 1 | Venuslaan Segment 2 | Venuslaan Segment 3 | Venuslaan Segment 4 | Plutolaan Segment 1 | Plutolaan Segment 2 | Plutolaan Segment 3 | Poolsterlaan Segment 1 | Poolsterlaan Segment 2 | Poolsterlaan Segment 3 | Spicastraat Segment 1 | Spicastraat Segment 2 | Siriusstraat Segment 1 | Siriusstraat Segment 2 | Siriusstraat Segment 3 | Wegalaan Segment 1 | Wegalaan Segment 2 | Wegalaan Segment 3 | Capellastraat Segment 1 | Capellastraat Segment 2 | Kometenstraat Segment 1 | Kometenstraat Segment 2 | Mercuriusstraat Segment 1 | Morgensterlaan Segment 1 | Morgensterlaan Segment 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rain barrels present** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No rain barrels | + 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 |
| 1 or more rain barrels | + 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | |
| **Permeable pavement (street or sidewalk)** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No permeable pavement in the street | + 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Permeable pavement sidewalk | + 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Permeable pavement street | + 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Permeable pavement sidewalk and street | + 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Bioswale** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| There is no bioswale nearby | + 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A biowale can be found within 50 m of the street | + 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Surface water** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| There is no surface water nearby | + 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| Surface water can be found within 50 m of the street | + 6 | 6 | | | | | | | | | | | | | 6 | 6 | 6 | | | | | | | | 6 | | | | | | | | | | | | | | | | | | 6 | 6 | 6 | 6 |
| **Max possible points (Blue category)** | **16** | **6** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **6** | **6** | **6** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **6** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **7** | **6** | **6** | **6** |

**Table 11.** Paddepoel north district grey category scores per street segment.

| | Score | | Marsstraat Segment 1 | Marsstraat Segment 2 | Marsstraat Segment 3 | Uranus straat Segment 1 | Uranus Straat Segment 2 | Uranus Straat Segment 3 | Neptunusstraat Segment 1 | Neptunusstraat Segment 2 | Neptunusstraat Segment 3 | Planetenlaan Segement 1 | Planetenlaan Segement 2 | Planetenlaan Segement 3 | Avondsterlaan Segement 1 | Avondsterlaan Segement 2 | Avondsterlaan Segement 3 | Jupiterstraat Segment 1 | Jupiterstraat Segment 2 | Jupiterstraat Segment 3 | Regulusstraat Segment 1 | Regulusstraat Segment 2 | Venuslaan Segment 1 | Venuslaan Segment 2 | Venuslaan Segment 3 | Venuslaan Segment 4 | Plutolaan Segment 1 | Plutolaan Segment 2 | Plutolaan Segment 3 | Poolsterlaan Segment 1 | Poolsterlaan Segment 2 | Poolsterlaan Segment 3 | Spicastraat Segment 1 | Spicastraat Segment 2 | Siriusstraat Segment 1 | Siriusstraat Segment 2 | Siriusstraat Segment 3 | Wegalaan Segment 1 | Wegalaan Segment 2 | Wegalaan Segment 3 | Capellastraat Segment 1 | Capellastraat Segment 2 | Kometenstraat Segment 1 | Kometenstraat Segment 2 | Mercuriusstraat Segment 1 | Morgensterlaan Segment 1 | Morgensterlaan Segment 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bonus and deduction** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Shaded areas (canopy)** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| No shaded areas present | + | 0 | | | | | | | 0 | | | | | | | | | 0 | | | | | 0 | | 0 | | | 0 | | | | | 0 | | | | | | | | | 0 | | | | | |
| Shades from trees (canopy) | + | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | | 1 | | 1 | 1 | | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 |
| Artifical shade provision | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **If present, unpaved surface located lower than paved surface** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Unpaved surface is located higher than paved surface | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unpaved surface is located lower than paved surface | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 2 | | | | | | | | | | | | | |
| **Parking spaces** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cars are parked in the street (no designated parking spaces) | | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Car free street | + | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Designated parking spaces are present | – | 2 | | | | | | 2 | | 2 | 2 | | | | | | | | | | | | | | | | 2 | 2 | 2 | | | 2 | 2 | 2 | | | | | | | | | | | | | |
| **Driving lanes** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Car free street | + | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 point deduction per driving lane | – | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Max possible points (Grey category)** | | **7** | **−1** | **−1** | **−1** | −1 | −1 | −3 | −2 | −3 | −3 | −1 | −1 | −1 | −1 | −1 | −1 | −2 | −1 | −1 | −1 | −1 | −2 | −1 | −2 | −1 | −3 | −4 | −3 | −1 | −1 | −3 | −2 | −1 | −1 | −1 | −1 | −1 | −1 | −1 | −1 | −2 | −1 | −1 | −1 | −1 | −1 |
| **Total score** | | **100** | **58** | **33** | **42** | **43** | **25** | **35** | **22** | **32** | **25** | **64** | **68** | **62** | **55** | **51** | **46** | **63** | **37** | **55** | **53** | **51** | **40** | **62** | **60** | **29** | **46** | **40** | **66** | **59** | **66** | **61** | **28** | **51** | **36** | **36** | **47** | **46** | **50** | **64** | **22** | **23** | **51** | **25** | **61** | **69** | **70** |

**Table 12.** Total score street segments for Paddepoel North district.

| | Total Score |
|---|---|
| Score | 100 |
| Marsstraat Segment 1 | 58 |
| Marsstraat Segment 2 | 33 |
| Marsstraat Segment 3 | 42 |
| Uranus Straat Segment 1 | 43 |
| Uranus Straat Segment 2 | 25 |
| Uranus Straat Segment 3 | 35 |
| Neptunusstraat Segment 1 | 22 |
| Neptunusstraat Segment 2 | 32 |
| Neptunusstraat Segment 3 | 25 |
| Planetenlaan Segement 1 | 64 |
| Planetenlaan Segement 2 | 68 |
| Planetenlaan Segement 3 | 62 |
| Avondsterlaan Segement 1 | 55 |
| Avondsterlaan Segement 2 | 51 |
| Avondsterlaan Segement 3 | 46 |
| Jupiterstraat Segment 1 | 63 |
| Jupiterstraat Segment 2 | 37 |
| Jupiterstraat Segment 3 | 55 |
| Regulusstraat Segment 1 | 53 |
| Regulusstraat Segment 2 | 51 |
| Venuslaan Segment 1 | 40 |
| Venuslaan Segment 2 | 62 |
| Venuslaan Segment 3 | 60 |
| Venuslaan Segment 4 | 29 |
| Plutolaan Segment 1 | 46 |
| Plutolaan Segment 2 | 40 |
| Plutolaan Segment 3 | 66 |
| Poolsterlaan Segment 1 | 59 |
| Poolsterlaan Segment 2 | 66 |
| Poolsterlaan Segment 3 | 61 |
| Spicastraat Segment 1 | 28 |
| Spicastraat Segment 2 | 51 |
| Siriusstraat Segment 1 | 36 |
| Siriusstraat Segment 2 | 36 |
| Siriusstraat Segment 3 | 47 |
| Wegalaan Segment 1 | 46 |
| Wegalaan Segment 2 | 50 |
| Wegalaan Segment 3 | 64 |
| Capellastraat Segment 1 | 22 |
| Capellastraat Segment 2 | 23 |
| Kometenstraat Segment 1 | 51 |
| Kometenstraat Segment 2 | 25 |
| Mercuriusstraat Segment 1 | 61 |
| Morgensterlaan Segment 1 | 69 |
| Morgensterlaan Segment 2 | 70 |

The highest score in the Paddepoel North district was observed in Morgensterlaan, segment 2. Morgensterlaan, segment 2, scored 35 points for trees, which was just below the maximum of 40 points. There were 0 points awarded for green walls, 16 points for green front yards (75–100%), 13 points for green strips, 1 point for climate adaptive roofs, and 0 points for green parking lots.

In the blue category, Morgensterlaan, segment 2, did not score any points for the presence of rain barrels, permeable streets, or pavement. The street scored six points for nearby surface water within 50 m.

In the grey category, Morgensterlaan, segment 2, scored one point for shadow from canopy and zero points for green areas. No deduction for the presence of (soil-sealed) parking spaces and a deduction of two points for the presence of two (soil-sealed) driving lanes were scored (Figures 12 and 13).


**Figure 12.** Morgensterlaan [51].


**Figure 13.** Morgensterlaan [51].

The lowest score in the Paddepoel North district, of 22 points, was in Capellastraat segment 1. Capellastraat segment 1, scored only nine points for trees, and zero points for green walls, fourteen points for green front yards (50–75%), zero points for green strips, zero points for climate adaptive roofs, and zero points for green parking lots.

In the blue category, Capellastraat, segment 1, did not score any points for the presence of rain barrels, permeable streets or pavements, or nearby surface water.

In the grey category, Capellastraat, segment 1, scored 1 point for shadow from a canopy, zero points for green areas, no deduction for the presence of (soil-sealed) parking spaces, and a deduction of two point for each (soil-sealed) driving lane (Figure 14).


**Figure 14.** Capellastraat [52].

## 4. Discussion

The aim of the study was to create a tool, a score card, that was relatively easy to use by community members and stakeholders that could assess the presence of climate adaptive measures in streets and give insight into the level of climate adaptation for a street segment or an entire street. At the neighborhood level, studies have already shown that there is a mismatch between demand and supply of ecosystem services in neighborhoods and values for different ecosystem services for cooling and run-off retention and air purification [9]. These studies do not assess and score climate adaptation measures for an entire street. The objective was therefore to come up with a scorecard that can label a street segment or an entire street with a score of 1–100 and a label from A+++ to G, similar to the new EU energy labels for selected appliances, which were effective as of 1 March 2021 [53].

The method that was used in this research enabled the assessment of the presence of climate adaptive measures in different street segments. The results show that the scorecard method generated a clear numerical distinction between streets and street segments that contain climate adaptive measures and streets that do not have such climate adaptive measures.

As streets vary in length and longer streets tend to differ in terms of the date of construction for the housing units and building style, it is more effective to work with street segments as the unit of analysis. Other research in other fields of study also use street segments as units of analysis, such as virtual street audits of front yards [18] or streetscapes studies [8,16], or studies related to crime behavior [17] or walking speed [18]. To make the analysis of different streets segments comparable, a conversation factor was used to recalculate the values for a 100 m street length. This recalculation of values for 100 m of street length was not discussed in other literature, but it was effective to compare the street segments.

A literature review was undertaken and the most important climate adaptation measures were selected. The selected measures are not complete as many other climate adaptation measures were found in the literature and on websites about green and blue measures 6. The selection of climate adaptation measures was based on the most common measures that are present in Dutch streets and cities. The contribution of urban green infrastructure (UGI) to human well-being has been demonstrated in several studies.

The first selected climate adaptation measure was urban trees, as they represent a large portion of urban tree canopy and provide a significant amount of ecosystem services for mitigation of the negative environmental impact [20], and they improve the outdoor human thermal comfort and indoor environment [23]. Front yards in private residence play an important role in the soil sealing problem of cities worldwide [27]. The impervious cover of front yards contributes to the problems of the urban heat island effect and urban floods, and makes urban neighborhoods less pleasant. Private gardens play an important role as urban green spaces, and can improve the microclimate and address the impacts of climate change—specifically the urban heat island (UHI) effect. Green strips constitute similar benefits as front yards.

Climate adaptive roofs are green roofs, roofs with a high albedo (highly reflective roofs, which absorb less heat [38]), and blue roofs. Green roofs were chosen as an upcoming adaptive measure that can easily be recognized on Google maps, because, from above, plants/grass and other greenery can be spotted. Green parking spaces are an upcoming climate adaptive measure and they differ from regular parking spaces because they allow the water to infiltrate and contribute significantly to reducing runoff [39]. If parking lots are made of porous paving materials, between the tiles of parking spots there are often patches of grass [44]. Rain barrels or rain water tanks store water and relieve some stress on the sewage system during heavy precipitation. Rain barrels delay the time that it takes for water to flow into the system. Water from a roof connected to a rain barrel does not flow immediately into the sewage system, and rain water harvesting can be used as a remedial measure and can help in flood reduction [41]. Water-permeable pavements are porous or laid so as to allow voids, have an open structure, or are made of partially pervious materials. They allow water to pass through or around them into the soil; rainwater can infiltrate into the ground, groundwater is replenished, and sewerage systems are relieved [44]. A bioswale is an adaptive measure that has the ability to store water during heavy rain and redirects surface water to groundwater [42]. The surface water nearby functions as natural water storage. If the surface water is located nearby and is lower than the street level, water can be channeled into the surface water with natural gravity, and is an important adaptive measure in times of heavy precipitation. If unpaved areas are present, they provide an additional storage capacity for precipitation and may provide cooling facilities through natural vegetation. Paved surfaces, however, especially parking lots, occupy a significant proportion of the horizontal surface area in cities. The low albedo of many of these parking lots contribute to the urban heat island (UHI) and affect the local microclimate around them. Parking spaces heat up during the day and contribute to a higher temperature. At night, these warm surfaces contribute to the urban heat island effect. Similarly, impermeable "grey" driving lanes with a low permeability similarly to the grey parking spaces occupy a significant proportion of the horizontal surface area in cities. At night, these warm surfaces contribute to the urban heat island effect [44].

The weight that was given to the different climate adaptive measures is based on their perceived impact to address the impacts of climate change and address heat stress and water management problems. After testing the scorecard with different weights, the maximum score for the urban trees measure was set at 40. Three different categories were given a different number of points. The maximum score for urban trees was 40 points, or 40% of the maximum score. Green walls is a less common adaptive measure and this was given a maximum of 4 points or 4% weight. Façade gardens/front yards were given a maximum of 16 points or 16% weight. Green strips were given 13 points, or 13% weight. Climate adaptive roofs were given 2 points, or 2% weight. Green parking places were given 2 points or 2% weight. Rain barrels were given one point or 1% weight. Permeable pavements were given 3 points, or 3% weight. Bioswale was given 6 points or 6% weight. Surface water was given 6 points or 6% weight. Shaded areas/artificial shade were given 2 points 2%. There was a deduction of 2 points for the presence of designated parking areas, or 2% weight, and a deduction of 1 point per soil sealed driving lane or 2% of the weight.

The weight that was given to the climate adaptation measures was mainly given after testing several times with different weights for each factor. An important criterium for the future successful application of the scorecard is easy assessment and the scorecard should be able to distinguish adaptive from none adaptive streets. (Large) Trees are an important factor for reducing heat stress and water storage in roots and leaves. After testing, the maximum score and weight for trees was set at 40%. Façade gardens and front yards are also an important factor in climate adaptation and provide a lot of ecosystem services. The weight was set at 16% after testing. Similarly, the weight for green strips was set at 13%. The other climate adaptive measures were set at lower weights.

The feedback from the community members that participated in the climate adaptation training in Rotterdam was that the scorecard method gave them insights into the lack of adaptation measures in their street and neighborhood, as well as the lack of ecosystem services in their outdoor living environment. The community members mentioned that the scorecard method enabled them to better understand climate change and the local effects, as well as the actions they could take themselves to address the effects of climate change in their locality with simple measures, such as green yards, more facade gardens, planting trees, and increasing the infiltration capacity. They could also see which streets are greener and are better prepared for the effects of climate change, which, according to the community members, puts them in a better position and leaves them better prepared to discuss these issues with the local government.

A weakness of this method is that after the comparative study between the two districts in Groningen and Rotterdam, it became clear that some measures were not present at all in the two districts. In the green category, these were climate adaptive roofs and green parking lots. In the blue category, these were rain barrels, permeable streets and sidewalks, bioswales, and surface water. For the scorecard 2.0, these adaptive measures could be left out of the scorecard. Bio swales and other climate adaptation measures can be linked to climatescan [53] during future climatecafes [54] and city scan activities [55]. The three categories, namely green, blue, and grey measures, could be omitted in scorecard 2.0 as the distinction between the categories was not relevant for the scorecard. Another weakness is that the weights of the different measures was not based on the geospatial data analysis, but through ocular inspection. Although, for the purpose of this scorecard, namely creating awareness and being easy to use by stakeholders in the community, this suffices.

The scores—numerical values—are non-dimensional and the scores are interpreted by the user. A reference card with reference pictures has been provided in order to reduce the chance of different interpretations. Different users of the method may interpret climate adaptive measures, for example the height of the trees, differently, which could lead to inaccurate scoring. However, as the scores were non-dimensional, and the scores were mainly used for comparing the different streets with each other in other to identify adaptation gaps, this might not impose a serious problem.

## 5. Conclusions

The objective of this study was to test a method that assesses the presence of climate adaptive measures in street segments and streets, and to provide a score between 1 and 100 that indicates to what degree the street is climate adaptive. Based on the score, a label can be given between A+++ and G, so that residents and decision makers are aware which streets are adaptive and which streets have an adaptation potential. In the Paddepoel North district in the city of Groningen, 17 streets were assessed, composed of 45 street segments with an average climate adaptiveness score of 47. In the Hillesluis district in the city of Rotterdam, 21 streets were assessed, composed of 21 streets with an average score of 29 points. The climate adaptive measures that were observed in the street segments were tabulated and each climate adaptive measure was given a weight based on the perceived ecosystem service of the measure. Based on the adaptive measures multiplied by the weight, a score for a street segment could be given. Each score corresponds with a climate adaptation label.

The results show that the method is useful to score street segments and to attach labels to streets segments and entire streets, so that residents that live in these communities are aware of the level of adaptation of their street. Similarly, local governments and other stakeholders know which streets score low and which streets have a larger adaptation "potential".

The study developed and tested a new method to label the level of adaptation of street segments and entire streets, so that streets can be compared with each other. The method was proven to be relatively simple and useful for street assessments, as the assessment was done after a short training with several community groups in the Hillesluis district in Rotterdam. The method can easily be duplicated and used by local governments and community groups in order to have better insight into the level of climate adaptation of their street. Labels for entire streets can be used to encourage residents to take action and expand the number of climate adaptation measures in their own street.

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Article

# Spatial and Temporal Measurement of the Interaction between the County Economy and Rural Transformation in Xinjiang, China

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**Abstract:** Given the background of urbanization and rural revitalization in the new era, it is important to explore the synergy between regional macroeconomics and rural transformation, as a balanced and coordinated urban–rural relationship must be built to promote regional sustainable development and rural revitalization. This paper used the spatial econometric model to study the spatiotemporal synergy and interaction between Xinjiang's county economy and rural transformation from 2007 to 2017. The conclusions were as follows. A clear spatial difference exists between the county economy and the rural transformation level, and regional bulk agricultural products lack competitiveness. The synergy between the county economy and rural transformation is weak, as the county economy is lagging while rural transformation progresses without collaboration, indicating different types of non-equivalence. The county economy has a stronger spatial dependence on rural transformation and insufficient spillover, a stagnating effect, mainly negative driving effects, and unstable interaction effects; while the unstable changes in rural transformation affect the county economy. The urbanization rate, urban wage level, rural employment structure, and planting area per capita were the main influencing factors. It is necessary to deepen rural transformation, consolidate and enhance its stability, cultivate regional growth poles, promote overall development, and promote regional coordination.

**Keywords:** rural transformation; spatial measurement; interaction effects; Xinjiang

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## 1. Introduction

In recent years, the steady development of regional economic policies has driven changes in the rural economic environment. The influence of talent return, capital and technology input, and rural factor-structure-function reconstruction has changed rural industry, populations, functions, and spatial structure [1], and feedback effects are further affecting regional macroeconomics [2]. Villages have built a new format for the rural economy based on their agricultural structure, planting structure, and the integration of traditional and emerging industries. These new dynamics of rural transformation and development and the coordinated development of regional macroeconomics are playing an important role in narrowing the gap between urban and rural areas, establishing a reasonable relationship between industry and agriculture, realizing broad and deep poverty reduction and achieving rural revitalization [3]. At present, the theory and methods of rural transformation research are gradually maturing. Phan Le conducted an extensive survey of 2150 households in 12 provinces in Vietnam to explain the microeconomic characteristics of the Southeast Asian economic activities involved in rural transformation [4]. Ben Belton verified the characteristics of rural transformation in the arid areas of Myanmar by examining the interaction between land ownership, agricultural mechanization, and population mobility [5]. Rahmalia Rifandin explored the role of egalitarianism, collective activities, and community organizations in rural transformation [6]. Anna Pudianti observed that culture promotes rural transformation by transforming into material power and resolving obstacles and that the related research topics tend to be diverse [7]. The mechanisms of rural transformation are understood as comprising three types, endogenous, exogenous, and endogenous/exogenous comprehensive, which emphasize the influence of rural self-development on rural transformation in urbanization and industrialization [8]. For all types, whether local participants can effectively use social and industrial networks to realize the transformation of resources into profits plays an important role [9]. Regional towns and rural networks are crucial in this process.

The transformation of production function, spatial consumption, and the commercialization of rural space have also become modes of rural transformation [10–12] that produce different results within the spatial transformation of the regional economy [13]. This process has undergone a transition from industrialization to deindustrialization, showing the characteristics of prosperity or decline in different eras [14] as well as changes in time and space with urban life [15]. The social and economic output in the process of rural transformation is released into the market and participates in the development of the regional economy as a new capital element. Such elements affect the regional economic pattern and development efficiency through time accumulation and spatial distribution heterogeneity. Therefore, exploring the relationship and state of rural transformation and regional economy from the perspective of time and space is essential to maintaining regional sustainable development.

Domestic research on rural transformation has focused mainly on the development of theoretical frameworks and the exploration of the paths of rural transformation [16,17], rural spatial transformation, rural organizational transformation, rural land use, and functional transformation [18–21]. The development dynamics and effects of rural transformation in the context of urbanization, rural revitalization, and poverty alleviation have been discussed [2,22–24]. Although there is systematic recognition of the effectiveness of rural transformation elements in the process of urban and rural evolution in southern China [9,13,14], very few studies have examined the northern region. In the current era of globalization, industrialization, and urbanization, China is entering a new era of profound economic and social transformation and accelerated reconstruction of urban–rural relations [25]. Rural transformation and county economies should complement each other and maintain a cooperative relationship. Despite the importance of cooperation, a phenomenon exists in which the county economy is developed but the rural transformation is lagging, or the county economy remains backward within a transforming rural area. Whether the two are synergistic is related to the effectiveness of the implementation of regional economic development with industry to promote agriculture and lead the township; the presence of such synergy also confirms whether the village has the ability to transform and develop itself. Identifying the state and type of the synergy between the two and discussing the evolutionary characteristics of temporal and spatial changes are issues that policy makers and scholars should explore as understanding these elements is of great significance to the promotion of urbanization and the improvement of rural poverty. For the vast underdeveloped regions, revealing the spatial correlation and interactive effects of county economy and rural transformation is an urgent frontier issue that needs to be resolved to accelerate the transformation and development of backward regions, maintain the economic competitiveness of developed regions, and ease regional development differences [25].

This research focuses on the level of rural transformation, the characteristics it exhibits, and the state of coordination with social and economic development, as well as the interactive process of and theoretical research on regional development and rural transformation. Xinjiang is located in the inland area of Northwest China, and its geographical environment is complex and diverse. As of 2017, the rural population in Xinjiang accounted for 50.62% of the total population. The rural area is vast and covers contiguous impoverished areas in the three prefectures of southern Xinjiang, and the overall development of the regional economy lags behind that of other areas. There is currently no relevant research on the level, characteristics, and coordination of social and economic development comprising Xinjiang's rural transformation and a lack of theoretical research on the interaction between regional development and rural transformation. The main direction of regional development in Xinjiang has been to realize the in-depth development of its rural economy, make full use of the policy advantage offered by "full-scale counterpart assistance to Xinjiang", improve the regional development level [26], and realize the coordinated development of urban and rural areas. Given the lack of research on this area, this article uses Xinjiang as the research area to conduct an empirical analysis of the temporal and spatial synergy of county economic levels and rural transformation, as well as spatial interaction effects, from 2007 to 2017. A quantitative analysis of the relationship between Xinjiang's macroeconomic development and rural transformation is performed, and the state and mechanism of the interaction between rural transformation and county economy is discussed. Revealing the influence and representation of spatiotemporal differences on this interaction provides examples and theoretical references for regulating the dynamic relationship between county economy and rural transformation and development in underdeveloped areas and promotes the coordinated development of urban and rural areas and rural revitalization.

## 2. Materials and Methods

### *2.1. Data*

The socioeconomic data used in this research come from the *Xinjiang Statistical Yearbook* (2008–2018), *China County Statistical Yearbook* (2008–2018) and the *Xinjiang Local National Economic Development Bulletin*; the research period is from 2007 to 2017. To avoid affecting the integrity of the data system, any counties and regions that changed after 2007 were merged. Due to the large dimensional differences in the selected indicators and differences in the same indicator, dimensionless and non-negative treatment was needed [27].

### *2.2. Method*

#### 2.2.1. Comprehensive Index Evaluation Method

To accurately assess the county economy and the level of rural transformation and development, when constructing an index system based on similar research [17,21,28], indicators that are commonly used to characterize the regional economic level are selected to reflect the county economic level. Rural transformation takes the rural population composition, rural production conditions, output levels, and rural industrial system as the entry points and selects indicators that reflect the transformation of the rural population structure, the improvement in production conditions, the growth of agricultural output value, the regional agglomeration of rural industry and the evolution of the system. To capture the level of transformation in the constituent elements of rural transformation, an index system and weights are shown in Table 1. To avoid subjective weighting, the entropy weight method is used to determine the index weights [29].

**Table 1.** Rating index for the time and space coordination system between the county economy and rural transformation in Xinjiang.

| Subsystem | Indexes | Definition | Weight |
|---|---|---|---|
| County economy | Real GDP per capita (yuan/per capita) | Regional real GDP per capita | 0.055 |
| | Urbanization level (%) | Urban population/total resident population at the end of the year | 0.0587 |
| | Urban wage level (yuan/per capita) | Average salary of urban non-private units | 0.0597 |
| | Per capita income (yuan/per capita) | Regional fiscal revenue/total regional population | 0.0422 |
| | Industrial output value per capita (yuan/per capita) | Gross industrial output value/total regional population | 0.043 |
| | Per capita consumption level (yuan/per capita) | Total retail sales of consumer goods/total regional population | 0.0495 |
| Rural transformation | Proportion of rural population (%) | Rural population/total regional population | 0.0602 |
| | Rural employment level (%) | Rural employed population/total regional population | 0.0602 |
| | Rural electricity consumption level (10,000 kWh) | Rural electricity consumption per capita | 0.0462 |
| | Labor productivity (10,000 yuan/person) | Gross agricultural production value/ rural employment population | 0.0481 |
| | Agricultural modernization level (kW/ha) | Total power of agricultural machinery/total planting area | 0.0569 |
| | Plastic film coverage rate (%) | Plastic film coverage/total planting area | 0.0592 |
| | Fertilizer application rate (ton/ha) | Fertilizer application rate/sown area | 0.0587 |
| | Per capita planting area (hectares/person) | Total crop planting area/total regional population | 0.0582 |
| | Agricultural production efficiency (10,000 yuan/ha) | Gross agricultural production value/total crop planting area | 0.0573 |
| | Livestock alfalfa possession (tons/head) | Total livestock production/total alfalfa production | 0.0362 |
| | Output system structure entropy | Indicates the regional agglomeration of agricultural product output [30] | 0.0601 |
| | Output system structure conversion rate | Indicates the comprehensive performance of the agricultural product output system [30] | 0.0312 |

For the index output system structure entropy in Table 1 [30], the calculation formula is:

$$x_1 = -\sum_{i=1}^{n} P_i \times \ln P_i$$

where $P_i$ is the proportion of the $i$-th agricultural output in the total output. The total output is the sum of per capita food, cotton, oil, vegetables, fruits and melons, and meat per capita, which is the same below. The calculation formula for the output system structure conversion rate [30] is:

$$x_2 = \sqrt{\sum_{i=1}^{n} \frac{(N_i - G)^2 \times K_i}{G}}$$

where $N_i$ and $G$ are, respectively, the average annual growth rate of the $i$-th agricultural output and total output, and $K_i$ is the proportion of the $i$-th agricultural output in the total output.

2.2.2. Coupling Model Method

The coupling model is used to measure the coordinated development level and development stage of the county economy and rural transformation [31]. For the numerical calculation of the coupling degree, refer to the research of Liao Chongbin [32]. To avoid the result wherein a high level of coupling is identified for two systems that happen to be at a low level at the same time, resulting in a situation that is inconsistent with reality, the calculation refers to the study of Sheng Yanchao to measure the development of coupling coordination [33]. The degree is calculated as follows:

$$C = \{f(x)g(y)/[\frac{f(x)+g(y)}{2}]^2\}^k, \quad (1)$$

$$D = \sqrt{C \times T}, T = \alpha f(x) + \beta g(y). \quad (2)$$

In the formula, $C$ represents the degree of coupling coordination, and $K$ represents the adjustment coefficient ($K \geq 2$). In this paper, $K = 2$. $C \in [0, 1]$, such that the larger the value of $C$, the stronger the correlation of the system is, and vice versa; $D$ is the coupling and coordinated development degree of county economy and rural transformation; $T$ is the comprehensive benefit index of county economy and rural transformation; and $\alpha$ and $\beta$ are undetermined coefficients. In this paper, $\alpha = \beta = 0.5$. According to similar research the coupling types are further divided (Table 2) [31].

**Table 2.** Coordinated development level of coupling.

| **Coupling Coordination Degree (D)** | 0–0.09 | 0.1–0.19 | 0.2–0.29 | 0.3–0.39 | 0.4–0.49 |
|---|---|---|---|---|---|
| **Type** | Extremely dysfunctional | Seriously dysfunctional | Moderately dysfunctional | Mildly dysfunctional | Slightly dysfunctional |
| **Coupling Coordination Degree (D)** | 0.5–0.59 | 0.6–0.69 | 0.7–0.79 | 0.8–0.89 | 0.9–1 |
| **Type** | Slight coordination | Primary coordination | Intermediate coordination | Good coordination | Quality coordination |

2.2.3. Spatial Measurement Method

Within a certain geographic space, the county economy and rural transformation in different spatial units are affected not only by capital but also by spillover effects and policies generated by investment activities in other surrounding areas, resulting in significant economic behavior exchange between regions, creating external effects that thereby form regional economic clusters [34]. The investigation of economic clusters is realized through spatial effects. The spatial measurement model examines how to deal with spatial interaction (spatial autocorrelation) and spatial structure (spatial nonuniformity) in the regression models of (cross-sectional data) and (panel data) [35,36]. The spatial measurement method used in this study can effectively interpret the differences in temporal and spatial changes and the synergistic interaction between the county economy and rural transformation, thereby revealing the differences in the overall and local impacts of the two.

(1) Spatial autocorrelation

Spatial autocorrelation is a method used to measure the spatial connection and correlation of different regional attributes [37]. It is mainly used to explore the spatial dependence of regional unit attributes from both the global and local perspectives.

① Global autocorrelation (Moran's I)

Global autocorrelation is applied to explore the spatial dependence of Xinjiang's county economy and rural transformation from a global perspective. This paper uses univariate and bivariate global autocorrelation to test the spatial dependence between the county economy and rural transformation. The formula is as follows [38]:

$$Moran's\ I = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})/s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \quad (3)$$

where $X_i$ and $X_j$ are the observation values of spatial units $i$ and $j$, respectively; n is the number of spatial units;$\overline{x}$ and $s^2$ are the mean and variance of the observation value $x$; $W_{ij}$ is a spatial weight matrix constructed based on neighboring criteria; and $Z_i$ and $Z_j$ are the standardized values of variance of the observations of spatial units $i$ and $j$ (the same below). *Moran's I*∈(−1,1), where 0 indicates negative correlation, equal to 0 indicates irrelevance, and greater than 0 indicates global positive correlation.

② Local autocorrelation (LISA)

To compensate for the shortcomings of the global autocorrelation assessment, which ignores the potential instability of the spatial process and lacks local variation, the local indicators of spatial connection are used to identify counties with local agglomeration and describe the spatial agglomeration between similar attribute units, revealing local spatial connections and differences in the synergy between county economies and rural transformation. The formula is as follows [38]:

$$LISA\ I_i = Z_i \sum_j w_{ij} z_j, z_i = \frac{x_i - \overline{x}}{\sqrt{\frac{1}{n}\sum(x_i - \overline{x})^2}} \quad (4)$$

where $i$ and $j$ represent the spatial unit; $n$ is the number of spatial units; $W_{ij}$ is the spatial weight matrix when two spatial units are adjacent to 1 (otherwise 0); $x$ is the observation value (i.e., the degree of coupling coordination); $\overline{x}$ is the average value of the observation value.

(2) Spatial lag model

Because of the spatial autocorrelation (spatial dependence) between the rural transformation and the county economy in each time section, the selected factors can be explored through the spatial panel measurement model by incorporating spatial and temporal effects on the basis of the ordinary panel data model. Impact on the changes in the temporal and spatial pattern between the county economy and rural transformation can thus be observed [36,39].

The spatial lag model can effectively explore the spillover effect and test the dynamic interactive feedback relationship between variables [40]. With the spatial lag model, the analysis reveals the strength of the impact of the county economy on rural transformation and vice versa. The formula is as follows [36,40]:

$$\ln ei_{it} = a_{it} + \rho \ln e_{it} + \beta_1 \ln urb_{it} + \beta_2 \ln ind_{it} + \beta_3 \ln fd_{it} + \beta_4 \ln open_{it} + \beta_5 \ln gdp_{it} \cdots + u_1 + \varepsilon_{it}. \quad (5)$$

In the formula, $ei_{it}$ represents the attribute of the $i$-th spatial subject in year $t$; $i$ = 1, 2, 3,..., $n$ stands for different spatial subjects; $t$ = 1, 2, 3,... stands for different years;

$a_{it}$ represents the longitudinal intercept; $m_i$ represents random individual differences; $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, $\beta_5$, $\beta_6$ indicate the parameter to be estimated; $\rho$ is the spatial autoregressive coefficient; $\varepsilon_{it}$ represents the random error term and satisfies the independent and identical distribution such that the expectation is 0, the variance is $\sigma^2$, that is, $\varepsilon_{it} \sim N[0, \sigma^2 I_N]$; and $i_N$ is the $N$-order unit matrix. All variables take the form of natural logarithms, so the estimated coefficients can be interpreted as elasticity.

(3) Spatial error model

The spatial error model supplements the spatial lag model by constructing driving factors and explores the influence of items causing random interference in interactions, such as uncertain factors, difficult-to-measure factors, and measurement errors in system operation. The formula is as follows [36,40]:

$$y = X\beta + \varepsilon, \varepsilon = \lambda W\varepsilon + \mu. \tag{6}$$

In the formula, $\varepsilon$ is the random error term vector, $\lambda$ is the spatial error coefficient of the n*1 order cross-sectional dependent variable vector, and $\mu$ is the random error vector of the normal distribution.

(4) Geographically-weighted regression (GWR)

The spatial lag model and spatial error model focus on evaluating the global driving effect, revealing insufficiencies in the local driving effect, evaluating the driving effect of the local area through geographically-weighted regression, and performing local regression on the variable coefficients for the functions capturing the county economy and the level of rural transformation. The estimated coefficients of the variable after regression are used to analyze the spatial variability characteristics [41,42], revealing the local differences and the types of interactions. The formula is as follows [41,43]:

$$y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{k} \beta_j(u_i, v_i)x_{ij} + \varepsilon_i. \tag{7}$$

In the formula, $(u_i, v_i)$ indicates the geographic coordinates of the sample $i$ spatial unit, and $\beta_j(u_i, v_i)$ is the value of the continuous function $\beta_j(u_i, v_i)$ in the sample $i$ spatial unit, which is a function of geographic location.

## 3. Results

To a certain extent, rural transformation can be understood as the development of a rural regional system through the accumulation and transformation of rural capital under the influence of progress in rural productivity and production methods and the diversification of group interest needs, all guided by economic benefits. Rural areas have been transformed, and the resulting transformation of rural production systems, labor, and employment, such as the output of surplus labor, non-agricultural employment in rural areas, and diversification of production and management, has promoted the upgrading and innovation of the functional forms of rural regional systems. In the process of rural capital accumulation and transformation in the output of rural labor services and adaptation to market supply and demand, the rural regional system exchanges value and realizes value with a regional economic system dominated by counties, districts, and cities, causing capital components to move between the village and the region. The change in the spatial pattern of flow and the formation of a new pattern of element flow and a new regional interaction structure are the manifestations of rural adaptation to market-oriented development. The spatial pattern of urban–rural capital flow through the feedback process will affect the stability of regional economic growth and the spatial pattern of rural transformation, resulting in the reorganization of the urban–rural regional system.

*3.1. The Interactive Process between the County Economy and Rural Transformation*

The spatiotemporal synergy of the county economy and rural transformation is a process in which the components and system functions of the two interact in time and space during a dynamic development process (Figure 1).

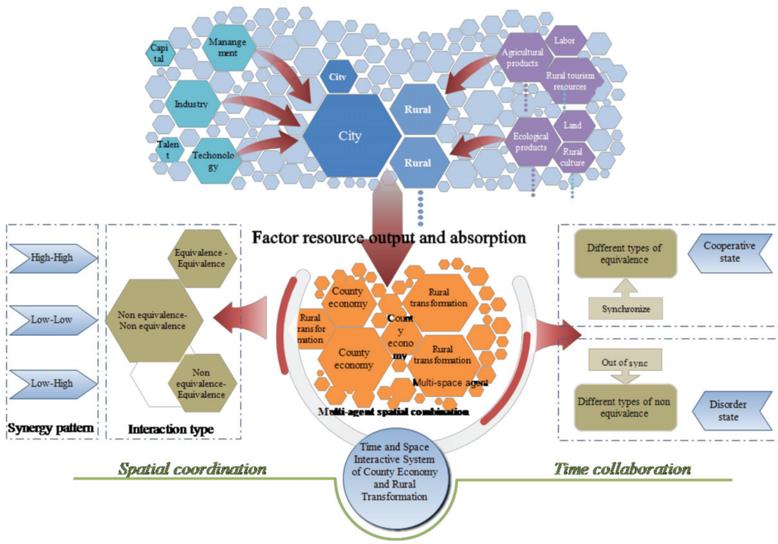



**Figure 1.** Time–space interaction process between the county economy and rural transformation.

The county economy and rural transformation have different characteristics of spatial and temporal evolution. Based on their respective development patterns, the spatial interactions of subsystems are formed through spatial adjacency, production and consumption links, and potential social, policy, and cultural links to constitute a coordinated system of county economy–rural transformation. The composition of the county economy and rural transformation in the system, the regional relationship, and the environmental background determine the system's integrity and function. The relationships between the components of the county economy–rural transformation coordination system or between the components, the hierarchy, and the system environment are changed and adjusted to ensure that they are coordinated. Thus, the overall county economy–rural transformation coordination system exhibits ideal interactive functions and achieves coordination.

In the county economy–rural transformation synergy system, when a region's county economy and rural transformation are in a state of "different equivalence" [44], that is, when the development levels of the two subsystems are relatively balanced, there is no significant topography. If the energy is poor, the polarization and diffusion effects are in an equal state and the two-way interaction process is balanced and sufficient, the development of the two is synchronized in time, and the region is in an ideal state of synergy. In contrast, an area can be characterized by "different types of non-equivalence", wherein the level of the county economy and rural transformation and development in this area is uneven, and there is a significant difference in potential energy. The chemical effect or the diffusion effect in this context is more prominent. The county economy and rural transformation do not match, and the two are not synchronized in time, eventually leading to the collapse of the coordination system between the county economy and rural transformation.

Between different spatial units, the degree to which "different types of equivalence" or "different types of non-equivalence" characterize the relationship of the county economy and rural transformation will vary, and two adjacent county intervals will produce different degrees of "equivalence–non-equivalence", "equivalence–equivalence" or "non-equivalence–non-equivalence"; these are three states of synergistic combination that correspond to the "high-low", "high-high" and "low-low" spatial coordination patterns. To achieve the spatial coordination of different county-regional economic-rural transformation systems, it is necessary to build a regional development model and solution strategy that focuses on improving the interactive process of the element structures and levels in the system to gradually realize the transformation from unbalanced to balanced regional development and achieve urban, rural, and regional synergy.

### *3.2. Temporal and Spatial Differentiation of the County Economy and Rural Transformation*

From 2007 to 2017, the economic development gap between Xinjiang's counties narrowed, and although there was local volatility, overall development stabilized. The low economic value areas were concentrated in the Kashgar, Ho Tan, Aksu, Ili Kazakh Autonomous Prefecture and Ta Cheng areas. The economic level of the county was high in the east and low in the west, and the economic level of some counties in northern Xinjiang had decreased. The annual average was at a high level, and development was stable.

In 2017, 19 counties (0.14–0.26) had strong rural transformation capabilities, accounting for 22.35% of the total number of samples. They were concentrated on the northern slope of the Tianshan Mountains and the eastern margin of the Tarim Basin, and their concentration was stronger than it had been in 2007. The lagging rural transformation counties were mainly distributed in the three prefectures of southern Xinjiang and the Kazakh Autonomous Prefecture of Ili. There tended to be alpine regions and deserts in these regions, with scarce land resources, slow economic and industrial development, and deep poverty.

In 2017, the average conversion rate of the output system structure was 0.00099, an increase of 90.38% over 2007 (0.00052). With the gradual establishment of Xinjiang's food security reserve base, high-quality cotton production base, characteristic forest and fruit industry base, and modern livestock product base [45], the comprehensive agricultural output capacity of Xinjiang was significantly improved, the production capacity of bulk agricultural products was improved and the output was tending toward stability. This provided a good agricultural economic foundation for rural transformation and development. The average entropy score of the output system in 2007 was 0.0203, while it was 0.0147 in 2017, a decrease of 27.58%. The regional agglomeration of the agricultural output system decreased, reflecting the scattered distribution of bulk agricultural products in Xinjiang, such as grain, cotton, oilseed, and vegetables; the spatial agglomeration of melon cultivation and meat production was reduced, and the region did not hold a competitive advantage. The development of characteristic regional agriculture could deliver obvious advantages for improving the competitiveness of county agricultural output, enhancing rural development and promoting transformation and development.

### *3.3. Space–Time Synergy Analysis*

By calculating the coupling model, the interaction intensity of the county economy and rural transformation from 2007 to 2017 was obtained, and the spatial distribution of its coupling grade was obtained (Figure 2). The main year parameters are shown in Table 3.

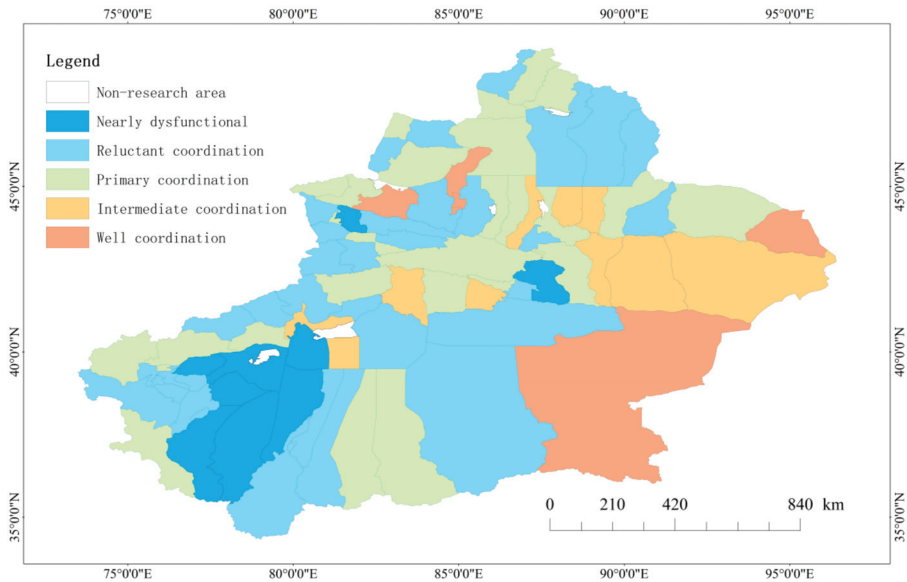



**Figure 2.** Spatial distribution of the coupling coordination between the county economy and rural transition in 2017.

**Table 3.** Statistics for the coupling level of the county economy and rural transition in 2007–2017.

| Type | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 | Average | Total |
|---|---|---|---|---|---|---|---|---|
| Moderately dysfunctional | | | 1 | | | | | 1 |
| Mildly dysfunctional | 5 | 1 | 4 | | | | | 10 |
| Slightly dysfunctional | 19 | 9 | 11 | 4 | 4 | 9 | 8 | 64 |
| Slight coordination | 15 | 20 | 21 | 19 | 16 | 35 | 21 | 147 |
| Primary coordination | 24 | 20 | 22 | 28 | 38 | 27 | 34 | 193 |
| Intermediate coordination | 15 | 25 | 14 | 25 | 17 | 9 | 15 | 120 |
| Good coordination | 5 | 7 | 9 | 9 | 9 | 5 | 6 | 50 |
| Quality coordination | 2 | 3 | 3 | | 1 | | 1 | 10 |

Table 3 shows that from 2007 to 2017, the coupling of the county economy and rural transformation in Xinjiang was at a medium level, with slight coordination, primary coordination, and intermediate coordination as the most common. In 2017, the coupling of the county economy and rural transformation showed a spatial distribution of high in the east and low in the west (Figure 2). The synergy of counties and districts in southern Xinjiang was at a low level, showing different types of non-equivalence, while in northern Xinjiang, the distribution of high and low was staggered. The five well-coordinated counties and districts were scattered in the north and south, and the spatial connection was weak. The nine counties and districts of Pishan, Awati, Yecheng, Maigaiti, Moyu, Bachu, Jiashi, Yining, and Heshuo were on the verge of imbalance, and all were lagging in the county economy. The transformation was not synchronized in time, and they were in a serious different state of equivalence. The shortcomings in county economic development urgently needed to be addressed.

The coupling univariate spatial autocorrelation test for 2017 showed that the county economy was positively correlated with the rural transformation coupling space, and the global Moran index was 0.2241. The local autocorrelation test (Figure 3) showed that the local area had formed a high-high agglomeration area with Buxel Mongolian Autonomous County–Tori County, Balikun Kazakh Autonomous County–Turpan City–Shanshan County as the core, which were centrally distributed in northern and eastern

Xinjiang. The low-low agglomerations were mainly in the Hotan-Kashi region of southern Xinjiang and Kazakh Autonomous Prefecture of Yili, and the coupling driving factors between counties were strongly correlated, forming contiguous low-level areas. High-low and low-high agglomerations reflected the cross-distribution of counties and districts with significant differences in coupling. The type of interaction and the interaction in space were unidirectional, contradictory, or contained and concentrated in central Xinjiang.

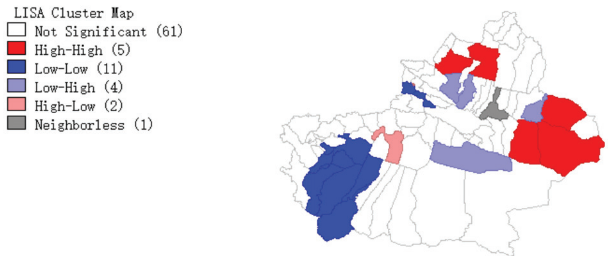



**Figure 3.** LISA map of the coupling county economy and rural transformation in Xinjiang.

## 4. Discussion

### *4.1. Spatial Effects of County Economy and Rural Transformation*

The 2017 county economy and rural transformation were tested with univariate and bivariate global spatial autocorrelation to explore the spatial correlation and dependence between the county economy and rural transformation and to reveal their interactive influence and strength.

(1) Global spatial autocorrelation univariate test

In 2017, the overall spatial autocorrelation test results for the county economy and rural transformation Moran's I index were 0.0872 and 0.1735, respectively, which passed the test of significance $p = 0.05$; the distribution of the two was positively correlated. Due to the similar development environment and the small spatial distance between adjacent counties, the interaction effect decreased with spatial distance, resulting in local aggregation.

(2) Global spatial autocorrelation bivariate cross-test

Bivariate cross-tests can test the correlation of two variables in the study area. Cross-check (A) takes the county economy as the independent variable and rural transformation as the dependent variable to reflect the spatial dependence of rural transformation on the county economy. Cross-check (B) takes rural transformation as the independent variable and the county economy as the dependent variable to reflect the spatial dependence of the county economy on rural transformation. Both cross-check (A) and cross-check (B) passed the significance test of 0.05, and the global Moran's I indexes were 0.2204 and 0.2206, respectively. The county economy and rural transformation showed positive spatial autocorrelation, and there was spatial dependence. The size of the Moran's I index showed that the county economy had a stronger spatial dependence on rural transformation, and this dependence was manifested in the fact that in Xinjiang's agricultural-based rural industrial system the rural population was the majority, and the objective reality was that the region had a huge agricultural economy that held a basic role in promoting regional economic development.

(3) Local autocorrelation test

The results of the local autocorrelation test (LISA map) of the county economy and rural transformation in 2017 are shown in Figure 4, in which three counties are high-high clusters and nine counties are low-low clusters. The spatial correlation of low-low clustering of the county economy was more obvious: the two clusters were differentiated from north to south, wherein the north was high, and the south was low. The low-low clustering areas were concentrated in Hotan and Kashgar, and the economic development of these subordinate areas was slow. These areas represented the main poverty-stricken areas in Xinjiang. The partial spatial correlation of rural transformation was stronger than that of the county economy. Among them, eight high-high cluster counties were distributed on the south side of the Tianshan Mountains and the east side of the Tarim Basin. The low-low cluster counties were the four counties of Luopu, Hotan, Atushi, and Yecheng in southern Xinjiang, and the county economy and rural transformation in southern Xinjiang were at a relatively low level.

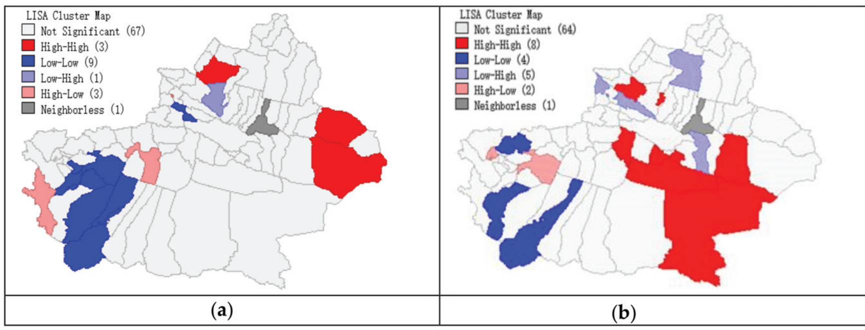



**Figure 4.** County economy and rural transformation LISA: (**a**) County economy; (**b**) Rural transformation.

### *4.2. Overall Interactive Driving Effect of the County Economy and Rural Transformation*

A previous article found that the county economy and rural transformation have significant spatial dependence, so spatial lag (spatial lag) and spatial error (spatial error) models were used to explore the diffusion and spillover effects between them in space, namely, their interactive drive. In this paper, the spatial weighting matrix of the adjacency relationship was used to test the spatial regression of the county economy and rural transformation in GeoDa, and the measurement parameters proposed by Anselin were used as test criteria (Table 4) to determine the suitability of the model to accurately reflect its spatial interaction [41].

In the regression test of the driving effect of the county economy on rural transformation in Model 1, LM and R-LM were significant at the levels of 1 and 10%, the statistics were similar, and the constants passed the 1% test. Compared with the spatial lag, spatial error had similar LogL, AIC, and SC values, and the difference in measurement statistics was small, but the fitting degree R2 of the spatial lag model was significantly greater than that of the spatial error. Therefore, the spatial lag model was more suitable for appraisal. The spatial lag regression coefficient was −0.0281, the spillover effect of county economic development had a negative relationship with the driving effect of rural transformation, and the economic spillover effect of county economic development was insufficient.

Model 2 showed the test of the driving effect of rural transformation on the county economy. Both spatial lag and spatial error LM failed the significance test, and R-LM was significant at the 5% level, which was insufficient to determine the choice of specific spatial models. Spatial lag and spatial error had similar R2, LogL, AIC, and SC values. The regression coefficient of rural transformation on the county economy spillover effect was 0.0173, and through a 10% confidence test, rural transformation had a good driving effect on the county economy. The error term of rural transformation was negatively correlated with the economic development of the county; that is, the random error of rural transformation, i.e., unstable changes, had a stagnating effect on the economic development of the county.

**Table 4.** Spatial lag and spatial error verification parameters.

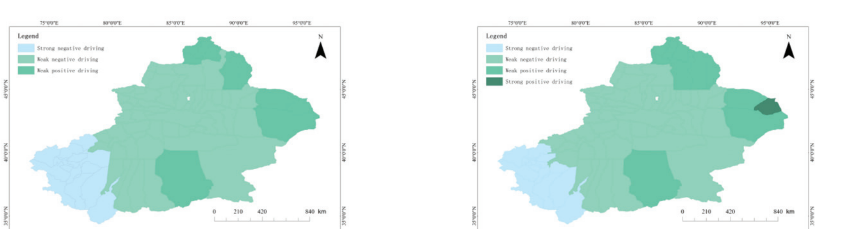
| **Model 1 The Driving Force of the County Economy on Rural Transformation** | | | **Model 2 The Driving Force of Rural Transformation on the County Economy** | | |
|---|---|---|---|---|---|
| **Parameter** | **Spatial Lag** | **Spatial Error** | **Parameter** | **Spatial Lag** | **Spatial Error** |
| C | 0.0831 (0.0000) * | 0.1304 (0.0000) * | C | 0.0792 (0.0000) * | 0.9001 (0.0000) * |
| Coefficient | −0.0281 (0.0774) *** | −0.1065 (0.0270) ** | Coefficient | 0.0173 (0.0121) *** | −0.0062 (0.0224) * |
| LAMDBA | | 0.3860 (0.0032) * | LAMDBA | - | 0.1009 (0.0151) ** |
| LogL | 165.629 | 166.0685 | LogL | 158.087 | 158.0774 |
| $R^2$ | 0.821 | 0.4701 | $R^2$ | 0.6179 | 0.6464 |
| AIC | −325.258 | −328.137 | AIC | −310.174 | −312.155 |
| SC | −317.3 | −323.252 | SC | −302.846 | −307.27 |
| LR | 5.0976 (0.0240) *** | 5.9701 (0.0145) ** | LR | 0.2789 (0.5974) | 0.2603 (0.0060) ** |
| BP | 0.6306 (0.0427) | 0.1477 (0.7007) | BP | 3.4228 (0.0643) | 3.1852 (0.0743) |
| LM (lag) | | 0.5635 (0.0183) ** | LM (lag) | | 0.2529 (0.5319) |
| R-LM (lag) | | 16.0101 (0.0000) * | R-LM (lag) | | 10.1065 (0.0014) ** |
| LM (error) | | 5.0771 (0.0242) ** | LM (error) | | 0.1674 (0.6824) |
| R-LM (error) | | 15.5237 (0.0000) * | R-LM (error) | | 10.0210 (0.0015) ** |

Note: The values in parentheses are P values, *, **, and *** represent significance at the 1, 5, and 10% confidence levels, respectively.

Comparing the spatial interaction between the county economy and rural transformation, the county economy negatively drove rural transformation, while rural transformation positively drove the county economy. This showed that the economic development of the county in Xinjiang had a low exogenous drive toward rural transformation, and rural transformation required an endogenous drive and evolution. The promotion of rural functional structure optimization, industrial development and upgrading, rural poverty alleviation, infrastructure improvement, and other rural development trends represents a potential market for county economic development, realizing rural revitalization and driving county economic growth.

### *4.3. Local Interactive Effects of County Economy and Rural Transformation*

Geographically-weighted regression (GWR) through ArcGIS was used to test the local driving effects of the county economy and rural transformation. The GWR test model R2 was 0.7628, the adjusted R2 was 0.7316, the AICc was −331.9280, and the residual sum of squares was 7.7607; the parameter R2 of the local driving test model of rural transformation to the county economy was 0.7883, the adjusted R2 was 0.7153, and the AICc was −3317.4592, the sum of squared residuals was 8.6809, and the model showed a better fit. The test showed that the regression coefficients of the two driving effects were between −0.7109 and 0.4352. According to the statistical characteristics of the regression coefficients, the driving effects were divided into four categories: strong negative drive, weak negative drive, weak positive drive, and strong positive drive. The results are shown in Figure 5.




(**a**) (**b**)

**Figure 5.** Distribution of the driving effects of the county economy and rural transformation: (**a**) The driving effect of the county economy on rural transformation. (**b**) The driving effect of rural transformation on the county economy.

The results showed that the local driving effect of the county economy and rural transformation was dominated by a negative drive, in which the county economy accounted for

88.09% of the rural negative drive areas, and rural transformation accounted for 85.71% of the county negative economic drive areas. A negative drive indicates that the interaction between the county economy and rural transformation is unstable in the local space, the synergy between county development and rural transformation is low, and the clustering of economic behaviors is weak.

Using the index layer in Table 1 as the hypothetical ideal factor, classical least squares regression (classic OLS) was used to perform attribution analysis on the influencing factors of the local driving effects of the county economy and rural transformation. In the OLS results, the urbanization rate, urban wage level, rural employment structure, and per capita planting area passed the T test, showing that they had a more significant impact on the local driving effect of the county economy and rural transformation. Therefore, improvement in the local driving effect requires the investment of more resources in the optimization of the urban system, rural urbanization, urban–rural industrial upgrading, agricultural modernization, and poverty alleviation in local areas, the cultivation of regional growth poles, and the development of regional industrial clusters with complementary functions. Population, industry, land, and environment are all starting points for building a coordinated urban–rural development system in line with Xinjiang's social, economic, and natural environment to promote regional development.

Rural transformation is a current characteristic of rural development and an inevitable process of rural revitalization. From the perspective of geographic time and space, the process of rural transformation requires accumulation of practice to realize the transformation from quantitative change to qualitative change over time, and to interact with the main body of the county and city in the process of quantitative change to form urban–rural collaboration. The rural transformation that occurs in the rural spatial entity is subject to spatial distribution and spatial distance coercion. The progress and degree of rural transformation are localized in the regional space. There are differences in the spatial synergy of rural transformation, and spatial asynchrony weakens rural area's spatial spillover effect and regional driving capacity of transformation to a certain extent. The process of realizing synergy between rural transformation and the county economy involves multiple subjects on the time and space scale. The time and space differences in multi-subject coordination represent systematic synergy. The empirical results show that Xinjiang's rural transformation and county economy are out of sync. The synergy needs to be further improved. However, both endogenous and external adjustment needs to be carried out to address the spatiotemporal synergy difference between rural transformation and county economic synergy at the regional scale. It is important to pay attention to the self-organizing evolution of the system and to strengthen the external adjustment of other organizations considering the function of the system. Structural and external environmental conditions should be established to begin rural transformation and improve the synergistic effect of the county economy. At the same time, as part of the urban–rural regional system, the functions of rural transformation and the county economy in the system need to be further identified and quantified to promote the synergy between them.

As a major arid area, Xinjiang's social and economic behaviors are restricted by the objective natural environment. While the region has abundant resource reserves, it also has inherent deficiencies, such as a fragile ecological environment and low ecological carrying capacity. The environmental dependence on industrial production and agricultural activities needs to be maintained at a low level, which makes it difficult to upgrade the regional economy. However, the gradual breakthrough in addressing practical problems, such as the cultivation of characteristic rural industries, the transformation of traditional agriculture, ecological protection and restoration, and poverty alleviation, has released the potential for rural development, which has significantly driven the overall development of the region. It is necessary to further expand rural development given the existing conditions, starting by stimulating the transformation of rural labor force, cultivating and optimizing the township industry system, enhancing urban–rural linkages, cultivating growth poles, and improving the quality of agricultural production, to further consolidate and enhance the steady progress of rural transformation and prevent unstable changes from slowing the overall development of the region.

## 5. Conclusions

This paper analyzes the spatial–temporal changes and interactive effects of the coordinated development between the county economy and rural transformation in the county-level units of Xinjiang from 2007 to 2017 using spatial measurement methods. The results are as follows. (1) There are significant spatial differences in the county economy and rural transformation levels in Xinjiang. The characteristics of a strong north and weak south and a strong east and weak west are obvious, and the three prefectures in southern Xinjiang and Ili Kazakh Autonomous Prefecture are significantly lagging. (2) The synergy between the county economy and the rural transformation level is weak, showing different types of non-equivalence, wherein rural transformation is ahead and the county economy is lagging. (3) There is positive spatial autocorrelation between the county economy and rural transformation, and the county economy has greater spatial dependence on rural transformation. The county economy is dominated by low-low spatial clustering, rural transformation has greater high-to-high agglomeration, and the difference between north and south is significant. The county economy and rural transformation in southern Xinjiang are at a low level, and the social and economic level needs to be improved. (4) The driving effect of county economic development on rural transformation is negative, and the economic spillover effect of county economic development is insufficient. Rural transformation positively drives the county economy, and unstable changes in rural transformation are slowing the development of the county economy. The local driving effect of the county economy on rural transformation is mainly negative, and the effects of local spatial interaction are unstable. The urbanization rate, urban wage level, rural employment structure, and per capita planting area are the main influencing factors.

The ultimate goal of rural transformation and county economic coordination is to achieve regional prosperity, eliminate urban–rural polarization, and break economic and geographic marginalization [46], thereby reducing the gap between urban–rural and regional development. Just as success in life requires the proper combination of material and spirit, realism and idealism, seriousness and playfulness, a modern society requires both cities and rural areas [47]. The result of rural transformation is not the complete urbanization and elimination of the countryside but the optimization and promotion of the countryside, maintaining rural characteristics even in the common development of the city. Although the level of urbanization is high, there are still a large number of people living in rural areas [48], and an increase in urbanization does not directly lead to the improvement of life in rural areas [49]. The spatial imbalance in regional development directly leads to this unequal distribution of capital and benefits and even triggers social conflicts [50]. Although spatial imbalance is a temporal phenomenon, it will decrease with economic development. Nonetheless, in this process, spatial inequality may be harmful to the development process itself [51]. Undifferentiated equalization does not improve the state of spatial imbalance [52]. Based on this situation, rural transformation and the coordinated development of the county economy can release their economic benefits to a certain extent through the externalities of economic behavior, stimulate the free flow and equal exchange of urban and rural capital within the space, and, consequently, narrow the urban–rural development gap. Due to differences in national conditions, we need to further understand the response of rural changes in different regions to regional economic development in the process of globalization, explore the synergistic characteristics of rural and regional transformation at different levels, and reveal the synergistic mechanism of rural and regional transformation in different regions. Focusing on breaking down barriers in social and geographic space, summarizing the rural and regional synergy strategies suitable for most regions, and building a bridge between rural and regional synergy by developing theories, practices, and policies should be the work of future research.

**Author Contributions:** B.T.: Conceptualization, methodology, software, writing—review and editing. H.W.: Conceptualization, supervision, writing—review and editing, resources. C.M.: Project administration, resources. X.W.: Data curation, software. J.Z.: Data curation. All authors have read and agreed to the published version of the manuscript.

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# Changes of Bioclimatic Conditions in the Kłodzko Region (SW Poland)

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**Abstract:** Despite continuous technological development, lack of data or discontinuity in meteorological measurements is still an issue affecting many stations. This study was devoted to determining the bioclimatic conditions in the Kłodzko region (SW Poland), where meteorological measurements have been discontinuous since 2006. Four stations with continuous measurements were analyzed. These localities are situated at Kłodzko and its health resorts. Bioclimatic conditions were determined using the Universal Thermal Climate Index (UTCI). The study of variability in UTCI was performed in different circulation epochs. Additionally, a non-linear model for SW Poland was used to reconstruct the long-term trend of air temperature in the Kłodzko region. Verification of this model was performed on the basis of own air temperature measurements in the period from April 2017 to March 2022. Analysis of thermal conditions in circulation phases showed higher air temperatures and UTCI values in epoch W (1989–present) compared to epoch E (1966–1988) at all analyzed stations. The non-linear model of meteorological data showed its applicability for data reconstruction in the region with an accuracy of about 67%. Further modification of the model may serve to increase its applicability to other locations in Europe or North America.

**Keywords:** health resort districts; UTCI; macrocirculation phenomena; non-linear reconstruction; time series analysis

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## 1. Introduction

Bioclimatic analyses of health resorts districts are among the information included in the Polish health resort inventory. In addition, such analyses find application in determining the tourism potential of a region [1–3], the impact of environmental conditions on human health [4–6], and determining extreme conditions on regional mortality gain [7,8], military activities [9], or socioeconomic endeavors [10]. Bioclimatic conditions are determined by various indicators. In the process of continuous improvement to measure the meteorological impact on the human body, more than 200 biometeorological indicators have been invented, whose differences in structure and application can be found in the review article of de Freitas and Grigorieva [11]. Depending on the complexity, de Freitas and Grigorieva divided them into eight groups that characterize differences between bioclimatic indexes: (A) simulation device for integrated measurement such as globe thermometer temperature, Tg [12]; (B) basic single-parametric indices such as wet bulb temperature, Twb [13] or saturation deficit [14] which rely more on determining detailed meteorological conditions than on ascertaining the impact on the human body; (C) algebraic or statistical model based on statistical models such as the humidex [15], insulation predicted index or Icpl [16]; (D) proxy thermal strain index, e.g., cold strain index, CSI [17]; (E) proxy thermal stress index, e.g., comfort index, CI [18]; (F) energy balance strain index, e.g., physiological subjective temperature [19]; (G) energy balance stress index that takes into account the exchange of thermal energy between humans and weather conditions, such as the Universal Thermal Climate Index, UTCI [20] or physiological equivalent temperature, PET [21]; (H) special purpose index with narrow utility such as heat tolerance index [22] to analyze reactions of the human body only in extreme conditions.

A detailed analysis of bioclimatic conditions in 43 health resorts in Poland for the period 1970–1990 was carried out by Kozłowska-Szczęsna et al. [2]. The characterization of bioclimatic conditions was performed with a uniform method for all 43 health resorts. According to the administrative report from 2002, in Dolnośląskie voivodship (a bigger administrative area in which Kłodzko region is located), 11 health resort statuses were granted at that time, 5 of which were situated in the Kłodzko region. These were Długopole-Zdrój, Duszniki-Zdrój, Polanica-Zdrój, Lądek-Zdrój, and Kudowa-Zdrój [2]. Currently, the health resort status is granted to the area of the district where five cities maintain their health resort status (i.e., Bystrzyca Kłodzka, Duszniki-Zdrój, Polanica-Zdrój, Lądek-Zdrój, and Kudowa-Zdrój).

Currently the only synoptic station in the Kłodzko region is Kłodzko. Two climate stations in Słoszów and Lądek-Zdrój were decommissioned in 2006, while the station in Długopole-Zdrój was decommissioned in 2014 (Figure 1). Monitoring environmental changes is not only important for maintaining the tourism potential of the region [23], but also to plan further actions for the increasing effects of climate change [24,25]. The causes of change are due to both human activities and greenhouse gas emissions [26] as well as macrocirculation phenomena such as the North Atlantic oscillation (NAO), Atlantic multidecadal oscillation (AMO), Arctic oscillation (AO), or the Scandinavia SCAND [27–34]. The Kłodzko region, as part of the Sudety massif, is additionally an area in which dynamic meteorological phenomena such as fen activity occur locally, which is typical for mountain areas. Fen phenomena due to their diversity still pose a challenge today in terms of forecasting and modeling [35,36].

This paper focuses on the use of bioclimatic indicators to determine bioclimatic changes in the area of Kłodzko for the period 1966–2020 based on measurement series conducted by the Polish MetOffice (Institute of Meteorology and Water Management—IMGW). The following measurement series were analyzed: 1980–2006 for the climate station in Słoszów and Lądek-Zdrój; 1980–2014 for climate station Długopole-Zdrój; and the synoptic station in Kłodzko (1966–2020). Bioclimatic conditions of the Kłodzko region were determined using the Universal Thermal Climate Index (UTCI). The UTCI index was selected based on a recommendation of the World Meteorological Organization (WMO), which was promoted during the meeting in April 2009 [37]. For more than 10 years this index has been tested by scientists from Poland and abroad confirming its applicability for different climatic conditions [8,38–40].

Air temperature data reconstruction was made via methods for non-stationary time series. Typical dynamics of climatic data at all scales and over the period of available measurements is considered as evidence of changes occurring in the Anthropocene [41]. This includes the long-term trend component, which in this paper is considered as a deterministic factor [28,30,42]. Additionally, climatic data can be decomposed by separating the (almost deterministic) seasonal and the stochastic components [43]. Stochastic-deterministic models constitute a good compromise between full deterministic precise but very time consuming modeling, and stochastic quick but wide margin of error approach [30,43]. This combination offers an opportunity to model or reconstruct the data to achieve mid-range forecasts. Stochastic modeling often requires large datasets to be performing [43] at time scales where the deterministic approach is not effective [44].

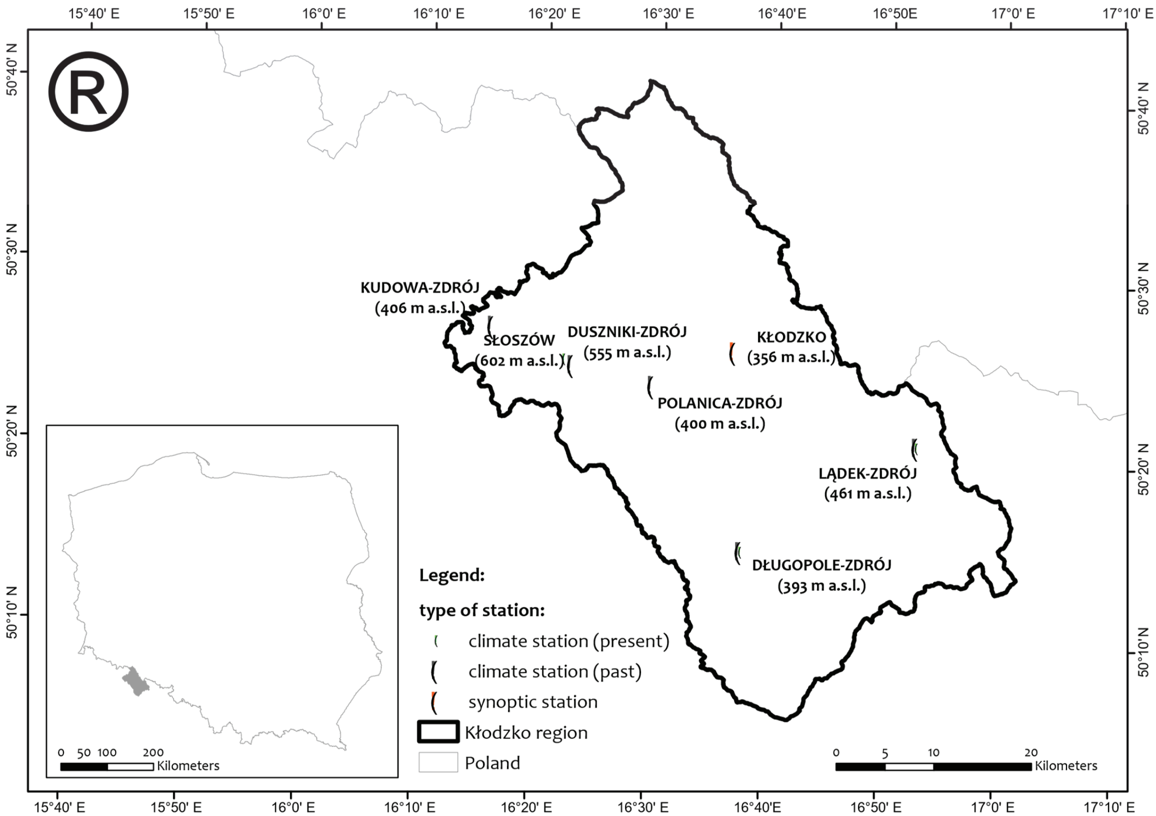


**Figure 1.** Location of synoptic and climate stations from the IMGW repository in the Kłodzko region (SW Poland) along with station heights in meters above sea level.

The novelty of this study is to apply a non-linear deterministic approach in combination with stochastic modelling in order to reconstruct climate change dynamics on the time series measured in the health resort cities of the Kłodzko region. The stochastic-deterministic model that reconstructs the temporal dynamics was developed on the basis of historical data from meteorological stations in Lower Silesia [28,33,45]. Eventually, the paper shows how bioclimatic conditions are affected by meso-tropospheric circulation that occurs in the northern hemisphere, which is in turn affected by climate changes.

The reconstruction results were verified on the basis of meteorological measurements conducted in Słoszów and Długopole-Zdrój over the five years period ranging from April 2017 to March 2022.

## 2. Materials and Methods

The Kłodzko region is located in the southern part of the Lower Silesia voivodship and is limited from the west by the Central Sudetes and from the southeast by the East Sudetes. The altitudinal diversity of the area ranges from 240 m a.s.l. in the northern part to the highest peak in the East Sudety–Śnieżnik mountain 1423 m a.s.l. (Figure 1). All the health resorts were in the VI bioclimatic region ("submontane and mountain") and characterized by a moderately stimulating and periodically strongly stimulating climate, with the exception of the Duszniki-Zdrój municipality which was characterized by a strongly stimulating and periodically moderately stimulating climate [2,46]. The size of the health resorts vary from 568 inhabitants in Długopole-Zdrój, which is the only village in the analyzed area, to almost 10,000 inhabitants in Kudowa-Zdrój.

Data provided by the Institute of Meteorology and Water Management (IMGW) cover the period 1980 to June 2014 for the Długopole-Zdrój station and the period 1980–2006 for Słoszów and Lądek-Zdrój stations. These stations have the status of climatic stations. Stations such as Kudowa-Zdrój or Polanica-Zdrój do not have archival data in the IMGW repository. The synoptic station in Kłodzko has complete meteorological records for the years 1966–2020. Access to the data was obtained using the climate tool of the R software environment [47,48]. Meteorological stations in health resort districts have the status of climate stations and measure wind speed and direction, air temperature, cloud cover, humidity, and precipitation. The synoptic station in Kłodzko meets WMO standards [49] and can be treated as a reference station for the whole region in the context of multiannual changes in the bioclimate of Kłodzko Land [45]. From April 2017 to March 2022, the author additionally conducted temperature and humidity measurements using HOBO U23 sensors. Data from 12 GMT were used to determine the bioclimatological conditions [50].

### 2.1. Bioclimatic Indexes

Indices such as UTCI require calculation of the components of the heat balance equation. The general human heat balance equation reads as follows:

$$M + Q + C + E + Res + Kd = S \quad (1)$$

where: $M$ is metabolic heat production (both during rest and physical activity), $Q$ is human absorbed solar radiation, $C$ is turbulent sensible heat transfer (convection), $E$ is turbulent latent heat transfer through evaporation (evaporation), $Res$ is heat loss due to respiration, $S$ is heat transfer balance. All heat fluxes are expressed in W·m$^{-2}$. Heat conductivity ($Kd$) with the ground is not included in the model due to negligible values. Components of heat balance between humans and the environment were determined according to equations described in MENEX [51]. Due to the application character of this work, the equations of human heat balance components will not be described in detail. Detailed descriptions can be found in the work of Błażejczyk [51].

### 2.2. Universal Thermal Climate Index (UTCI)

The UTCI is a function of air temperature $T_a$ (°C), wind speed $v$ (m·s$^{-1}$), water vapor pressure $e$ (hPa), and mean radiant temperature $T_{mrt}$ (°C) [52]:

$$UTCI = f(T_a, v, e, T_{mrt}) \quad (2)$$

The mean radiant temperature was also calculated using Bioklima 2.6 software [53] as in the following formula:

$$T_{mrt} = \left( \frac{\frac{R}{Irc} + 0.5L_g + 0.5\ L_a}{sh \cdot \sigma} \right)^{0.25} - 273 \quad (3)$$

where $R$ is the absorbed solar radiation by the human body (W·m$^{-2}$), $Irc$ is the coefficient reducing convective and radiative heat transfer through clothing, $L_g$ is the ground radiation (W·m$^{-2}$), $L_a$ is the atmosphere's back radiation (W·m$^{-2}$), $sh$ is the emissivity coefficient for humans (0.95), and $\sigma$ is the Stefan–Boltzmann constant (5.667·10$^{-8}$ W·m$^{-2}$·K$^{-4}$). The absorbed solar radiation ($R$) was calculated using the SolAlt model based on cloudiness ($n$ [%]) and position of the sun ($hSl$ [°]). The detailed formulas have been reported by Błażejczyk [51].

The scale of thermal stress was taken from the physiological model and is presented in Table 1. The range of limiting conditions in order for UTCI to be applicable is as follows: wind speed between 0.5 and 20 m·s$^{-1}$ [39], air temperature from −50 to 50 °C, mean radiant temperature and air temperature difference ($T_{mrt}-T_a$) should be from −30 to 70 °C, and relative humidity needs to be higher than 5% [54]. In the analysis presented here, only wind speeds that exceeded assumptions are presented above. There were 3261 observations in which the wind speed did not exceed 0.5 m·s$^{-1}$ (6%). For these values, measurements were set to the lower limiting condition of 0.5 m·s$^{-1}$ [39]. For other limiting conditions such as high wind speed, air temperature limits, and differences between mean radiant temperature and air temperature ($T_{mrt} - T_a$), no values exceeded the assumptions.

**Table 1.** Assessment scale of UTCI [20].

| UTCI (°C) | Heat Stress Classes |
|---|---|
| UTCI > 46 | Extreme heat stress |
| 38.1 < UTCI < 46 | Very strong heat stress |
| 32.1 < UTCI < 38 | Strong heat stress |
| 26.1 < UTCI < 32 | Moderate heat stress |
| 9.1 < UTCI < 26 | No thermal stress |
| 0.1 < UTCI < 9 | Slight cold stress |
| −12.9 < UTCI < 0 | Moderate cold stress |
| −26.9 < UTCI < −13.0 | Strong cold stress |
| −39.9 < UTCI < −27.0 | Very strong cold stress |
| UTCI ≤ −40 | Extreme cold stress |

### *2.3. Nonlinear Reconstruction of Historical Time Series and Validation with Current Meteorological Measurements*

Reconstruction of the missing air temperature data for Słoszów and Długopole-Zdrój, where additional air temperature measurements were conducted, was based on the previous work performed in the Lower Silesia region [28,45]. In general, time series $x(t)$ can be described as follows:

$$x(t) = x_s(t) + x_f(t) \tag{4}$$

where $x_s(t)$ is the long-term trend (slow component), whereas the fast component, $x_f(t)$, may contain yearly seasonal variability, $x_{f_s}(t)$ *and* correlated noise fluctuations $x_{f_c}(t)$, so that the original data can be further described as:

$$x(t) = x_s(t) + x_f(t) = x_s(t) + x_{f_s}(t) + x_{f_c}(t) \tag{5}$$

The seasonal variability $x_{f_s}(t)$ can be very well described by monthly average multi-year values and in order to determine the monthly fluctuations $x_{f_c}(t)$, it has to be decomposed from the original time series along with the long-term trend. After standardization the correlated monthly fluctuations of $x_{f_c}(t)$ can be obtained using linear stochastic models, e.g., autoregressive AR(p) [43,45,55]:

$$x_{f_c}(t) = \sum_{j=1}^{p} \phi_j \left( x_{f_c}(t-j) - \mu \right) + \varepsilon_t \tag{6}$$

with $p$ being the autoregressive parameters ϕ(1), … ϕ($p$), while the noise $\varepsilon_t$ is an uncorrelated Gaussian process with zero mean and unit variance [55].

The multi-year trend of $x_s(t)$ using a 3-dimensional autonomous system of ordinary differential equations (ODEs) based on 117 years of data for Wroclaw (1891–2007) has been presented in previous papers by Bryś and Bryś [56,57] and Głogowski et al. [28]. The autonomous system of differential equations (Equation (7)) used in the work of Głogowski et al. [28] was used to perform a nonlinear time series reconstruction to fill in the missing measurement history for the health resorts and the model coefficients are presented in Table 2:

$$\begin{cases} \dot{x} = c_{1,1} + c_{1,2}x + c_{1,3}y + c_{1,4}z + \ldots + c_{1,10}z^3 \\ \dot{y} = c_{2,1} + c_{2,2}x + c_{2,3}y + c_{2,4}z + \ldots + c_{2,10}z^3 \\ \dot{z} = c_{3,1} + c_{3,2}x + c_{3,3}y + c_{3,4}z + \ldots + c_{3,10}z^3 \end{cases} \tag{7}$$

Validation of the time series reconstruction was performed on the basis of HOBO U23 sensor measurements from 2017 to 2022. Reconstruction of air temperature trend for these stations was performed on the basis of column $\dot{x}$, whose coefficients fill the equation $\dot{x}$ that corresponds to air temperature.

**Table 2.** Coefficients of a 3-dimensional autonomous system of ordinary differential equations (ODEs).

| | x (1) | y (2) | z (3) |
|---|---|---|---|
| c1 | −62.579494850917 | −4.486403039801 | 0.477293701549 |
| c2 | 0.4331222988862 | −0.033412364441 | 0.002145656022 |
| c3 | −0.2237615300582 | −0.100186141212 | 0.023175707507 |
| c4 | 8.5159117999514 | 2.161665825319 | −0.264916946833 |
| c5 | $6.1482989371 \times 10^{-6}$ | $4.680494293 \times 10^{-6}$ | $8.651454913 \times 10^{-8}$ |
| c6 | −0.0441722346235 | 0.005695657529 | −0.000427317332 |
| c7 | −0.0075634983308 | 0.019210919277 | 0.000941485688 |
| c8 | −0.0001590541067 | $-6.605875852 \times 10^{-5}$ | $6.194962197 \times 10^{-6}$ |
| c9 | 0.0033515051403 | −0.000693175621 | −0.000325469465 |
| c10 | −0.1197790303992 | −0.223554032039 | 0.015477710082 |

## 3. Results and Discussion

### *3.1. Annual and Seasonal Variability of Bioclimatic Indicators in Health Resorts of the Kłodzko Region*

On the basis of available meteorological data for all 4 analyzed stations (1980–2006), we can observe differences in bioclimatic conditions based on UTCI thermal classes (Figure 2). All stations are located within 20 km distance from Kłodzko in a straight line, while differences in altitude above sea level between the stations do not exceed 200 m (Kłodzko—356 m a.s.l., Długopole-Zdrój—398 m a.s.l., Słoszów—602 m a.s.l., and Lądek-Zdrój—461 m a.s.l.). Topoclimatic conditions are crucial for differences in bioclimatic conditions that occur in the region [2,23]. As part of Sudety Massif the region is associated with relatively frequent occurrence of foehn or foehn-like phenomena [36,58]. Due to denivelation as well as the diversity of land use, the area is prone to local convections and local wind circulation conditioned by orography, which is clearly visible in local variability of frequencies of particular thermal classes despite small distances between the examined stations.

Analyzing the annual variability of thermal classes (Figure 2), "Extreme cold stress" occurred with a frequency of 1.2% in Długopole-Zdrój and less than 0.4% in Kłodzko, Słoszow and Lądek-Zdrój; "Very strong cold stress" occurred with a frequency of 4.4% in Długopole-Zdrój, 3.2% Kłodzko, 2.4% Słoszów, and 2% Lądek-Zdrój; "Strong cold stress" occurred with a frequency of 11.2% in Długopole-Zdrój, 12.8% Kłodzko, 8.8% Słoszów, and 12.4% Lądek-Zdrój; "Moderate cold stress" occurred with a frequency of 21.2% in Długopole-Zdrój, 21.2% Kłodzko, 25.2% Słoszów, and 22.4% Lądek-Zdrój; "Slight cold stress" occurred with a frequency of 18% in Długopole-Zdrój, 18.4% Kłodzko, 19.2% Słoszów, and 20.4% Lądek-Zdrój; "No thermal stress" occurred with a frequency of 36% in Długopole-Zdrój, 36% Kłodzko, 34% Słoszów, and 40% Lądek-Zdrój; "Moderate heat stress" occurred with a frequency of 6% in Długopole-Zdrój, 6% Kłodzko, 4% Słoszów, and 8% Ladek-Zdrój; "Strong heat stress" occurred with a frequency of 1.6% in Długopole-Zdrój, 1% Kłodzko, 1% Słoszów, and 0.8% Lądek-Zdrój; "Very strong heat stress" occurred 6 times in Długopole-Zdrój, 1 time in Kłodzko, 3 times in both Słoszów and Lądek-Zdrój (Figure 2). The results are similar to those in studies by others conducting research in Poland [5,16,33,45,58–63].

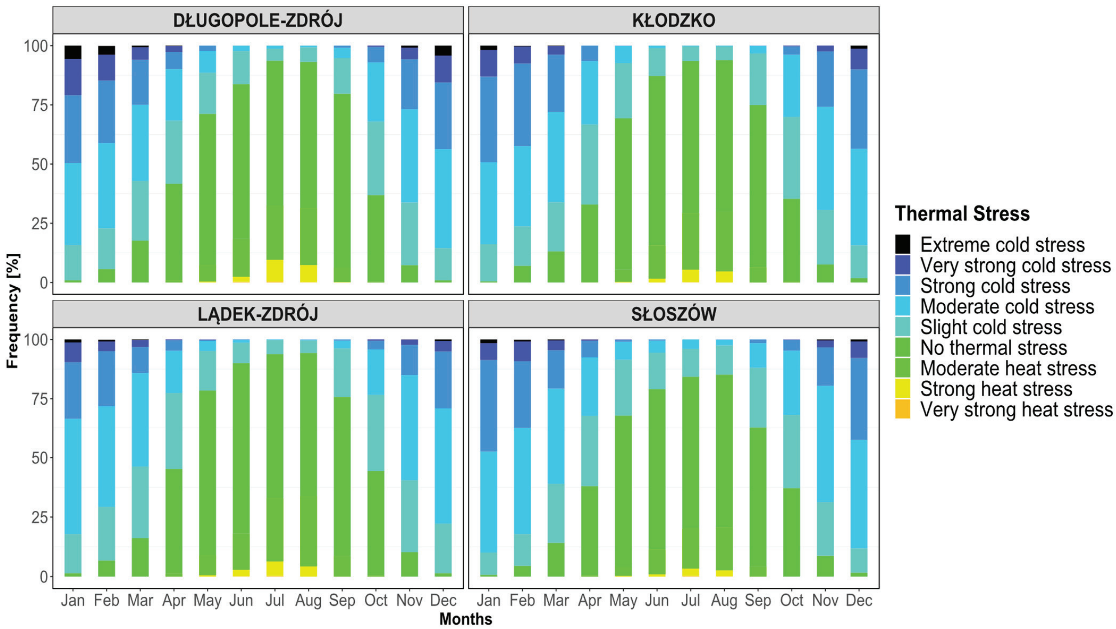


**Figure 2.** Occurrence of UTCI thermal stress for the period 1980–2006 in the Kłodzko region.

The station characterized by colder thermal conditions is Słoszów, where thermal classes connected to cold occurred 5–10% more often than in the other three stations. The station Długopole-Zdrój experienced "Extreme cold stress" (33 times in December, 44 in January, 27 in February, and 6 in March—a total of 110). For comparison, in winter (DJFM) in Kłodzko classes characterized by "Extreme cold stress" were 29, in Słoszów 30, and in Lądek-Zdrój 23. The situation is similar for extreme heat classes. In the period 1980–2006, "Extreme heat stress" was never recorded; however, the next extreme thermal class "Very strong heat stress" occurred 6 times in Dlugopole-Zdrój during summer (JJAS), in Kłodzko 1 time, and in Lądek-Zdrój and Słoszów 3 times. "Strong heat stress" occurred in Długopole-Zdrój 144 times, while in Kłodzko 89 times, in Słoszów 50 times, and in Lądek-Zdrój 90 times. The frequency of occurrence of thermal classes for the period 1980–2006 shows that the most comparable bioclimatic conditions according to UTCI occur in Kłodzko and Lądek-Zdrój. Długopole-Zdrój is characterized by the most frequent occurrence of extreme thermal classes, while Słoszów is clearly cooler than the other three meteorological stations.

Annual courses of minimum, mean, and maximum values reflect thermal variability typical for the transitional climate of Poland (Figure 3). The minimum UTCI values in the Kłodzko region in 1980–2006 were as follows: −61.8 °C for Długopole-Zdrój in January, −55.4 °C for Słoszów in December, −52.9 °C for Lądek-Zdrój in December, and −49.5 °C for Kłodzko in December. The maximum UTCI values were 40.7 °C for Długopole-Zdrój in June, 40.4 °C for Słoszów in July, 39.4 °C for Lądek-Zdrój in July, and 38.3 °C for Kłodzko in July (Figure 3).

High standard deviations for individual months are also typical of UTCI variability (Table 3). The reason for such high variability is the sensitivity of UTCI to different meteorological components such as wind speed or air humidity. In January where the minimum UTCI value in Długopole-Zdrój was −61.8 °C, the maximum UTCI value was 12.9 °C which gives a difference of 74.7 °C. UTCI value of −61.8 °C occurred on January 15, 1987 at air temperature of 15.3 °C, relative humidity 82%, wind speed 12 m·s$^{-1}$, and full cloud cover, while a UTCI value of 12.9 °C occurred at air temperature of 11.1 °C, humidity 78%, wind speed 2 m·s$^{-1}$, and no cloud cover. The annual mean values along with maximum and minimum values correspond to the results of other bioclimatic analyses conducted in Poland [5,16,59,64].

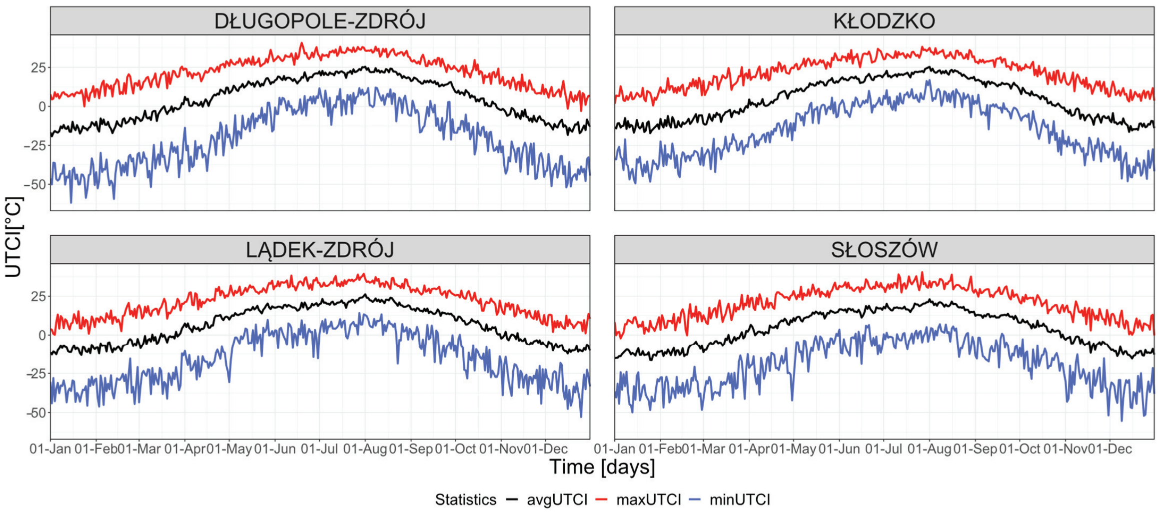


**Figure 3.** Annual courses of minimal, average, and maximal UTCI values for multi-annual period 1980–2006 in the Kłodzko region.

**Table 3.** Mean monthly values and their standard deviations (sd) for meteorological stations in the Kłodzko region in period 1980–2006.

| Station | | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Długopole-Zdrój | Mean | −14.4 | −11.0 | −3.7 | 4.8 | 13.7 | 18.2 | 21.9 | 21.8 | 15.2 | 4.7 | −5.8 | −12.9 |
| | sd | 14.5 | 14.4 | 13.5 | 12.9 | 10.3 | 8.4 | 7.9 | 7.8 | 8.5 | 10.8 | 12.1 | 13.1 |
| Kłodzko | Mean | −12.9 | −12.9 | −9.8 | −5.2 | 4.3 | 13.6 | 18.0 | 21.1 | 21.3 | 14.6 | 5.0 | −6.0 |
| | sd | 12.0 | 12.1 | 11.7 | 10.5 | 8.6 | 7.7 | 7.5 | 7.3 | 7.8 | 9.7 | 10.5 | 11.7 |
| Lądek-Zdrój | Mean | −9.9 | −7.5 | −2.0 | 7.3 | 15.6 | 18.4 | 21.4 | 21.5 | 14.9 | 6.6 | −3.1 | −8.8 |
| | sd | 11.0 | 11.4 | 11.3 | 10.7 | 8.6 | 8.1 | 7.6 | 7.6 | 8.2 | 10.0 | 10.0 | 10.3 |
| Słoszów | Mean | −12.7 | −12.7 | −10.1 | −3.9 | 5.0 | 12.8 | 15.9 | 18.1 | 18.7 | 12.1 | 4.9 | −5.0 |
| | sd | 10.4 | 11.2 | 11.9 | 11.0 | 8.8 | 9.0 | 9.0 | 8.5 | 9.5 | 9.9 | 10.6 | 10.7 |

### *3.2. Influence of Meso-Tropospheric Circulation on Changes in Bioclimatic Conditions*

The analysis of the significance of changes in bioclimatic conditions was based on meso-tropospheric circulation epochs according to Degirmendžić and Kożuchowski [65]. Previous analyses [28,33] of bioclimate variability in the region showed a considerable influence of macrocirculatory phenomena such as North Atlantic oscillation (NAO) or Atlantic multiannual oscillation (AMO) on basic meteorological parameters and UTCI index. The reconstruction of a 180-year sequence of meteorological measurements of temperature, precipitation, and insolation for Wroclaw based on an autonomous system of ordinary differential equations [30,42,66] showed a dynamical behavior sharing the AMO periodicity [67]. Based on a previous study, the analyzed bioclimatic conditions were therefore divided according to the epochs of the meso-tropospheric circulation macrotypes E (1964–1988) and W (1989–2022) [29,34,65,68,69]. The boundaries of these epochs are consistent with the phase boundaries of the North Atlantic thermohaline circulation (NA TCH) [34,70]. Comparing the UTCI values by circulation epochs E (before 1988) and W (after 1988) accordingly to two comparative division variants of years: (a) 1966–1988; 1989–2011 for Kłodzko as a reference station (Figure 4), (b) 1980–1988; 1989–1997 for all analyzed stations (Figure 5). In both situations the higher UTCI values were observed in the W circulation phase in relation to E at all four stations.

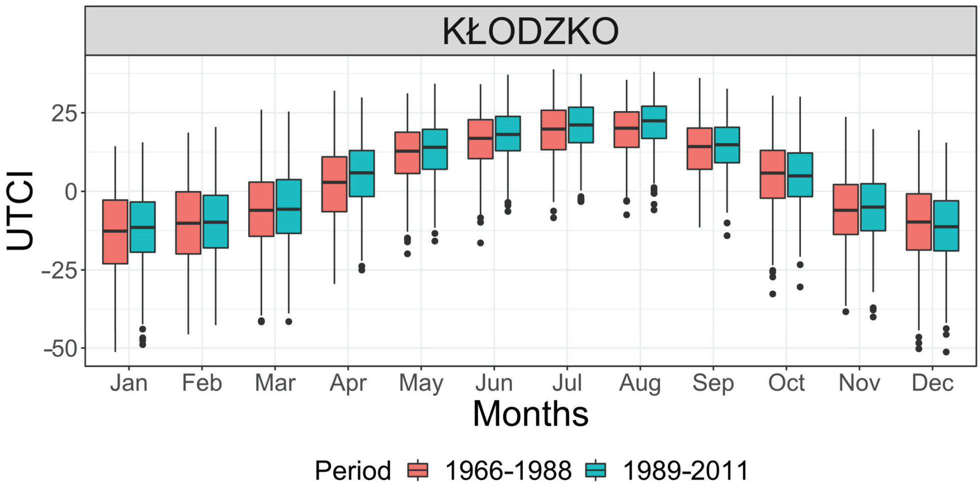


**Figure 4.** Boxplots of bioclimatic conditions in Kłodzko with division into E (1966–1988) and W (1989–2011) circulation epochs. Black dots represent statistically outstanding values.

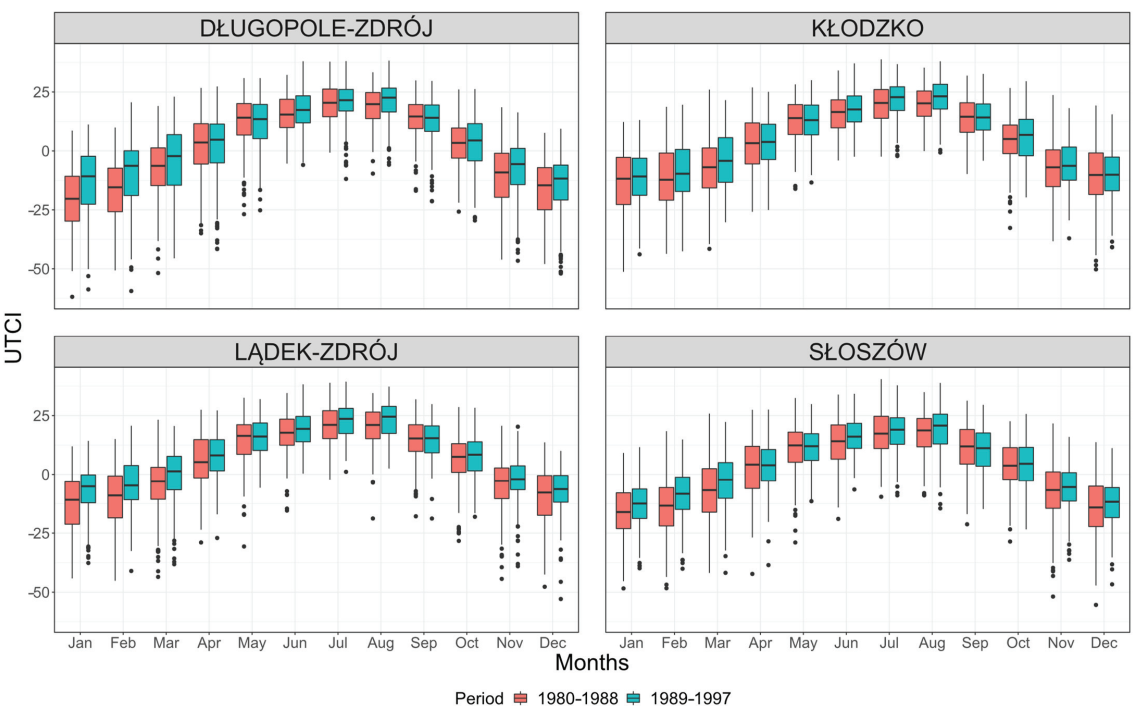


**Figure 5.** Boxplots of bioclimatic conditions in all four stations with division into E (1980–1988) and W (1989–1997) circulation epochs. Black dots represent statistically outstanding values.

The main factor that determines UTCI values is air temperature ($T_a$), but it should be borne in mind that wind speed ($v$), water vapor pressure ($e$), or mean solar radiation

($T_{mrt}$) also have an impact on UTCI. In the study by Głogowski et al. [33] for Kłodzko, a bioclimatic analysis as well as an analysis of individual meteorological parameters in terms of NAO was performed. Each of the analyzed elements showed a different correlation with respect to NAO phases; for example, cloudiness ($n$), which is a component of mean solar radiation ($T_{mrt}$) [33], showed an inverse correlation with NAO.

The influence of meso-troposphere E and W circulation epochs on bioclimate of the Kłodzko region was determined on the basis of differences between those epochs in mean air temperatures (Figure 6) and UTCI index (Figure 7) for period 1980–1997. Additionally, for the periods determined, a 30-day moving average was calculated (Figures 6 and 7 red dashed line). We can observe that air temperature is higher in the W epoch on average from 0.5 °C to even 5 °C throughout the year for all analyzed stations (Figure 6). In the case of the UTCI index, this dependence is visible in three out of the four analyzed stations (Figure 7).

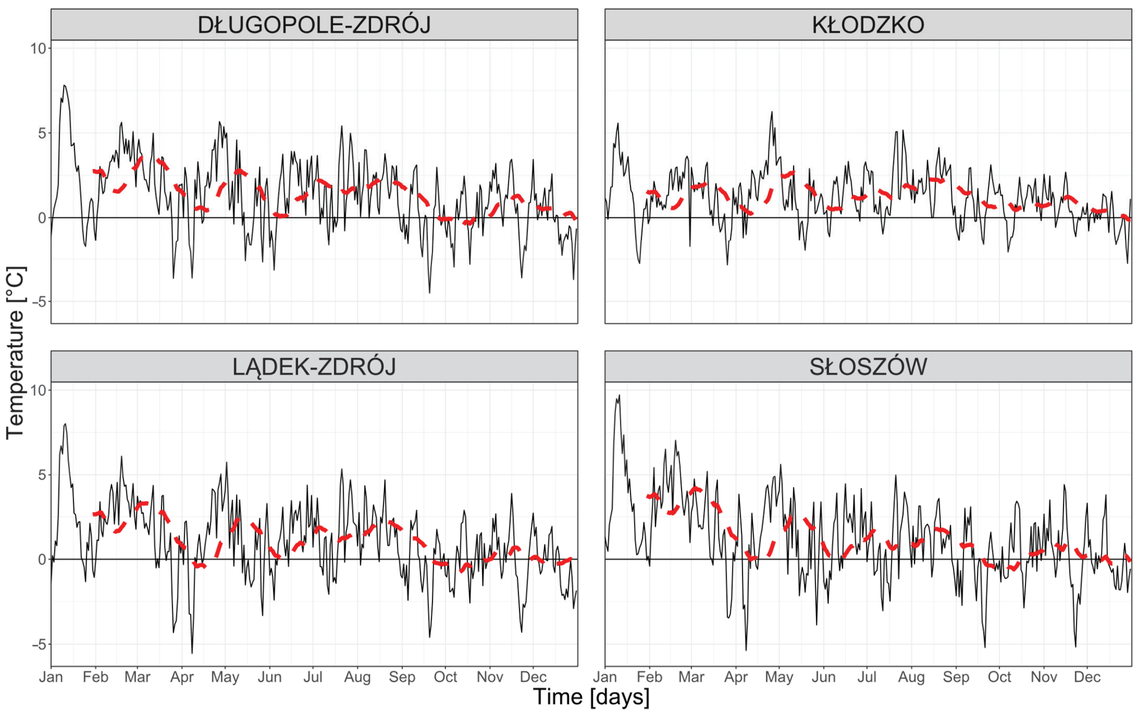


**Figure 6.** Differences in mean annual air temperature courses between W and E (W–E) circulation epochs in the Kłodzko region in years 1980–1997. The red dashed line indicates 30-day moving average.

In Kłodzko, UTCI differences between circulation epochs are less visible in a period January–March than in other stations. The lowest situated station is Kłodzko (Figure 1) whose local climate is influenced by evaporation of the Nysa Kłodzka River and its several tributaries located on the outskirts of the town. The city is surrounded by Bardzkie Mountains, but the meteorological station is located on their distant plain foreground. This favors both the catabatic inflow of cold air and the formation of cold stagnation and radiation fogs, as well as their longer persistence during the day. As a result, Kłodzko is characterized by higher relative humidity than the other stations studied, which is also evident in the water vapor pressure [71]. Hygric differences between epochs W and E are small in Kłodzko in contrast to the other stations. These stations are not connected with hydrographic nodes and their topoclimate features are shaped by higher altitude, different exposure, local wind circulation determined by their mid-mountain and forest surroundings. Słoszów situated on the Lewińskie Hills is surrounded by the Stołowe Mountains to the north and the Orlickie Mountains to the south, Długopole-Zdrój—the Bystrzyckie Mountains to the southwest, Lądek-Zdrój—the Złote Mountains to the north and east, the Śnieżnik Massif to the south, and the Krowiarki Mountains to the west, which are the northern extension of the massif. Terrain evaporation in the vicinity of these stations is related to the availability of water in the soil, i.e., precipitation and duration of snow cover, which change in the subsequent periods of circulation. In consequence, the role of evaporation in the surroundings is weaker than in Kłodzko. Therefore, the bioclimate of these stations is more sensitive, especially in winter, to the variability of circulation epochs in comparison to Kłodzko.

Due to the fact that the Kłodzko land contained valued health resorts, the observed bioclimatic differences are an important argument for further conducting meteorological measurements there in order to trace changes impossible to capture by a single synoptic station in such a naturally diversified region of Sudety.

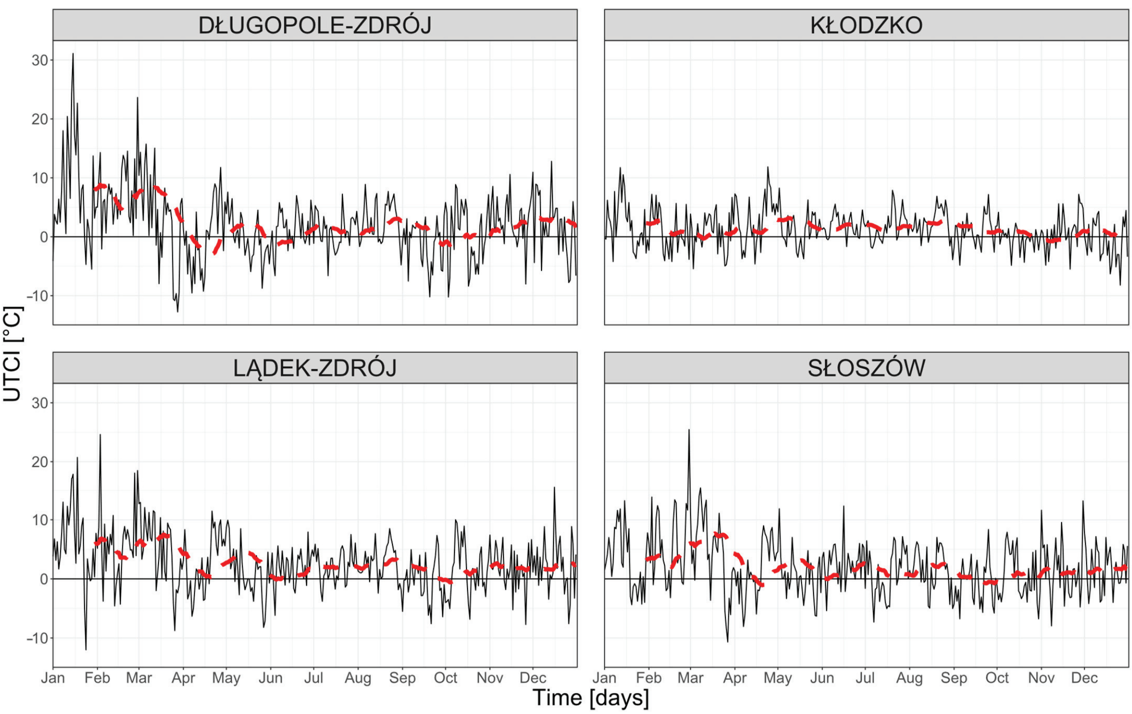


**Figure 7.** Differences in mean annual UTCI runs between the W and E (W–E) circulation epochs in the Kłodzko region in years 1980–1997. Red dashed line indicates 30-day moving average.

### 3.3. Reconstruction and Verification of Air Temperature in Słoszów and Długopole-Zdrój

The bioclimate of the Kłodzko region for the stations Słoszów, Długopole-Zdrój, and Lądek-Zdrój was previously analyzed for heat waves [60]. The linear increase in days considered as heat waves (Tair > 30 °C) as well as the increase in days with the thermal class "Very strong heat stress" (UTCI > 32 °C) for the multi-year period 1971–2010 and in the same multi-year period with atmospheric circulation according to Ojrzyńska [32] was presented. In that study, Miszuk [60] showed that the number of heat wave days for both air temperature (Tair > 30 °C) and UTCI (UTCI > 32 °C) is not increasing in a linear manner, but it is a dynamic variability with a positive trend over time. An attempt was made to map the non-linear variability of the long-term trend in air temperature over time for the analyzed stations with reference to the author's earlier work [28], in which a non-linear model based on a system of differential equations was made on the basis of almost 120 years of observations of air temperature, precipitation, and insolation in Wrocław. This model further correlated well with the AMO [67].

The $T_a$ time series generated by the model with parameters based on Table 2 was fitted to the respective stations of Długopole-Zdrój, Lądek-Zdrój, Słoszów, and Kłodzko by rescaling the initial condition of the model from dependence on the difference in altitude between the stations (100 m a.s.l. = +1 °C).

Figure 8 shows the 10-year moving average of air temperature, matched with the long-term trend of air temperature generated prior to the model from Table 2 [28]. The analysis of the residuals shows that the mean square error is respectively 0.25, 0.22, 0.27, and 0.23 for Długopole-Zdrój, Kłodzko, Lądek-Zdrój, and Słoszów. With such a performant fit, it was decided to reconstruct the data for Długopole-Zdrój and Słoszów, while comparing them with the author's measurements collected using the Hobo-U23 sensor during the course of the study from April 2017 to March 2022. Although the model performed well in reproducing the measured data set, an increase of air temperature of about 1 °C was also observed. Oscillation caused by the AMO or NAO phenomena were likely triggered by past stress on the global climate caused by severe anthropic activities [24]. Those changes may be related both to regional increase of urbanization [72] and gas emissions [26,73] but also by global stressors, which are also responsible for the rising temperature of the oceans [74]. Such variability of air temperature for now is not above the accepted level of adaptation for humans but may change diversity of different species [75]. Increased air temperature by 1 °C also corresponds to the analysis by IPCC [25].

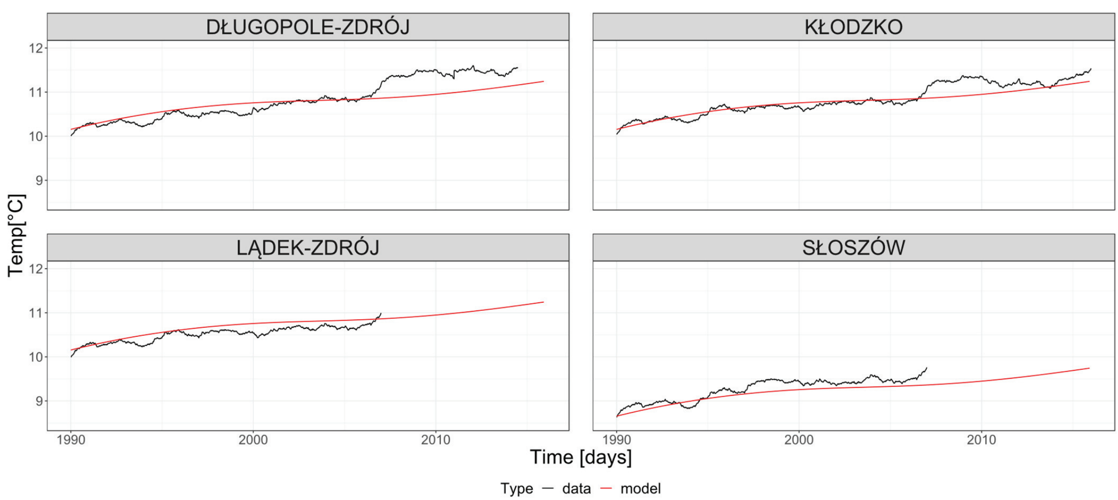


**Figure 8.** Reconstructed long-term trend (red line) with comparison of 10-year moving average (black line) for four climate stations: 16 years for Lądek-Zdrój and Słoszów stations (1990–2006), 24 years for Klodzko and Długopole-Zdrój stations (1990–2014).

Data reconstructions were performed on the basis of three components: (1) non-linear long-term trend [28], (2) correlated fluctuations generated from the stochastic autoregression model [43] with parameter $p = 1$; AR(1) [45], and (3) seasonal variability as monthly mean values and the corresponding standard deviation. Components 1 and 2 were generated with a daily interval, while component 3 was aggregated according to respective months.

In accordance with the 3-σ law [76], the reconstructed data are within the interval defined by one standard deviation (σ-1) from the 30-day moving average of air temperature between autumn and winter (Figure 9). This means that the reconstructed data in Słoszów correctly represents the air temperature in relation to the measured data by about 67% or higher. The model overestimates values in the summer period for Słoszów. In Długopole-Zdrój, the model represents the values of air temperature in the period from spring to autumn with similar efficiency but overestimates the values in winter. These differences can be caused by topoclimatic conditions. The stations are located not only in different mountain massifs, but are also characterized by different exposures. For example, Słoszów, has an eastern exposure, while Długopole-Zdrój has northern exposure. Topoclimatic differences cause, for example, changes in the local direction and speed of the wind which explain the differences in UTCI between the stations studied.

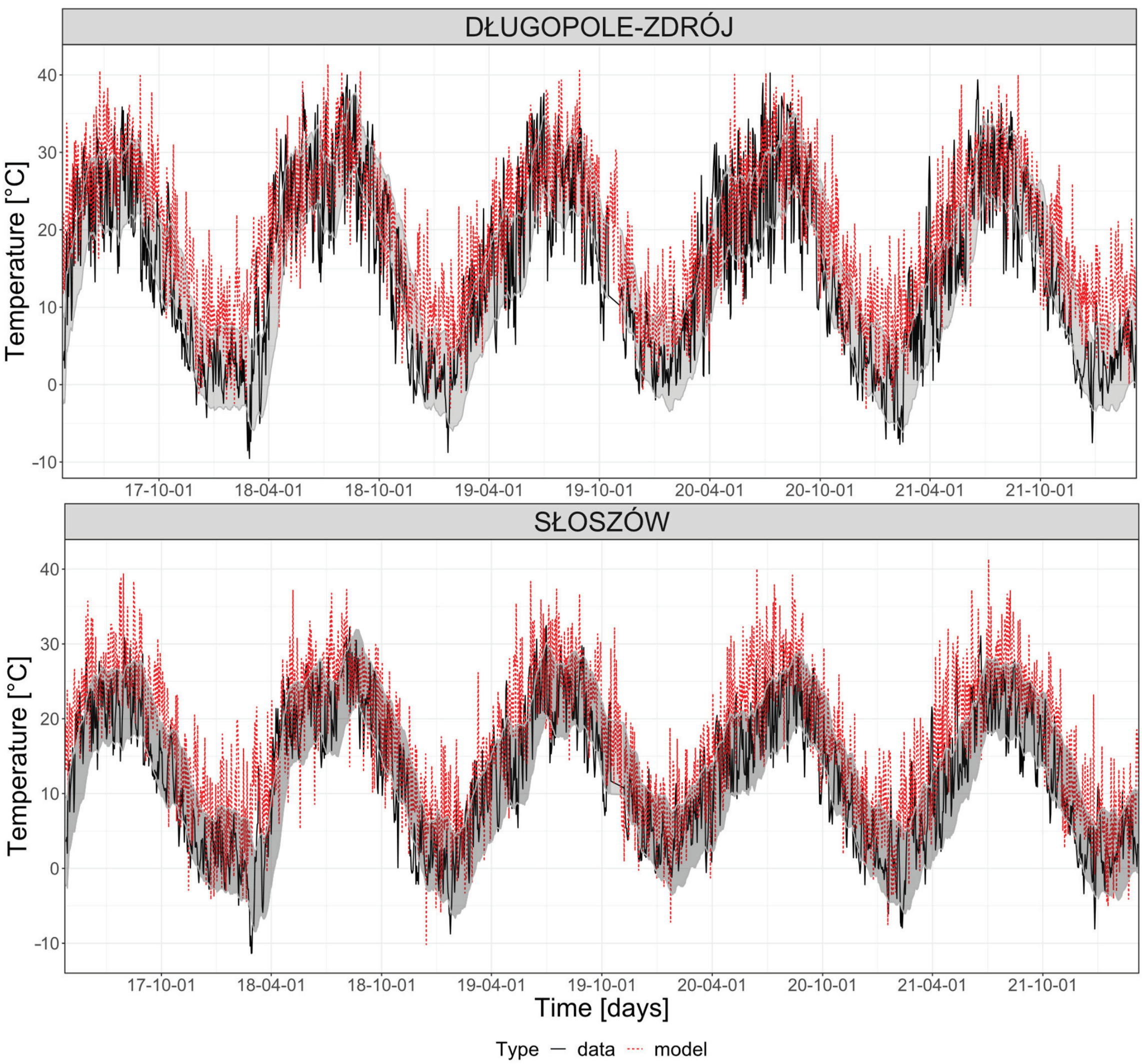


**Figure 9.** Reconstruction of air temperature (red dashed line) together with verification of own meteorological data (black line) made with HOBO-23U logger for two stations (Długopole-Zdrój and Słoszów) in the period April 2017 to March 2022. The grey box on the graph marks the sigma-1 area from the 30-day moving average air temperature.

Further monitoring of meteorological parameters such as wind speed and direction as well as air humidity will allow for a more precise estimation of changes both in the context of climate analysis and reconstruction, as well for short- and mid-term forecasting. Currently, despite the widespread use of climate models and reanalyses, the effectiveness of forecasts in places with different topoclimatic conditions is characterized by a much lower predictability.

In the long term, the reconstruction efficiency is sufficient and, despite dynamic climate changes in recent years, it is still able to reproduce the measured air temperature. The presented model has application potential for any location in the region that does not have a documented measurement history of meteorological conditions. Further research to determine the influence of macrocirculatory phenomena such as NAO and AMO on bioclimate may allow the described model to be used more universally for other locations where the influence of macrocirculatory phenomena is evident on a long-term basis. The model can also be used to reconstruct the meteorological data in Central Europe. Because the AMO oscillation also affects North America, the application of the model can be extended previa correcting the estimation parameters. Further investigation may also lead to extend its applicability not only to meteorological parameters but also to model bioclimatic conditions.

## 4. Conclusions

Bioclimatic analyses were performed for four localities of the Kłodzko region in the years 1980–2006 for Słoszów and Lądek-Zdrój, 1980–2014 for Długopole-Zdrój, and 1966–2020 for Kłodzko.based on data provided by the IMGW repository. Air temperature reconstruction dynamics were also performed on measurements done with HOBO-U23 loggers in Słoszów and Długopole-Zdrój during the five-year period (2017–2022). With the exception of Kłodzko, these localities are located in health resort districts where further meteorological measurements were discontinuous. The UTCI index was used to determine the bioclimate. Kłodzko was analyzed because it is the only synoptic station which serves as a reference point. It was shown that, in the Kłodzko region, despite its diversified topoclimatic conditions, the influence of macrocirculation phenomena plays a major role from a long-term perspective. The bioclimatic conditions in the multi-year period did not show anomalies both in terms of the occurrence of thermal stress classes and annual runs. The bioclimatic conditions were evaluated according to the cyclonic epochs of two periods: E (1980–1988) and W (1989–2006). It was shown that epoch W is characterized by a warmer air temperature in all analyzed stations, while bioclimatic conditions were higher in Długopole-Zdrój, Słoszów, and Lądek-Zdrój. Kłodzko shows almost identical conditions in both epochs, which may be caused by the available longer time-series. In addition, these differences may be caused by topoclimatic conditions and the lack of a mountain massif in close proximity compared to other stations.

In the next part of the study, an attempt was made to reconstruct air temperature as the main factor for determining the stimulus of most bioclimatic indices. It was shown that the model presented for Wrocław on the basis of data for 1891–2007 [28] built on a system of differential equations can be applied in the Kłodzko region after adjusting differences in altitude above sea level between Wrocław and the analyzed stations. The model of multiyear trend very accurately approximates the non-linear climate variability in a multiyear perspective for each of the four analyzed stations. The mean square error in the period 1990–2006 for Słoszów and Lądek-Zdrój and in the period 1990–2014 for Kłodzko and Długopole-Zdrój for each of the models after fitting ranged from 0.22 to 0.27.

In addition, model verification was performed by reconstruction based on three components: (1) non-linear multi-year trend, (2) correlated fluctuations generated on the basis of the stochastic AR(1) model, and (3) seasonal variability. Components 1 and 2 were generated with a daily interval, while component 3 was aggregated according to respective months. The reconstructed values were compared with the values of air temperature measured with our own HOBO-U23 logger in Słoszów and Długopole-Zdrój during the five-year period (2017–2022). The model correctly represented the air temperature in autumn, winter, and spring (in Słoszów at least 67%). Overestimated values were repeated cyclically every year in the summer period. In Długopole-Zdrój, on the other hand, the model was similarly effective in reproducing the values of air temperature in the period from spring to autumn, but overestimated the values of air temperature in winter. The model shows great potential for replication not only in the region, but also for different locations in Central Europe and after modification also in North America where the Atlantic oscillations are present. Presented analysis is beneficial for places that require meteorological analysis, but lack of continued measurement history is the issue. Since the model shows a high correlation with macrocirculatory phenomena such as NAO and AMO, further research to determine the impact of these phenomena on other locations may well allow the model to be used universally.

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# Research on Green and Low-Carbon Rural Development in China: A Scientometric Analysis Using CiteSpace (1979–2021)

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**Abstract:** Green and low-carbon rural development (GLRD) is becoming an important way to explore sustainable development in rural areas of China. It is significant for the sustainable development of the rural economy and of society to build a rural carbon sink system, advocate low-carbon emissions in rural areas, and promote the development of rural green industries and rural transformation. In this study, the existing knowledge system of GLRD was analyzed using CiteSpace. Keywords related to GLRD and their occurrence frequency were identified using keyword co-occurrence analysis. The knowledge evolution stages of GLRD were explored using citation burst analysis. Thus, the evolution of the research related to GLRD was revealed. The summary of Chinese GLRD-related research literature shows that: (1) according to the CiteSpace analysis, the GLRD research can be divided into three stages: starting, rising, and expanding and deepening; (2) GLRD research has focused on low-carbon development, green development, and then green and low-carbon integrated development, thus forming three major research content systems; (3) GLRD's research content gradually became rich, as over time, the research focus became increasingly prominent and research integration was gradually strengthened; (4) the GLRD literature still has some limitations, e.g., nonunified measurement standards, insufficient research depth and practical significance, and relatively weak innovative policy research; (5) future research should strengthen the scientific evaluation and prediction of rural green and low-carbon functions. The industrial development pathways and regional characteristic modes of GLRD should be further studied. Innovative GLRD policies should be proposed to provide a theoretical basis and decision-making reference for GLRD and construction.

**Keywords:** green and low-carbon; research hotspot; research stage; content system; China; rural area

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## 1. Introduction

With the rapid economic and social development of recent years, energy shortages and environmental degradation are the two major problems for urban and rural development [1,2]. Global warming is an ecological and environmental problem worldwide. Environmental disasters caused by global warming have changed how human society produces, lives, and consumes. It has raised concerns about reducing pollution and resource waste [3,4]. The United Nations Conference on Environment and Development has formulated some international rules for this purpose. The World Commission on Environment and Development (WCED) formally proposed a sustainable development strategy in its report "Our Common Future" published in 1987 [5]. The Rio Declaration of Environment and Development and Agenda 21 were presented at the Conference on Environmental Development in Rio de Janeiro, Brazil in 1992 [6]. The development of green and low-carbon measures has deepened due to continuously improved global carbon emission requirements [7–9]. China has put forward a series of major development strategies as a positive response and made significant contributions to global green energy and low-carbon development [10]. In 2007, China set the goal of 20% energy conservation within five years. In 2020, China proposed the strategic goal of "striving to peak its carbon emissions by 2030 and achieving carbon neutrality by 2060" (i.e., the "dual-carbon" goal).

Studies on "green" and "low carbon" in China have received wide attention worldwide [11,12]. Rural areas are an important global source of greenhouse gas emissions and a huge carbon sink system with significant potential contributions to achieving the "dual-carbon" goal [13]. Therefore, agricultural and rural carbon emissions, carbon sinks, carbon reduction measures, and green development are becoming hot interdisciplinary research issues [14–16]. Particularly, green agriculture, green agricultural development, and low-carbon agriculture are the main research objects [17–19]. Green development evaluation and measurement, carbon emission accounting, and the influence mechanisms of quantitative studies are the mainstream research directions [20–22]. However, most existing research content involves field studies independent of rural "green" or "low carbon" [23]. Integrated research and analysis of green and low-carbon rural development (GLRD) are still lacking.

The GLRD concept is an indispensable part of China's ecological civilization construction. It is one of the basic principles of rural revitalization in the new era [24]. Under the guidance of the "dual-carbon" goal, agricultural and rural development will certainly face new requirements and challenges. Green and low-carbon transformation is an important topic for future rural development. The GLRD literature is comprehensive and interdisciplinary. Thus, it is expected to become a new field of interdisciplinary attention in agricultural economics, rural geography, ecology and environment science, and ecological economics.

Citespace is mainly used to identify and demonstrate new situations and trends in scientific literature. It is a diversified, dynamic and practical software for visual analysis. Citespace can identify research progress, frontiers, and corresponding knowledge bases in a certain disciplinary field and facilitate reflection of the overall situation of this field [25]. In this study, a bibliometric analysis was conducted using CiteSpace combined with qualitative research to achieve a systematic review of the GLRD research literature during 1979–2021. This study included the following objectives: (1) to explain the emergence and occurrence of GLRD research keywords; (2) to divide research stages systematically; (3) to sort out the research content system; (4) to determine research trends. This study is intended to provide a reference for better determining research directions and concise research issues. The research findings can also provide a theoretical basis and decision-making reference for future GLRD and construction in China.

## 2. Materials and Methods

### 2.1. Research Methods

CiteSpace has obvious advantages in sorting out relevant research topics, research backgrounds, evolution processes, and other aspects [26]. This study used CiteSpace 5.8 according to the following process: keywords; professional terms; data collection; extraction of research frontier terms; time zone segmentation; threshold selection; visual display; visual editing; detection application. This study focused on the GLRD issues in China and can improve the objectivity of related research progress reviews [26].

### 2.2. Data Source

First, as the most important Chinese academic database in China, China National Knowledge Infrastructure (CNKI) was used to conduct advanced searches targeting the research objects. The keywords "green & rural area" and "low carbon & rural area" were searched on the CNKI data platform on 2 November. Then, 8787 articles were obtained. The secondary literature screening process was as follows. First, the advanced search was conducted in the CNKI database. The literature type was set as journal papers. Then, precise searches of directly related literature were conducted using "name" as the search condition. CSCD and CSSCI are the sub-databases of CNKI, which only include high-quality articles.

Therefore, they were selected as the literature sources. Precise literature searches were conducted for "low carbon", "green", "carbon emission", "agriculture", "rural area", and "rural areas". More than five references were selected from other core journals such as Agriculture Economy and World Agriculture. After book reviews, reports, and other irrelevant documents were excluded, a total of 1154 literature records were obtained. Then, CiteSpace was used to analyze keyword co-occurrence, burst, and temporal evolution based on the 1154 articles. The main evolution characteristics of GLRD research were summarized through visual analysis.

## 3. Knowledge Graph Analysis Using Citespace

### *3.1. Main Research Interests in GLRD: Keyword Co-Occurrence Analysis*

The co-occurrence network of GLRD's keywords in 1979–2021 (Figure 1) shows that the keywords with higher frequency include low-carbon agriculture (231 times), carbon emissions (230 times), carbon neutrality (133 times), influencing factors (128 times), rural revitalization (112 times), and green agriculture (101 times). Other high-frequency keywords included index system, low-carbon economy, green development, agricultural economy, agricultural production, ecological agriculture, agricultural carbon sink, development mode, regional differences, development countermeasures, low carbon energy, low carbon consumption, energy conservation and emission reduction, agricultural pollution, farmland use, organic agriculture, and biogas engineering. The involved regions mainly included Jiangsu, Jiangxi, and Henan. Only 15.8% of the literature had keywords with more than five occurrences. This indicates that the keywords in GLRD literature have low centrality and exhibit a significant diversification phenomenon.

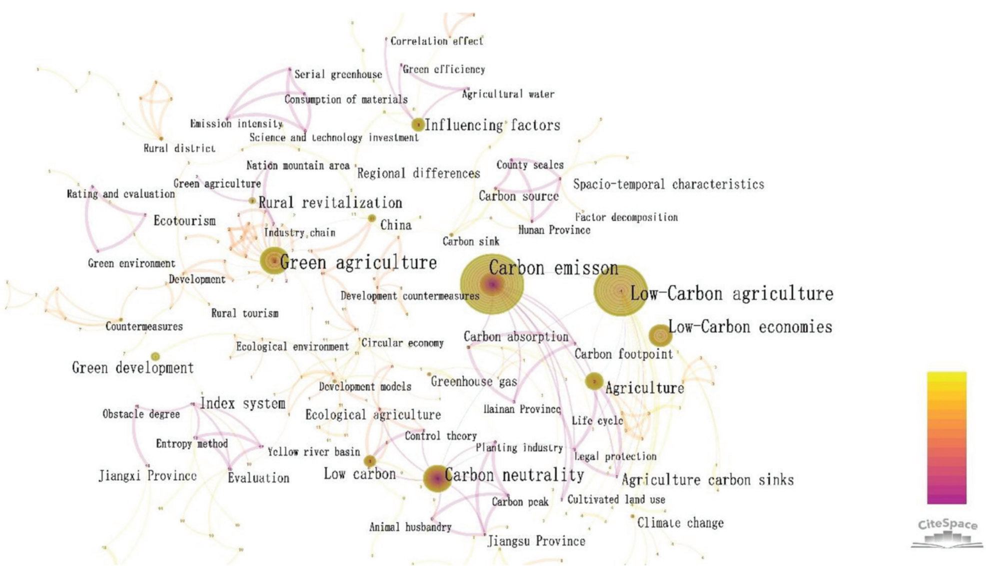


**Figure 1.** Co-occurrence network analysis of keywords in GLRD literature.

The keyword burst intensity of GLRD literature in 1979 (Figure 2) shows that the sudden staged characteristics of the keywords bursting were significant. The year 2007 was taken as the main node. Before 2007, legal guarantee, plant protection, material consumption, county scale, emission intensity, cybernetics, carbon absorption, and other keywords were research hotspots. Since 2008, low-carbon economy, agriculture, and green development have become the latest hotspots of direct GLRD research, with the burst intensity reaching 19.88, 47.72, and 20.85, respectively.


**Figure 2.** Keyword burst intensity in GLRD literature.

### *3.2. Study Stage Division*

The background of international rules and the important policies of China were sorted out (Figure 3). Combined with the deduction of the knowledge evolution process of GLRD research based on the time zone distribution of keywords in CiteSpace (Figure 4), the GLRD research stage can be divided into the starting, rising, and expanding and deepening stages (Figure 5).

#### 3.2.1. The Starting Stage: 1979–1991

In the 1980s, the concept of sustainable development occurred, and the "green revolution" was launched abroad [27]. Due to the reform and opening up, agricultural production reforms were triggered in China's rural areas, focusing on areas such as ecological agriculture and low-carbon agriculture. The research on GLRD mainly focused on exploring agricultural production and reform. There was a small amount of research content on green system construction and agricultural development, the experience and lessons from the "green revolution", and ecological issues in rural agricultural production. In China's rural areas, the development of biogas as biomass energy was intended to reduce carbon dioxide emissions, thus starting the research on rural low-carbon development. In this stage, the research scope and horizon were relatively narrow, and the investigation mainly focused on the research method.

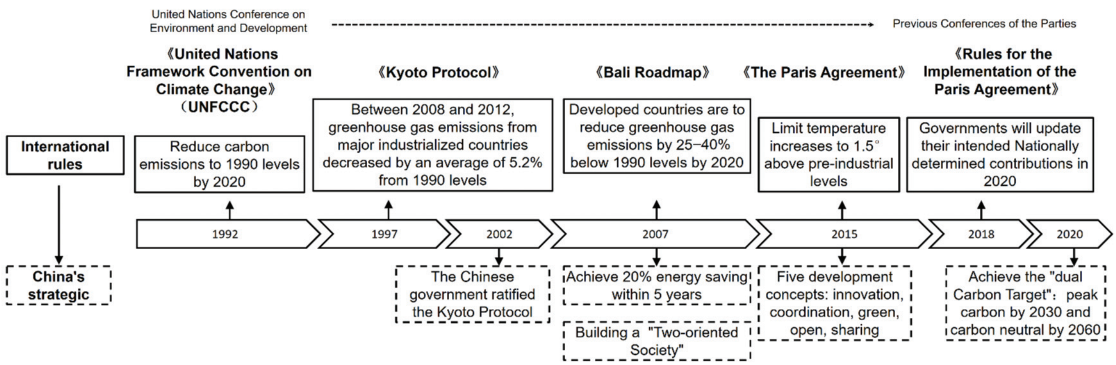


**Figure 3.** Evolution of international rules and domestic development strategies.

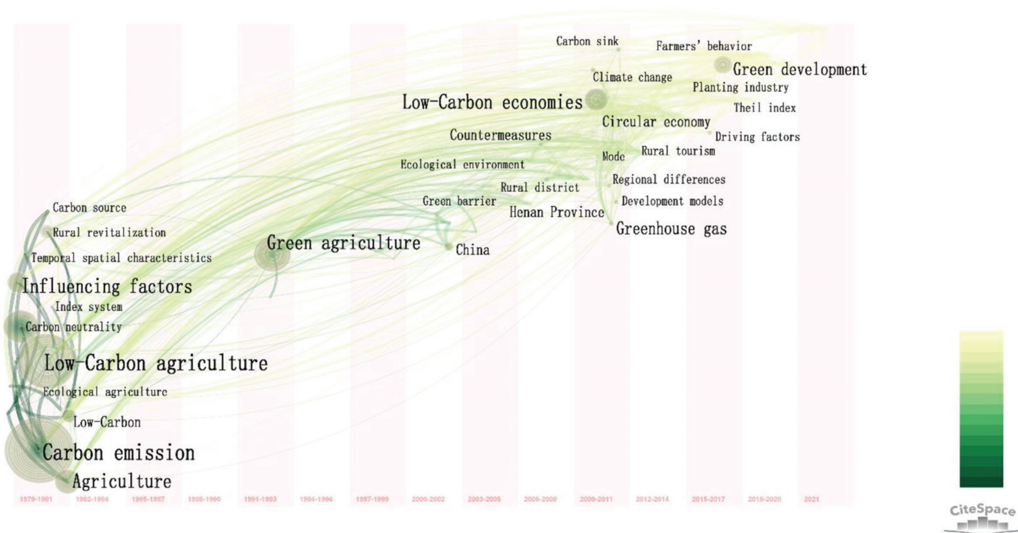


**Figure 4.** Time zone distribution of keywords in GLRD literature.

### 3.2.2. The Rising Stage: 1992–2007

From the United Nations Framework Convention on Climate Change in 1992 to the Kyoto Protocol in 1997, the quantitative emission reduction targets for global carbon emission requirements have been gradually clarified. This has greatly impacted China's industrialization, urbanization, and marketization. Rural green development and construction have gradually received attention in China. In addition, with China's accession to the WTO in 2001, "green barriers" have greatly impacted agricultural production. In this stage, green agriculture was the main research hotspot. Other related hotspots include sustainable agriculture, agricultural pollution, and development countermeasures. The overall research level was relatively macroscopic, focusing on development strategy research at the national level. The research area was mainly in the developed eastern provinces. There was also some research on ecosystem carbon emissions in some special geographical environment areas. In this stage, qualitative research methods were mainly the above research as well as comparative analysis and countermeasure analysis. Quantitative analysis had rarely been conducted at this stage.

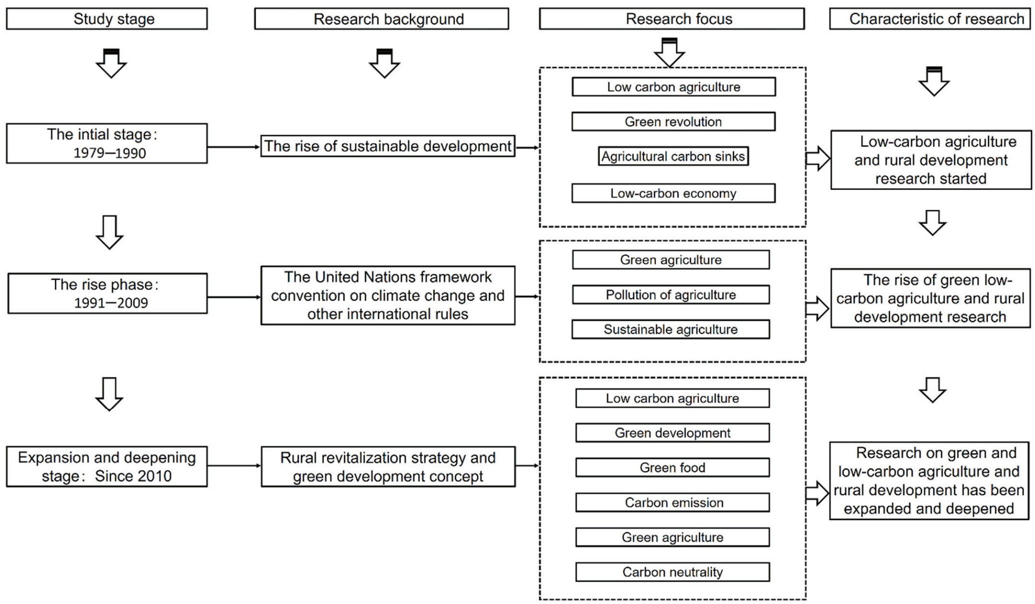


**Figure 5.** Division of GLRD research stages.

### 3.2.3. The Expanding and Deepening Stage: 2008–Present

In 2007, the adoption of the Bali Road Map resolution tightened carbon emission requirements. China actively responded to the relevant requirements and put forward the development strategy of establishing a "two-oriented society". During this period, with the deepening of the development strategies of new socialist countryside construction, beautiful countryside and rural revitalization, China's rural development entered a comprehensive transformation stage. The GLRD research expanded to carbon emission, low-carbon agriculture, carbon neutrality, and green development. Low-carbon agriculture has high relevance in Chinese academic circles. The hotspots emerged in 2010 and 2011. Green agriculture is a modern mode characterized by providing green, safe, high-quality, and high-technology content of agricultural products, and it has become a hot topic for further refinement research [28,29]. In addition, the intersection of rural green, low-carbon, and ecological technology systems promoted the research integration trend among them. The research scope mainly lay within developed coastal areas. Among them, large regional-scale research of urban agglomerations, economic belts, and provinces was the main focus of the research content [30]. In these studies, quantitative analysis methods such as model analysis and the global ML index method were most often used [31].

## 4. Research Content System for Green and Low-Carbon Rural Development

Research on GLRD has experienced low-carbon, green, and green–low-carbon integrated development research stages. Thus, three research content systems were formed (Figure 6). There is no obvious chronological order between low-carbon and green development research. These two research types both have green development and low-carbon development of agriculture as their main foci, with certain intersections in independent systems. However, with the introduction of various green and low-carbon policies in rural areas, the integration trend of the two major studies is significant.

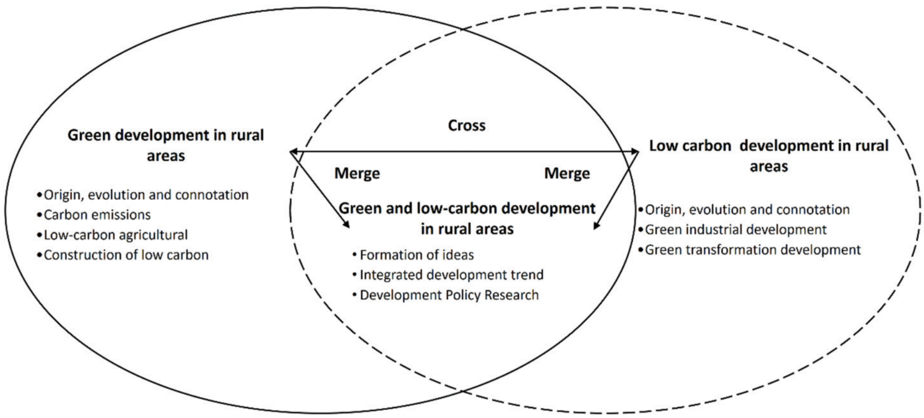


**Figure 6.** Research content systems of green and low-carbon rural development.

### *4.1. Research on Rural Low-Carbon Development*

#### 4.1.1. Origin, Evolution, and Connotation of Rural Low-Carbon Development

The development of the "low-carbon" concept spawned from the 2003 UK Energy White Paper "the future of our energy—creating a low carbon economy". It became popular worldwide after being used by the World Bank in 2006. A low-carbon economy with low energy consumption, low material consumption, low emissions, and low pollution is the new option for economic development in the 21st century [32]. It has led to the development of low-carbon cities, industries, buildings, and other fields. Rural low-carbon development includes low-carbon agricultural development, low-carbon rural living environment, low-carbon tourism development, and other content systems. Among them, low-carbon agricultural development is the most important component, which has the core goal of using agroecosystems to mitigate and adapt to climate change [33]. The specific pathways of rural low-carbon development includes reducing energy consumption, pollution, and emissions as well as increasing carbon sinks [34].

#### 4.1.2. Research on Rural Carbon Emissions

The research objects of rural carbon emissions mainly include agricultural and rural living environment carbon emission research. Main rural carbon emission sources include agricultural and residential living systems. The former mainly includes the energy consumption of agricultural machinery and the use of chemical fertilizers and pesticides, whereas the latter involves project construction processes, construction operation and management of its energy consumption, and transportation and its energy consumption [35]. Rural heating energy consumption is also significant [36]. Currently, the accounting method for agricultural carbon emissions mainly adopts the inventory preparation method, carbon emission coefficients, the LMDI method, and the Environmental Kuznets Curve (EKC) [37]. In addition, carbon emission measurement includes not only large-scale regional carbon emission research from national to interprovincial levels and from provincial to municipal levels, but also small-scale carbon emission research within specific spaces, such as residential communities and rural settlements. Due to the huge differences in production conditions and resource endowment, agricultural economic development levels, agricultural structures, and agricultural production modes vary greatly among cities [38]. This leads to significant differences in the spatial and temporal distribution of agricultural carbon emissions. Reducing rural carbon emissions mainly includes strengthening rural ecosystem carbon sinks and reducing agricultural carbon emissions. Studies of carbon sinks in ecosystems (such as forests, wetlands, and farmland) have been the focus of research in recent years, e.g., forest ecosystem carbon revenue and expenditure as well as the regional distribution and reserve changes of soil-organic carbon [39,40]. The emission reduction ideas and specific suggestions to drive green agricultural transformation with low carbon include increasing carbon constraint indicators in combination with agricultural and rural development planning, accelerating the construction of agricultural carbon emission accounting methodology, actively developing agricultural carbon markets, and using financial measures to promote low-carbon agricultural technologies [13].

#### 4.1.3. Research on Rural Low-Carbon Agricultural Development

Low-carbon agriculture is modern agriculture with "low consumption, low emission, and low pollution". It meets the objective requirements of controlling agricultural greenhouse gas emissions and slowing down global warming [41]. The low-carbon agricultural economy is developing into a new mode and concept that affects the "low-carbon" of China's agricultural industry chain [42]. However, it also faces some problems, such as low agricultural modernization level, difficulties in large-scale land production, weak agricultural infrastructure, lack of scientific and technological innovation capabilities, and extensive agricultural production modes [43,44]. The research content involves research on the transformation pathways of promoting low-carbon agricultural development [45], low-carbon agricultural development modes under different rural regional types, and low-carbon innovation of agricultural enterprises. The development pathways of low-carbon agriculture include transforming agricultural development modes, promoting agricultural energy conservation and emission reduction technologies, reducing agricultural non-point source pollution, and improving rural energy utilization efficiency [46]. The main factors affecting low-carbon innovation of agricultural enterprises include low-carbon innovation cost, the increase of low-carbon innovation revenue, and governmental regulation [47].

#### 4.1.4. Research on Rural Low-Carbon Construction

Under the wave of low-carbon town construction, research on low-carbon rural development (e.g., low-carbon rural construction, tourism development, rural planning, communities, industry and energy-carbon residential development and design) is gradually emerging. The pathways of low-carbon rural construction mainly include expanding rural carbon sinks and reducing rural carbon sources. Low-carbon rural tourism advocates low-carbon consumption, reduces resource consumption, and pays attention to low-carbon rural landscape construction [48]. Low-carbon-friendly town construction methods include advanced road transportation systems, water environment ecosystems, green building energy systems, and resource utilization [49]. The research on the rural low-carbon community includes evaluating the degree of low-carbon reformations by constructing the index system for planning and layout [50], road and transportation, residential design, and environmental engineering. Low-carbon energy reform leads to the development of rural low-carbon industry [51]. Research on rural low-carbon residential technologies in different climatic areas is in-depth, such as research on key technology systems of rural low-carbon construction in cold winters and hot summers [52] as well asresearch on the technology systems and implementation pathways of rural distributed photovoltaics in areas with rich solar energy resources [53].In addition, farmers' low-carbon production decisions directly affect the carbon emission reduction and sustainable development of agriculture [54]. Research shows that farmers' willingness to participate in low-carbon agriculture is often affected by income levels and the technical difficulties of agricultural production [55].

### *4.2. Research on Rural Green Development*

#### 4.2.1. Origin, Evolution, and Connotation of Rural Green Development

In August 2005, Comrade Xi Jinping first proposed the "two-mountain theory" during his visit to Yucun in Anji County, Zhejiang Province, advocating the green transformation of traditional economic development modes. The 2018 Central Rural Work Conference introduced the road to green development in rural areas. Rural green development has a relatively complete conceptual connotation and theoretical framework. Its scientific connotation lies in achieving sustainable resource use, green agricultural development, urban–rural relationship coordination, rural living environment reconstruction, and local complexes [24]. As an important component of rural green development, sustainable green agricultural development has far-reaching significance [56]. Green agricultural development is a mode relative to the cost of excessive consumption and environmental damage [57]. It takes resource environment carrying capacity, resource utilization efficiency, and ecological conservation as fundamental requirements, environmental friendliness as an intrinsic property, and green product supply as the important goal [17]. Based on the system deconstruction and construction perspective, agricultural green development systems include three subsystems (i.e., agricultural production, agricultural ecology, and social and economic systems), as well as coordination, correlation coupling, ecological threshold, and sustainable development theory support systems [17]. In addition, the theoretical research of rural green development has high permeability and guidance. The organic combination of rural green development and rural poverty governance forms the green poverty reduction theory [58].

#### 4.2.2. Research on Green Development of Rural Industry

First, research on green agriculture development modes, industrial clusters, innovation and entrepreneurship, agricultural green transformation and development, and agricultural green development measurement have emerged [15,59,60]. Second, agricultural green development research focuses on rural industries' green development, mainly including green development measurement, agricultural green production efficiency, constraint factors, development countermeasures, and realization pathways. The findings of the evaluation of agricultural green development levels in Chinese provinces show that China's agricultural green development levels vary greatly. The growth of agricultural output value in eastern regions is significantly higher than that of central, western, and northeast regions [60]. According to the research conclusion of the comprehensive evaluation of green agricultural development in Zhejiang Province from 2002 to 2016, the comprehensive utilization index of green agricultural resources showed a fluctuating upward trend and regular changes in different development stages [21]. The research on the implementation pathways of green development of rural industries includes large-scale operations, construction of green agricultural industry chains, and improvement of socialized service levels of green agricultural production [61]. Third, from a micro perspective, individual farmers and new business entities are chosen as the research objects to study their green production willingness and behavior-influencing factors. The research shows that general value, cost risk, government incentives, sales prospects, and environmental value are relevant factors affecting farmers' green production [62]. The transformation of green production of new business entities can be guided by cultivating a market environment, reducing endowment constraints based on economic guidance, and adhering to classified policies [63].

#### 4.2.3. Research on Rural Green Transformation and Development

The research types include different regional modes (such as water towns and mountainous areas) and different location modes [64] (such as economically developed areas and suburban integration areas). The ecological mulberry-based fish pond mode in water towns is one way to promote green transformation [65]. The green development in mountainous areas has formed specific countermeasures to four systems: green livability, green industry, green support systems, and green governance [66]. The research content includes overall rural transformation, green transformation of rural micro and small enterprises and industries, and rural green infrastructure. The evaluation research of rural green development is mainly based on quantitative research, showing the increasing efficiency of rural green development in China. However, there are certain interprovincial differences: green development efficiency in economically underdeveloped areas is higher than in economically developed areas; the efficiency in coastal areas is higher than inland areas [67]. In terms of the evaluation system of rural green development, some studies have constructed the index system of rural green development in China from three dimensions: rural ecological environment quality, intensive and efficient rural production, and a healthy and livable rural living environment. The conclusion shows regional differences and spatial agglomeration characteristics in China's rural green development level [20].

### *4.3. Research on Green and Low-Carbon Integrated Rural Development*

#### 4.3.1. Formation of the Concept of Green and Low-Carbon Rural Development

The broad concept of green development focuses on ecology and low-carbon fields. It forms the overall concept and practice system of GLRD. In 2021, the Guiding Opinions of The State Council on Accelerating the Establishment and Improvement of the Economic System for Green, Low-Carbon, and Circular Development proposed to establish and improve an economic system for green, low-carbon, and circular development. The Law of the Promotion of the People's Republic of China in 2021 proposed to promote the reduction of agricultural inputs, cleaner production, and industrial ecological modes to guide rural society to form green and low-carbon modes of production, life, and consumption. The introduction of various important policies, measures and construction standards, such as the Evaluation Index for Green and Low-Carbon Key Small Towns (Trial) (2011), Guidelines for Low-Carbon Community Pilot Construction (2015), and Opinions on Strengthening Green and Low-Carbon Construction in Counties (2021), marks the gradual formation of the concept of GLRD.

#### 4.3.2. Research on Green–Low-Carbon Integrated Development in Rural Areas

First, "green" and "low carbon" are more integrated in terms of technical systems. Taking the study on green agriculture and green agricultural development as an example, low-carbon production conditions are important indicators of the comprehensive evaluation of green agriculture. The specific indicators include carbon emissions from agricultural production activities and material utilization, $N_2O$ emissions caused in the crop planting process, and $CH_4$ emissions produced in rice fields [68]. The agricultural green development technology system includes promoting biopesticide and degradable film production technology and constructing a low-carbon circular ecological agricultural production system. Second, driving rural and agricultural green transformation using low carbon has become a possible way of reducing carbon emissions [13]. Green and low-carbon coordinated development is transforming into new urbanization [69]. Third, GLRD also has interactions. For example, excessive agricultural carbon emissions are mainly responsible for the low efficiency of agricultural ecology. Strengthening agricultural carbon emission control is an important way to improve agricultural ecological efficiency [70].

#### 4.3.3. Policy Research on Green and Low-Carbon Rural Development

Foreign experience and research mainly include three directions. The first direction involves the experiences of other developed Asian countries, such as Japan's agricultural development policy of building a value chain through agricultural cooperatives and regulating greenhouse gas emissions through differentiated regional budget distribution policies [71,72]. The second is focused on the GLRD transformation experience and policies of developed agricultural countries or regions in Europe, such as the Netherlands, Germany, and Israel. Their experience includes: (1) a sustainable development mode, strict agricultural resources, and environment supervision systems (water management) and government support systems in the Netherlands [73,74]; (2) focusing on the improvement of a protection mechanism for farmers' interests in the EU Common Agricultural Policy [75]; (3) efficient use of water and soil resources embodied in the management policies, utilization efficiency priorities, efficient use of innovative resources, and public participation and publicity in Israel [76]. The third direction involves advanced management GLRD policies in the United States, such as the carbon pricing policy [77] and low-energy building verification policy [78]. Meanwhile, the United States has also formed a low-carbon agricultural policy system, including specific topics such as soil conservation and tillage, agricultural carbon energy, and agricultural carbon trading. China's rural green development policies are constantly evolving and improving [79], and they have limitations of unbalanced policy tool structures and a low coordination of policy subjects [80]. There are more policy recommendations on green and inclusive finance [81], whereas relatively few studies were conducted on land use and space control policies that address actual GLRD needs.

## 5. Research Trends in GLRD in China

In general, the research on GLRD in China has the following characteristics. First, the research content is gradually enriched. The research on rural low-carbon development and green development not only includes efficiency evaluation, evolution and drive, technology system, development policy and other research dimensions but also covers multiple research levels (theory, practice and trend) and research objects (agricultural industry, rural living environment, rural communities and farmers). Second, the research focus is becoming increasingly prominent. The research on green and low-carbon development of the rural industry is the most important research content and always runs through all levels of rural green and low-carbon research. The research content of green and low-carbon development in rural industries mainly covers agricultural transformation, micro and small rural enterprises, rural tourism, rural industrial chain and rural green agricultural products. Third, research integration gradually gets strengthened. Low-carbon and green development research is the continuation and transformation of ecological and sustainable development research. From one-way research to green and low-carbon integrated research, it is mainly reflected in the scientific connotation, overall goal, technical system and other aspects.

However, there are still some limitations. First, measurement standards are non-unified. It is difficult to unify the measurement standards of carbon emissions, carbon sink income and green development in rural areas. It is necessary to study rural green development, green agricultural development and various evaluation index systems. For example, the green agricultural development evaluation index system can be established from the three dimensions of water resource utilization, environmental pollution and quality and growth quality [82]. Second, the research depth should be strengthened. Existing studies are mainly conducted on national, provincial and other large regional scales, whereas there are few micro studies on small regional scales and farmers at the county (city) level. There are many quantitative studies on agricultural carbon emission measurement and low-carbon level evaluation, whereas relatively few systematic studies on GLRD technologies are available. This led to a lack of targeted green and low-carbon technologies and microemission reduction measures. The research focuses on green and low-carbon rural production with less attention to green and low-carbon rural life. Third, policy research is relatively weak. It mainly focuses on agricultural green and low-carbon development policy, and the overall policy research content of GLRD is relatively weak.

The research should be strengthened in the following aspects. First, the scientific evaluation of green and low-carbon rural functions should be strengthen. Due to the operational contradictions between agricultural economic growth and carbon emission decoupling, the scientific evaluation research of rural green and low-carbon functions is particularly important. We should further strengthen the data collection and statistical research of rural green ecological resources and green and low-carbon evaluation, identification, and potential assessment research. Second, the development pathways of green and low-carbon rural industries should be studied in depth. Green and low-carbon development of rural industries is still the key. Other countries have taken green development modes and carbon emission reduction as important measures to deal with climate change [83,84]. Some experience has been obtained in terms of the measures to reduce agricultural carbon emissions, including improving agricultural planting technology by changing the crop density of crops and reducing the absolute practical amount by improving the efficiency of nitrogen fertilizers. These measures can effectively reduce agricultural carbon emissions [85,86]. In terms of strengthening agricultural carbon emission management, the carbon tax can feed farmers and change their consumption habits to a certain extent, thus facilitating reducing agricultural carbon emissions. Afforestation and strengthening the sustainable use of biofuels can also reduce agricultural carbon emissions [87]. It is necessary to further deepen the research on the development pathways of green and low-carbon rural industries in technology, organization, and operation. The research should be expanded from microresearch perspectives of farmers, agricultural enterprises, and new agricultural business entities so as to provide specific countermeasures for the green and low-carbon transformation of China's rural industries. Third, the typical characteristic GLRD mode should be studied in depth. Relative to the rise of green rural construction modes, rural green tourism development modes, and rural capital-led development modes worldwide [88], the current China-only traditional village tourism green development mode and a small number of related studies should be expanded to different regional environments, locations, industries, and operation management systems under the typical mode of rural green and low-carbon transformation research. Finally, we should innovate GLRD policies. The legal guarantee should be strengthened by regional cooperation, compensation, and comprehensive governance mechanisms. The policies and laws in key areas should be improved. The supervision and feedback mechanisms should be established under diversified cogovernance. The incentive system suitable for multiple subjects should be improved to provide a demonstration of the smooth realization of the "dual-carbon" goal in rural areas [89]. Guided by green and low-carbon development, the compensation system should be innovated for green and low-carbon development in agriculture and rural areas. The types and contents of compensation for GLRD should be systematically divided [90]. We should also establish a comprehensive rural management mechanism, strengthen the protection and restoration of rural green ecological environments, and realize the coordinated development of rural economy and social ecology in institutional design.

## 6. Conclusions

As an ancient country with a long history of agrarian civilization, China's rural production and life contain profound low-carbon and green wisdom and ideas. At present, the "dual-carbon" goal that China is promoting is an important measure to build a community with a shared future for humans. It is significant for the sustainable development of the human economy and society. China's vast rural area plays an important role in achieving "carbon peaking" and "carbon neutrality". Therefore, rural green and low-carbon research have become hot topics in Chinese academic research. Therefore, this paper used CiteSpace to analyze 1154 Chinese core journal articles and combined quantitative analysis and qualitative summary research to comprehensively analyze the knowledge system of rural green and low-carbon research in China. The following research conclusions were achieved.

First, quantitative analysis was conducted to summarize the commonality of keywords in the GLRD research field, its staged research characteristics, and its research background as well as the evolution of the three research stages in detail. The high-frequency keywords (such as "low carbon agriculture", "carbon emission", "influence factors" and "rural revitalization") reflect that the research on GLRD focuses on agricultural industry development, has clear research objectives, and focuses on studying impact mechanisms. The research scope gradually evolves from narrow to wide and from local areas to macroscopic and overall areas. The carbon sink function of ecosystems in rural areas with a special geographic environment has been given attention. The research methods used gradually evolved from survey to quantitative analysis (such as model analysis, global ML index, and spatial analysis). Second, the qualitative summary research was conducted from three aspects (rural low-carbon development, rural green development, and green–low-carbon integrated development). The research was implemented into specific contents (such as connotation requirements, overall development and transformation of agricultural and rural industries, green and low-carbon rural construction measures, and green and low-carbon policies). It is also clear that rural low-carbon development, rural green development, and green–

low-carbon integrated development directly reflect the evolutionary results of a series of development policies in China. The green and low-carbon agricultural development mode, technological innovation for agricultural production, and the production mode transformation promote overall rural transformation. Green and low-carbon construction measures in villages and towns, residential construction, rural tourism, and related infrastructure have been studied to a large extent. China's rural green development policies are constantly evolving and improving and have been focusing on GLRD policies in developed regions. Land use and spatial control policies for actual GLRD needs are expected to become the next important research topic.

The description of GLRD research in China in this paper mainly analyzes and summarizes the stages, processes, and frontiers of GLRD research while also reviewing the research shortcomings and presenting the research outlook. This study better follows the requirements of the literature research review style and writing standards. In addition, this study collates several research contents, such as the connotation, development modes, development evaluation, and development policy of GLRD. This is expected to provide relevant ideas for China and other developing or developed countries to build a green and low-carbon urban–rural community. In addition, this study will provide some references for studying rural geography, economics, and ecology and may extend current research to broader special research fields. However, this study has some limitations because the research data are mainly from Chinese CSSCI and CSCD databases. The representativeness of the research literature may be lacking. The research contents that should be focused on may not be in-depth enough. The GLRD research should be a research topic with practical guidance. Despite these limitations, this study has more theoretical significance than practical significance. It is necessary to combine specific GLRD practices as much as possible to form more valuable research content in further research.

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MDPI

*Technical Note*

# Monitoring and Prediction of Particulate Matter ($PM_{2.5}$ and $PM_{10}$) around the Ipbeja Campus

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**Abstract:** Nowadays, most of the world's population lives in urban centres, where air quality levels are not strictly checked; citizens are exposed to air quality levels over the limits of the World Health Organization. The interaction between the issuing and atmospheric sources influences the air quality or level. The local climate conditions (temperature, humidity, winds, rainfall) determine a greater or less dispersion of the pollutants present in the atmosphere. In this sense, this work aimed to build a math modelling prediction to control the air quality around the campus of IPBeja, which is in the vicinity of a car traffic zone. The researchers have been analysing the data from the last months, particle matter ($PM_{10}$ and $PM_{2.5}$), and meteorological parameters for prediction using NARX. The results show a considerable increase in particles in occasional periods, reaching average values of 135 μg/m$^3$ for $PM_{10}$ and 52 μg/m$^3$ for $PM_{2.5}$. Thus, the monitoring and prediction serve as a warning to perceive these changes and be able to relate them to natural phenomena or issuing sources in specific cases.

**Keywords:** particulate matter; air quality; neural networks; NARX

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## 1. Introduction

The growth of urban agglomerations has created adverse conditions for the quality of life in urban areas in recent decades [1,2]. One of the systems that has most suffered from this degradation is atmospheric air. It has drawn much more public attention over the past couple of years and has become a severe global environmental issue [3,4].

Air pollution is directly related to air quality, which depends on pollutant emissions and weather conditions in a given location. The occurrence of natural disasters (floods, cyclones) and the conditions of atmospheric stability may contribute to the dispersion of pollutants, or, on the other hand, it may support their continued presence in the lower atmospheres [5]. Air pollution poses a great environmental risk to health. Exposure to outdoor fine particulate matter (particulate matter with an aerodynamic diameter < 2.5 μm) is the fifth leading risk factor for death in the world, accounting for 4.2 million deaths and >103 million disability-adjusted life years lost, according to the Global Burden of Disease Report. The World Health Organization attributes 3.8 million additional deaths to indoor air pollution. Air pollution can cause acute harm, usually manifested by respiratory or cardiac symptoms, as well as chronically, potentially affecting every organ in the body. It can cause, complicate, or exacerbate many adverse health conditions [6].

Thurston et al. [7] agree with this consideration and discuss in their work how this is a significant risk factor for chronic respiratory diseases (CRDs) with well-documented adverse health impacts on humans. They primarily studied the effects of air pollution on the respiratory system and the effects of air pollution on human health from an extensive review. Nowadays, the majority of reviews investigate health outcomes of respiratory diseases in children, as well as cardiovascular diseases at all ages. The study by [8] combined health outcomes and air pollutants; $PM_{2.5}$ was included in the health outcomes of a higher number of reviews, mainly cardiovascular diseases.

In addition, the particles and gases contain toxic chemical compounds which can have harmful health effects and may have carcinogenic potential. The particle matter with the most significant human health effects consists of particles smaller than 10 μm, as they are so small that they can reach the respiratory tract. Moreover, particles of less than 2.5 μm can reach the alveoli. The exacerbating factor is that such fine dust can remain suspended for long periods. Another aggravating factor is that the wind transports them over considerable distances from the source [4,9].

Urban centres usually have a great number of sources: industrial activities, a large vehicle fleet and high levels of traffic. Such sources promote significantly higher anthropogenic pollution in city centre areas and surroundings. As a result, the use of sensors to monitor the particle material for sampling is appropriate [10,11]. Castanho, A.D.A.; Artaxo, P. (2002) [12] in research conducted in Patras, Greece, estimated that vehicle emissions accounted for 12 percent of $PM_{10}$. Badura, M. et al. (2020) [13] identified the main sources of atmospheric $PM_{2.5}$ in the metropolitan region of São Paulo as vehicles, re-suspension of soil particles, fuel combustion and industrial emissions.

According to [14], low-cost sensors provide an opportunity to improve the spatial and temporal resolution of air quality measurements. Networks of such devices may complement traditional air quality monitoring and provide some useful information about pollutants and their impact on health. This could be observed with nodes arranged vertically on two buildings. $PM_{2.5}$ concentrations were two to four times greater near the top parts of the buildings than near the ground. The effect of stratification of $PM_{2.5}$ levels was observed under conditions of temperature inversion.

According to Elaine Lui [4], in recent years, forecast models of particle matter have been proposed as a helpful tool for the management of air quality in several cities around the world. There are many deterministic models to assess and predict the dispersion of pollutants in urban areas; however, most of them are causal and therefore fail to predict extreme concentrations [15]. Artificial intelligence models, such as neural networks, have already proven to be efficient in several areas and have shown excellent results in the modelling and prediction of time series [16–18]. Moursi et al. [19] worked with an extensive $PM_{2.5}$ dataset from the cities of Beijing and Manchester and presented improved accuracy using the combination of models based on the nonlinear autoregressive exogenous (NARX) approach.

This work explored and adapted the skills of nonlinear self-regressive networks with exogenous input (NARX) in the predicting of particle matter $PM_{10}$ and $PM_{2.5}$ measured at the Polytechnic Institute of Beja, located in the city of Beja, in the Alentejo Region, Portugal. This NARX network was successfully applied for the prediction of the $PM_{10}$ particle material collected in the city of São Carlos (state of São Paulo, Brazil [4] and Agadir, Morocco [20]) and $PM_{10}$/PM in the city of Punjab, Pakistan [21].

NARX models relate the current value of a time series to past values of the same time series and to the current and past values of other exogenous time series. It can perform predictions of an entire sequence at once; that is, an output neuron predicts a vector with multiple values. It is necessary to use the same length for input and output sequences.

This study is an exploratory work and will be the beginning of this type of work, which has not yet been carried out in this region of Portugal. The use of these tools is an essential upgrade for the future since climate change brings us new challenges every day.

## 2. Materials and Methods

The experimental equipment quantifies the concentration of particulate matter in the air and monitors the meteorological parameters in the Agrarian School of the Polytechnic Institute of Beja in the Alentejo Region in Portugal (Figure 1). It is housed on the first floor, about five meters high and four meters away from the street, where there is intense vehicle traffic.


**Figure 1.** Location of the sensor on the map 247 G + 6 R Beja.

Figure 2 shows the inside of the equipment, containing a NOVA SDS011 particle sensor (1), an ESP8266 NodeMCUv3 microcontroller (2), a BME280 temperature, humidity and pressure sensor (3) and a suction tube (4).

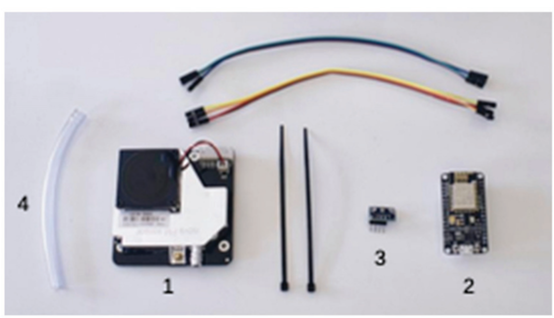


**Figure 2.** Inside of the equipment.

Figure 3 shows the data acquisition scheme, step by step, where the sensor received the reflected IR light from an IR LED. After this, the data are sent to a microcontroller that sends the data to the internet by Wi-Fi, after which it is possible to verify the data and see the particle concentration in graphics.

The particle sensor has a measuring device accuracy of 0–999.9 $\mu g/m^3$ and a detection threshold of 0.3 $\mu m$. The operation conditions are temperature −20–50 degrees Celsius and humidity up to approximately 70 percent. Its lifespan is around 5 years. [22] evaluated the accuracy of the equipment, and as the Nova SDS011 sensor presented coefficients of variation below 10%, the sensor has acceptable accuracy according to the EPA standard.

The equipment can take 30 measurements per hour of $PM_{10}$ and $PM_{2.5}$, which are then tracked and stored on a website via the internet. Data analysis in this paper focuses on the results of the measurements carried out between February 2022 and July 2022, which in Portugal comprises spring and summer, reaching temperatures of 42 degrees Celsius. This period was chosen because it is the longest period of time without interruption that could be obtained.

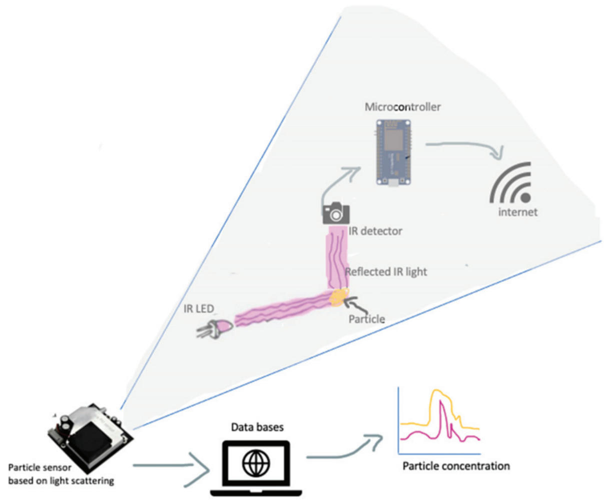


**Figure 3.** Data acquisition scheme.

*NARX Predictive Models*

The architecture of the NARX network allows the selection of the number of exogenous inputs and what delay should be used in the training and prediction process. This neural network model has been extensively used for time series prediction. The NARX- type neural network (nonlinear autoregressive exogenous model) was used as described in the work of Schornobay–Lui et al. [4] because, in that work, the NARX network proved to be more efficient than the neural architecture of multi-layer perceptron (MLP). The NARX-type network architecture receives data from the feedback itself with time delay, thus making the result dynamic; that is, values obtained previously influence the later results, and this occurs in the concentration values of particulate matter, further justifying its use in this type of work.

In this work, the mean values of temperature and daily concentration of $PM_{2.5}$ and $PM_{10}$ were used as network data, and, as a network output, particulate matter concentration data were used. To build and apply NARX models, MATLAB 2022b (Math-works Inc., Natick, MA, USA, 2022) was used and the Deep Learning Toolbox. Temperature and concentration data were normalised and ranged from 0.1 to 0.9.

The NARX neural network, which was used in this study, was run with the Levenberg-Marquardt training algorithm and the stop criterion was absolute error close to $10^{-3}$ after 150 validation error checks.

## 3. Results and Discussion

The results of the monitoring of particulate matter 10 and 2.5 obtained during the spring and summer in the city of Beja in Alentejo, Portugal, are shown in Figure 4. The results mostly remain within the standards reviewed by the legislation. Beja is the capital of Alentejo, but the region is not very populous and has a large geographical area that helps in the dispersion of pollutants.

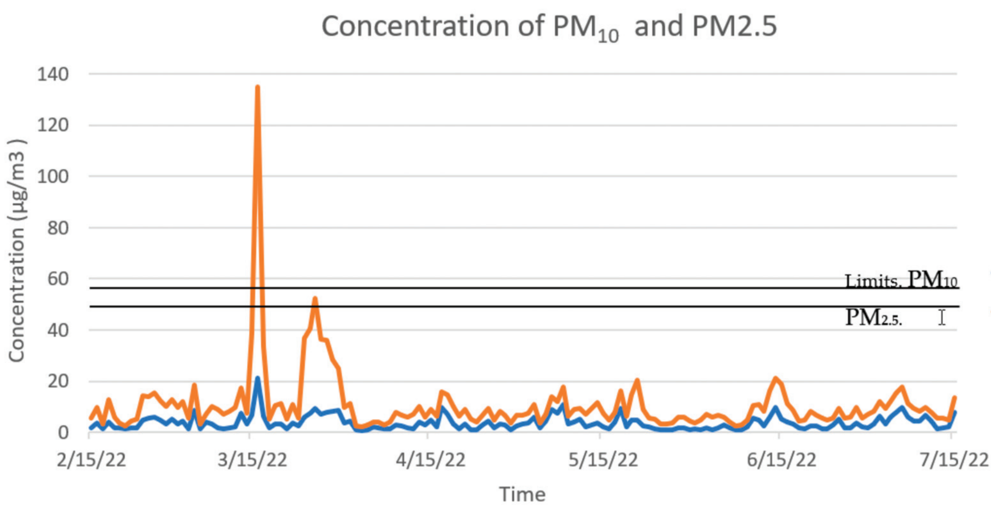


**Figure 4.** Result of the $PM_{2.5}$ and $PM_{10}$ concentration by a sensor.

On the other hand, some natural phenomena can increase this problem, for example, sand coming from the Sahara Desert, carried by rain and wind. Due to the atmospheric depression "Célia", the city of Beja, located in the south of Portugal, has shown high levels of particle matter ($PM_{10}$ and $PM_{2.5}$) at certain times of the year. Research has been conducted [23] about the dust that is carried from the Sahara Desert in the Iberian Peninsula (IP), and one of the results obtained from this research showed that dust events across the IP were induced by different circulation weather types, affecting air quality. These results are also important as an aid to air quality forecasting since the high concentrations of atmospheric pollution and intrusion events are associated with less frequent circulation weather types. The occurrence of these circulation weather types can therefore be used as a warning signal for the occurrence of extreme events [23].

The results obtained show a considerable increase in particles in the air during the monitoring period, reaching values of 135 µg/$m^3$ for $PM_{10}$ and 52 µg/$m^3$ for $PM_{2.5}$. These values are above the maximum limit indicated by Portuguese legislation, according to Decree-Law No 102/2010. In its second amendment (Decree-Law 47/2017), the maximum limit for a period of 24 hours of sampling is 50 µg/$m^3$ ($PM_{10}$), which cannot be exceeded more than 35 times per year, while for particulate matter $PM_{2.5}$, the annual limit is 40 µg/$m^3$ [24].

This phenomenon occurs more frequently in this region of Portugal due to climate change, putting the health of the population at risk. Air quality monitoring is of paramount importance to the effects of pollution control on the environment and human health [25].

*NARX Predictive Models*

The results of the prediction model were produced with MatLab. The data were submitted to training, validation and testing steps by the NARX neural network, with these divisions occurring randomly in the data set.

Figures 5 and 6 show the results obtained by predicting $PM_{10}$ and $PM_{2.5}$ concentrations using the NARX model. Data adjustment by the prediction model was more efficient for $PM_{10}$ than for $PM_{2.5}$ on the NARX network. The input data in the NARX model were normalised and ranged from 0.1 to 0.9. The prediction results of $PM_{10}$ and $PM_{2.5}$ concentration covered the extreme values on a smaller scale. Analysing the graphs, it can be observed that the forecast for $PM_{2.5}$ presented a greater distance between the monitored and the predicted data. This means that the network presented a greater capacity to capture the variations that occurred in $PM_{10}$, including the data with higher concentration (135 µg/$m^3$) from an atypical event in the region.

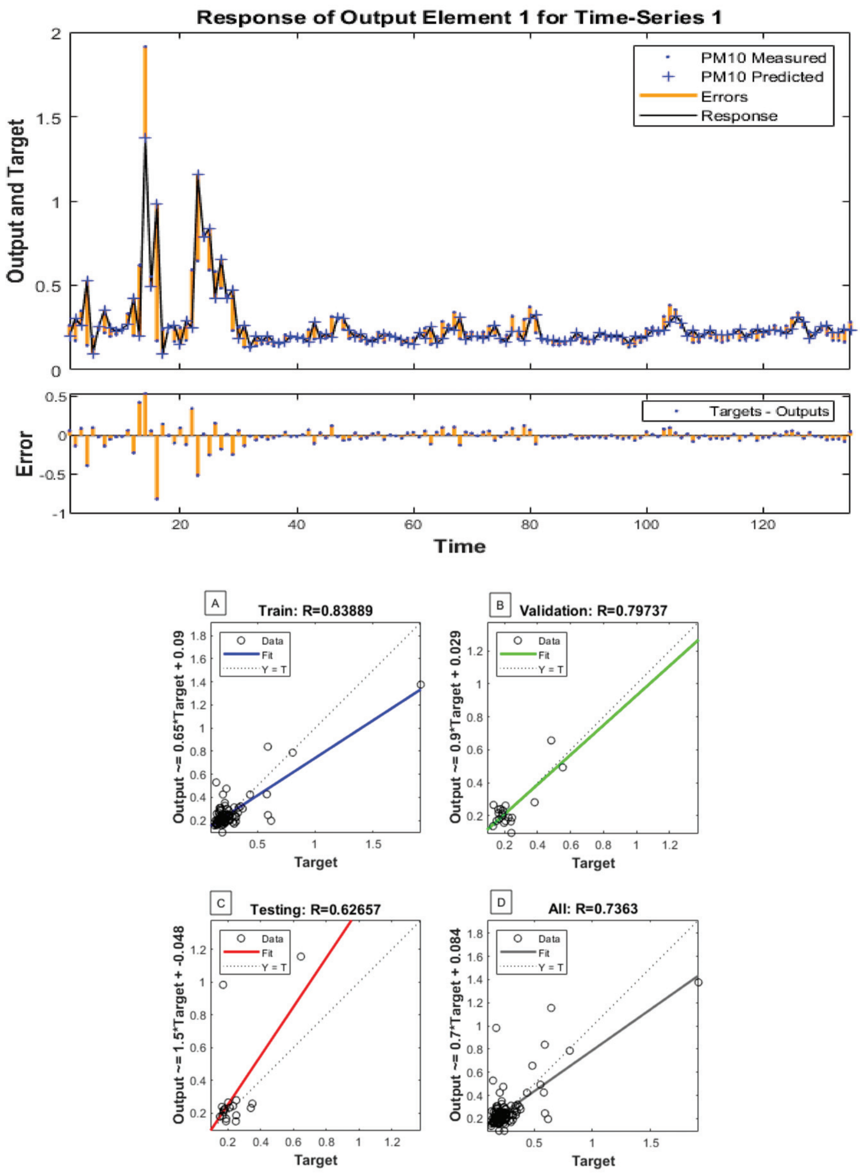


**Figure 5.** Result of the $PM_{10}$ concentration prediction of the NARX model and regression charts for (**A**) training, (**B**) validation, (**C**) test and (**D**) all data considering the NARX $PM_{10}$ model.

Figure 6 shows the regression graphs that compare the measured and predicted values of the two best results, considering the training, validation, and testing stages of the total data set. Comparing the regression graphs, the NARX-$PM_{10}$ presented slightly better efficiency in the training, validation and test stages when compared with NARX-$PM_{2.5}$. The NARX-$PM_{10}$ network presented faster convergence with more minor deviations of forecast validation than the NARX-$PM_{2.5}$ network. In future work for the region, investigations will be done to improve the understanding of the interactions between $PM_{10}$ and $PM_{2.5}$, which could improve the efficiency of prediction models for inhalable particulate matter.

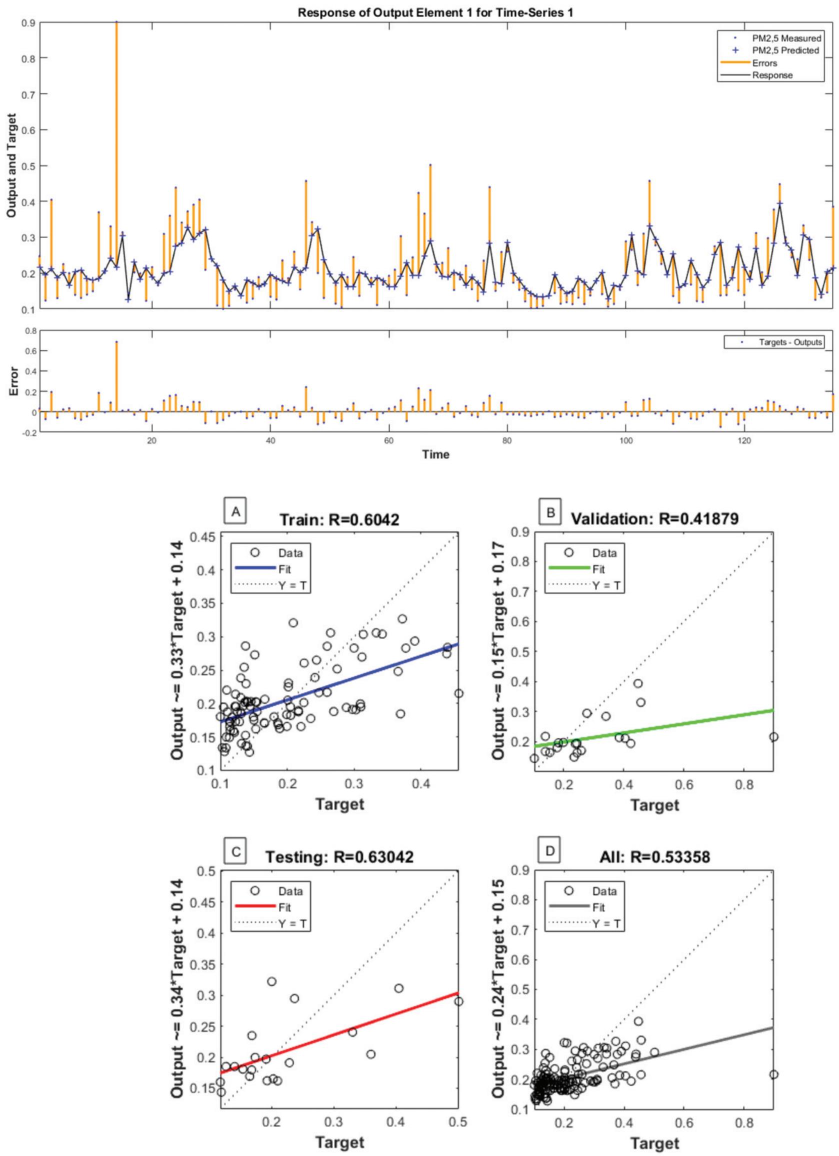


**Figure 6.** Result of the $PM_{2.5}$ concentration prediction of the NARX model and regression charts for (**A**) training, (**B**) validation, (**C**) testing, and (**D**) all data considering the NARX $PM_{2.5}$ model.

Evaluations with neural network models, which manage to capture trends which are often not possible in the more traditional statistical models, are also interesting for a better understanding over time of variations due to climate change. This approach can be highly valuable and can be easily used as a complementary tool for forecasts, distinguishing between air masses coming from different areas and, therefore, is an advantage of the impact of studies which intend to assess the effects of dust on human health, ecosystems, or rain composition.

## 4. Conclusions

Regarding the data collected, it was compared to the data feed on the NARX network for $PM_{10}$ and $MP_{2.5}$. There was a decrease in the concentration of $PM_{10}$ over time, and while the concentration of $PM_{2.5}$ remained variable over time, it was not able to predict a tendency to decrease or increase the levels of this $PM_{2.5}$ particulate matter.

Overall, the concentration of particulate matter in this place is stable without significant changes because it has a low demographic and a vast expanse of land without many industries or transit agglomerations.

Additionally, a natural phenomenon occurring more and more in Europe is the dust from the Sahara Desert that is swept by the wind into this region. Thus, it was possible to observe the variation in this period of the year resulting from this phenomenon.

The neural network could not effectively identify the behaviour of $PM_{2.5}$. The network architecture used was applied and described in the work of Schornobay-Lui et al. [4]; specific conditions for the IPBeja region will be considered in future work and over a longer period of time. Nevertheless, the conclusion of this research was that with the data obtained from the monitoring around the IPBeja campus, it was possible to make a prediction using the NARX tool, so the continuity of work in the use of NARX will be promising for future works.

Future studies will be conducted with a database that is more extensive to analyse the influence of other weather variables, such as temperature, in the prediction of particulate matter in this region.

Finally, the contribution of this work is the availability, discussion and search of the understanding of the concentration data of particulate matter for the IPBeja region, with the lack of data on air quality. This is essential for understanding the behaviour and origin of pollution sources over time, especially with the present-day modification of patterns due to climate change.

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# Potential Efficiency of Wild Plant Species (*Pluchea dioscoridis* (L.) DC.) for Phytoremediation of Trace Elements on Contaminated Locations

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**Abstract:** The current study outlines the potential of wild plant species (*Pluchea dioscoridis* (L.) DC.) for the phytoremediation of trace elements (TEs) such as Pb, Cd, Zn, Mn, and Cu at various contaminated locations: an industrial area (S1); a residential area with a high traffic load (S2); and a rural area (S3). Data showed that the photosynthetic pigments and flavonoids decreased significantly at S1, at which TEs accumulated with high concentrations. This drop in chlorophyll concentration reflects foliar damage caused by TE contamination. The carotenoids/chlorophyll index (Car/Chl) ratio showed non-significant variations for all studied spheres. High values of chlorophyll ratio (a/b) were also recorded in plant leaves which faced TE stress. The translocation factors (TF); enrichment coefficient for root (ECR); and shoot (ECS) varied clearly among the TEs as well as the studied sites, proving the ability of the plant to carry out phytoremediation of Pb, Cd, and Zn. The highest values of the metal accumulation index (MAI) were recorded at S1. Significant positive correlations for the pairs Cd and Pb in soil versus *P. dioscoridis* tissues indicated its usefulness as a phytoextraction strategy for these elements. The management of residential and rural areas should be exploiting the natural wild phytoremediation potential of this plant.

**Keywords:** *Pluchea dioscoridis*; wild plants; phytoremediation; TEs; phytoextraction

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## 1. Introduction

Increased urbanization activities globally, together with a growing transport infrastructure and traffic volume, are the main sources of water, soil, and air pollution with toxic trace metals (TEs). The injuries from direct/indirect exposure to TEs are endless, and are mainly due to the excessive accumulation of TEs in the environment [1–3]. Phytoremediation is an eco-friendly green technology in which plants has the capability and capacity to accumulate pollutants effectively and, accordingly, can grow in contaminated regions successfully [4–7]. In recent decades, trace metals have been investigated, and a large amount of results have been published on this point. In addition, significant evidence indicates that TE phytoremediation has evolved as one of the most dynamic fields of development [8]. The phytoremediation of TE-polluted habitats has, lately, progressed from the identification of hyperaccumulator plants to the study of the internal growth and development mechanisms of plants [9,10]. For example, plant growth and different physiological activities within the plants' cells differ significantly when exposed to harsh environmental stresses [11–13]. The exposure of some plants to TE stress may lead to inhibition in the photosynthetic capacity within the plant cells due to the deterioration of chloroplasts, which, in turn, negatively affects the metabolic pathways. The capacity of plants to adjust their photosynthesis systems under severe TE stress is considered a characteristic of TE stress tolerance [14,15]. Another tolerance characteristic of TE stress is the accumulation of alkaloids and flavonoids, which are represented by their ability to chelate metal ions transmission and inhibit the formation of reactive oxygen species (ROS), which helps to overcome oxidative stress [16,17].

*P. dioscoridis* (L.) DC. is an important wild evergreen shrub that grows to a height from one to three meters. It has hairy and glandular surfaces and is densely branching. It is common throughout the Middle East and neighboring African countries. In Egypt, it is abundant throughout the Nile area, western desert oasis, Mediterranean coastal strip, Eastern Desert, and Sinai Peninsula [18]. In general, wetland locations, damp settings, abandoned fields, demolished houses, depressions along highways and railways, and abandoned fields are all regions where it can be found [19]. It was recently recorded in urban areas in the Nile Delta, including residential areas, highways, and wastelands. *P. dioscoridis* is known as the "mosquito tree" in Egypt because of its insect-repelling properties [20]. Residential areas include a high rate of human activities that may negatively affect the ambient air quality, such as cutting and digging works. Using a phytoremediation strategy as an alternative solution in these circumstances can create a sustainable environment. Also, the use of phytoremediation as a solution will not corrupt the structure and texture of the polluted soil. Consequently, *P. dioscoridis* was selected for phytoremediation in this study.

The phytochemistry, ecology, and distribution of wild plants in metal-contaminated areas in Egypt have been previously studied [21]. *Pluchea dioscoridis* (L.) DC. belongs to the family Asteraceae [20]. It is a perennial invasive weed that has various important considerations at the medicinal and ecological levels. *P. dioscoridis* has been recorded as a weed in Egypt's desert reclaimed lands and abandoned fields. Many studies have declared the ability of *P. dioscoridis* to stabilize TEs such as Cu, Pb, Cd, and Zn, and could be considered a biomonitor and bioindicator for Pb and Cd pollution [21]. Many allelopathic, herbicidal, and larvicidal effects of *P. dioscoridis* have been recorded [22,23]. Medicinally, it is commonly used to treat rheumatic pains, children's epilepsy, colic, ulcers, and colds, as well as having carminative effects [24]. Its extract has anti-diarrheal, anti-inflammatory, antimicrobial, and anti-nociceptive properties [25–27].

The aim of this work was to test the phytoremediation efficiency of *P. dioscoridis*, one of the most common wild species in Sohag Governorate (Egypt). The TEs that were tested were Cd, Mn, Cu, Pb, and Zn, the most common pollutants in the studied area. The plant species were collected as they are naturally occurring in the studied area so that they may have been well-adapted species to deal with TE-induced stress.

## 2. Materials and Methods

### *2.1. Description of the Study Area*

The current research was conducted mainly in Sohag Governorate's residential districts, in Egypt (from latitude 26°6′54″ to 27°9′26″ N and from longitude 31°13′18″ to 32°36′50″ E). In the Nile Valley, Sohag Governorate is located between Cairo and Aswan. The total area is 1574 $km^2$. It stretches over 125 km along the River Nile's banks, with widths ranging from 16 to 25 km. In the Sohag Governorate, seasonal rainfall ranges from 0 mm in the summer to 0.3 mm in the winter. In spite of such dry a desert climate, rainfall may occur suddenly at an extreme rate [28]. In general, the climate of Sohag is warm, with an average annual minimum temperature of 13.2 °C in January and a maximum temperature of 42 °C in June. Relative humidity ranges from 45% to 60% in winter and 25% to 35% in summer, with an annual average of about 40%. (https://globalweather.tamu.edu/database, 2016–2017).

The main anthropogenic activities in the study areas are urbanization, the use of automobiles, and the use of different industrial materials including paints, plastics, fertilizers, and untreated waste(industrial and agricultural). For the current study, three residential areas in Sohag Governorate were selected (Figure 1). The first site (S1) is an industrial zone of Sohag Governorate (El-Kawther district); the second site (S2) is a residential area with heavy traffic load (Akhmiem town); to the third site is a rural zone with low pollution level (University Garden, Sohag city, S3). The first site (S1) was 8.4 km from the second site (S2) and 15.2 km from the third site (S3), while the distance between the second and the third sites was 5.3 km. Each site is divided into 10 permanent quadrates (each 10 m × 10 m). All samples in the three locations were collected during the same period of the growing season of the plant.

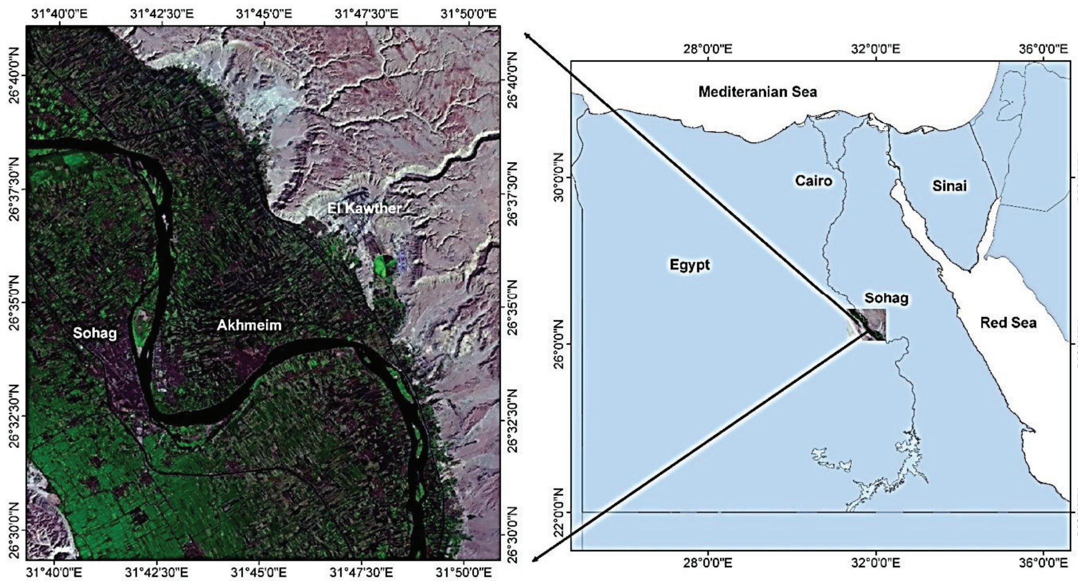


**Figure 1.** Location map of Egypt showing the Sohag Governorate and distribution of the studied sites.

### *2.2. Growth Parameters*

For leaf area (LA), specific leaf area (SLA), and water content (WC) estimation, leaves of *P. dioscoridis* were cut off from each site at a height of 1.3–2.0 m above the ground, while wearing polyethylene gloves. Care was also taken to avoid defective leaves such as those with bird droppings, insect invasion, or pesticide treatment [29]. The collected leaves were stored in plastic bags and taken to the laboratory for further analysis. According to Ref. [30], leaf area was measured (LA, $cm^2$) using a Leaf Area Meter (CI-202 Portable Laser Area Meter, USA). Specific leaf area (SLA, $cm^2/g$) was calculated as leaf area ratio to leaf dry weight [31].

Relative water content (RWC) was determined according to the method described in Ref. [32]. Plant leaves were weighed as soon as they were sampled. The leaves were submerged in water overnight, then wiped dry and weighed again to determine turbid weight. To obtain the constant dry weight, the turbid leaves were dried in an oven at 95 °C for 24 h. The relative water content was calculated using the following formula:

$$\text{Relative water content (RWC) (\%)} = (FW - DW)/(TW - DW) \times 100 \quad (1)$$

where FW expresses fresh weight; DW is dry weight, and TW is turbid weight.

### *2.3. Shoot Biomass Estimation*

For shoot biomass estimation, 15 healthy individuals of *P. dioscoridis* were randomly chosen from each site. Each individual was cut on a root collar to estimate shoot biomass. Stems, leaves, and flowers were separated from the shoot sample. Control samples were prepared with the same steps. To make the weighing process easier, the stem was separated into smaller sections. For each individual, all shoot compartments were collected, and an electronic balance was used to determine the field fresh weight (FW). For DW estimation, each shoot compartment was oven-dried at 95 °C until it reached a consistent dry weight (DW). The fresh and dry weights of the shoot parts were determined according to Ref. [22].

### 2.4. Root Biomass Estimation

The roots of the 15 healthy individuals of *P. dioscoridis* in each site had a long taproot that grew vertically, as well as numerous thinner lateral roots that were likely exposed to the wind [33]. Therefore, the current work focused only on sampling coarse roots (diameter > 2 mm), while fine roots (diameter < 2 mm) have been excluded due to loss during excavation. All coarse roots were cut using a hand saw, were collected, and the field FW of each individual was measured using an electronic balance. The collected coarse root subsamples were transported to the laboratory and oven-dried (95 °C) until a constant DW was reached. The dry weight of coarse roots in all individuals and control samples was measured according to Ref. [21].

### 2.5. Estimation of Pigments, Alkaloids and Flavonoids

In each site, 10 quadrats (each 10 m × 10 m) were chosen. Six individuals were randomly selected in each quadrate. Three medium-sized leaves were collected from the six selected individuals. Photosynthetic pigments were evaluated by UV spectrophotometry (LAMBDA 850+ UV/Vis) at 645 nm and 663 nm [34]. A total of 0.2 g fresh leaf tissue was ground in acetone (80%) and then filtered through Whatman No. 1 filter paper. The different photosynthetic pigment concentrations (Chl a, Chl b, Chl a + b, and Car.) were estimated as milligrams per gram fresh weight (mg/g f.w) following the standard equations:

$$\text{Chl a (mg/g)} = [(12.7 \times A663) - (2.6 \times A645)] \times \text{ml acetone/mg leaf tissue} \quad (2)$$

$$\text{Chl b (mg/g)} = [(22.9 \times A645) - (4.68 \times A663)] \times \text{ml acetone/mg leaf tissue} \quad (3)$$

$$\text{Total chlorophyll content (mg/g)} = \text{Chl a} + \text{Chl b} \quad (4)$$

The ratios of Chl a/b and Car/Chl were also estimated.

Flavonoids were determined using the Bohm and Kocipai-Abyazan techniques [35]. At room temperature, 1.0 g of the plant material was extracted with 100 mL of aqueous methanol (80%) prepared *v*/*v* as 20% water and 80% methanol. The solution was filtered through Whatman filter paper No. 42. The filtrate was transferred to a crucible and evaporated into dryness over a water bath and weighed to a constant weight. For alkaloid determination, 5 g of dried plant tissue was weighed, followed by adding 200 mL aqueous solution (*v*/*v*), of 10% acetic acid in ethanol (100%), then left to stand for 4 h before filtration. The filtrate was concentrated to one-quarter of its original volume in a water bath. The final extract was treated with drops of concentrated ammonium hydroxide ($NH_4OH$). The produced precipitate was allowed to settle, then was collected, washed with dilute ammonium hydroxide ($NH_4OH$), and filtered. The residue was dried and weighed [36].

### 2.6. Proline and Soluble Carbohydrates Estimation

The acid ninhydrin assay was used for Proline content estimation [37]. A total of 0.1 gm of leaf tissue powder was mixed with 3% (*w*/*v*) 5-sulfosalicylic acid. For full extraction, it was vortexed for 5 min at 1 min intervals. After extraction, the samples were centrifuged at 13,000 rpm for 10 min, and then the supernatants were transferred to clean tubes and spun again. A total of 15 µL of 3.0 M Na-acetate and 200 µL ninhydrin solution 0.15% (*w*/*v*) ninhydrin in glacial acetic acid were added to the supernatants. The background absorbance of proline was detected at 352 nm.

The phenol-sulfuric acid method [38] used for total water-soluble carbohydrate determination involved adding 1 mL of 5% phenol solution and 5 mL of concentrated sulfuric acid to 200 µL of the samples. The absorbance was detected at 510 nm. Sucrose was used as standard.

### 2.7. Plant Analysis for NPK and TEs

For the determination of N, P, and K, plant shoots and roots were rinsed with tap water many times, followed by washing with distilled water and deionized water twice.

They were then oven-dried to constant weights at 60 °C for 48 h. The dried samples were ground and passed through a sieve (2 mm mesh size). According to Refs. [39,40], a mixture of $HClO_4$, HCl, and $H_2SO_4$ 5:1:1 (*v*/*v*) was added to 0.50 g powdered sample for digestion in a metal digestion apparatus (HotBlock, VELP Scientifica, DK8s, Italy). After complete digestion, samples were left to cool at room temperature, filtered through filter paper (Whatman No. 42), and, finally, the sample volume was completed to 25 mL with distilled water. Total phosphorus (P) was quantified by following the method reported by Jackson (1958) based on the molybdenum blue technique. Total nitrogen (N) was detected by the micro-Kjeldahldahll technique, and total potassium (K) was determined by the methods described by Refs. [39,40], based on the flame photometer technique.

According to the method described in Ref. [41] and modified by Ref. [42], after drying and homogenization, plant samples were digested in an acid mixture of HCl and $HNO_3$ (aqua regia (AQ) at a 3:1 ratio (*v*/*v*). In a 25 mL beaker, 0.50 g of tissue powder was weighed. A total of 1 mL $HNO_3$ was added to 3 mL HCl, then an additional 1 mL $HNO_3$ was added to the plant sample, which was heated for digestion for at least 3 h, or until brown fumes ceased emerging, indicating full digestion. After cooling, the sample was filtered into a 25 mL volumetric flask using an acid-resistant filter (Whatman filter No. 42), made to the mark with 2% $HNO_3$, and stored at 4 °C until analysis. A blank sample was prepared with the same volumes of acids but without a plant sample. Inductive Coupled Plasma Optic Emission Spectroscopy (ICP-OES, Perkin Elmer 8000 Optima) was used to determine the absorptions of TEs (Cu, Pb, Cd, Zn, and Mn).

### *2.8. Soil Sampling and Analysis*

Three representative soil samples were collected from each site for the 0–50 cm topsoil. pH value of the soil samples was measured using a pH meter and electrode (PHS-3B) according to the method used in Ref. [21] in a 1:1 (*v*/*v*) soil/water mixture (5 g NCR-13 soil scoop/5 mL DI water).

Total N, P, and K were determined using the method of Refs. [39,40] as illustrated previously in the plant analysis section. Soil samples were collected randomly from the studied sites, air-dried, and ground, then sieved through an 80-mesh sieve. The concentration of N was detected at 440 nm. The molybdenum blue phosphorus technique was used to determine the concentration of P at 660 nm. The turbidimetric technique with sodium tetraphenylboron, $NaB(C_6H_5)_4$, was used to determine the concentration of K in soil samples by laboratory turbidimeter (LTC3000w).

For the detection of TEs in soil samples, the method described in Refs. [41,42] was used. After drying and grinding of soil samples, 10 mL of 65% nitric acid was added to 0.5 gm of soil sample. The solution was left at room temperature for 12 h, then at 100 °C for 4 h, and, finally, for 4 h at 140 °C until the color of the solution became clear. After cooling, the solution was then diluted to 50 mL with ultrapure deionized water and filtered through 0.42 L Whatman filter paper. Cu, Pb, Cd, Zn, and Mn were ermined using ICP-OES (Perkin Elmer 8000 Optima, PerkinElmer, Waltham, MA, USA). Each sample was digested three times.

### *2.9. BCF, TF, ECS, ECR, and MAI Calculation*

Bioconcentration factors (BCF) were estimated by dividing the TE concentration into plant parts by those in soil from respective locations.

$$\text{Bioconcentration Factors (BCF)} = \text{TEs plant}/\text{TEs soil} \tag{5}$$

where TEs plant and TEs soil represent the TEs concentration in extracts of plants and soils, respectively, grown in the contaminated environment [43]. A value of BCF above 1 indicates a higher uptake of TEs in crop/plant than in soil, while a BCF of less than 1 means more TE concentration in soil than was taken up by plants.

The translocation factors (TF) were described as the proportion of TEs in the shoot to those in the root. TF was calculated according to Ref. [43]:

$$\text{Translocation factors (TF)} = \text{TEs shoot}/\text{TEs root} \quad (6)$$

where TEs shoot and TEs root are the trace metal concentrations in the plant shoot and root, respectively.

Metal enrichment coefficients (ECS) were utilized to investigate both metal accumulation and transport from the soil to plant organs. The enrichment coefficient of the root (ECR) and the enrichment coefficient of the shoot (ECS) are the main two types of enrichment coefficients [44].

The coefficients were calculated as follows:

$$\text{ECS} = \text{TEs concentration in the shoot}/\text{TEs concentration in the soil} \quad (7)$$

$$\text{ECR} = \text{TEs concentration in the root}/\text{TEs concentration in the soil} \quad (8)$$

Mohotti et al. [45] stated that plants with BCF value > 1.0 are fitted for phytoextraction, while Cheraghi et al. [46] reported that plants with ECR > 1 and TF < 1 have the potential for phytostabilization.

The method described in Ref. [3] was used to calculate the metal accumulation index (MAI). MAI was used to detect the TE accumulation efficiencies of the plants using the standard formula;

$$\text{MAI} = (1/\text{N}) \cdot \Sigma \cdot \text{IJ}; \text{IJ} = \text{X}/\delta \cdot \text{X} \quad (9)$$

where N shows the total number of trace elements studied, and IJ is the sub-index of J gained by dividing the metal concentration (X) by its standard deviation (δX).

### *2.10. Data Analysis*

The recorded data were analyzed using One-way ANOVA with Post Hoc Tukey test (version 22.0) using SPSS (IBM Corp., Armonk, NY, USA). To assess the relationship between concentrations of TEs in soils, roots, and shoots, Pearson's correlation relationship analysis (r values) was calculated.

## 3. Results

### *3.1. Growth Parameters*

The results recorded in Table 1 show a drastic impact of the accumulation of trace elements on the SLA, LA, and RWC of *P. Dioscorides*. The SLA value in leaves collected from S1 was 51.76 $cm^2/g$ d.w., and was followed by values of leaf samples collected from S2 (high traffic site) with the value of 61.40 $cm^2/g$ d.w. The same trend of results was reported for LA. Accordingly, LA recorded the lowest measured value in the leaf samples collected from S1 with a value of 3.47 $cm^2$, while the highest LA values were recorded in samples collected from S3 with a value of 6.42 $cm^2$. For the results of relative water content (RWC), the highest value was recorded at 276.81% in the leaf samples collected from S3 (Table 1), while the lowest value was recorded in the leaf samples of S1 with a value of 122.76%.

### *3.2. Estimation of the Shoot and Root Biomass*

The obtained results, shown in Table 2, revealed that a high accumulation of TEs has a significant impact ($p \leq 0.05$) on both the fresh and dry weights of shoot and root. The trends of both shoot and root biomass were similar (Table 1), with lower values at S1 compared to the other two sites. It should be mentioned that, at S1, the accumulation of TEs was higher in shoots and roots than for other sites. The lowest FW values of shoot parts (leaf, stem, and flower) in addition to root were recorded as 6.18, 19.59, 2.32, and 11.04 g, respectively, compared to control samples (9.17, 27.45, 16.3, and 3.62 g). The same results were detected for Dw for the same organs, with values of 4.67, 17.83, 2.11, and 9.7 g, respectively, compared to control values (7.78, 25.75, 3.01, and 13.0 g).

**Table 1.** Values of Specific leaf area (SLA); relative water content (RWC); leaf area (LA); fresh weight (FW); dry weight (DW) of shoot parts (leaf, stem, and flower) and root of *P. dioscoridis* at the different studied sites.

| Site | Ind. No | Growth Parameters | | | Biomass Estimation | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Leaf | | Stem | | Flower | | Root | |
| | | SLA ($cm^2$/g d.w.) | RWC (%) | LA ($cm^2$) | Fw (g) | Dw (g) | Fw (g) | Dw (g) | Fw (g) | Dw (g) | Fw (g) | Dw (g) |
| S1 | 1 | 75.91 | 149.03 | 4.51 | 7.56 | 6.71 | 21.61 | 18.81 | 2.32 | 2.11 | 13.9 | 12.1 |
| | 2 | 51.76 | 156.24 | 3.5 | 7.03 | 5.91 | 21.73 | 19.97 | 3.65 | 2.52 | 12.4 | 11.8 |
| | 3 | 67.93 | 135.32 | 3.55 | 6.31 | 5.36 | 20.66 | 18.88 | 2.77 | 1.31 | 11.9 | 10.0 |
| | 4 | 71.35 | 130.66 | 4.59 | 7.84 | 5.4 | 21.20 | 18.93 | 3.93 | 2.42 | 13.7 | 11.82 |
| | 5 | 78.34 | 122.76 | 3.47 | 6.18 | 4.67 | 19.59 | 17.83 | 3.85 | 2.89 | 11.04 | 9.7 |
| S2 | 6 | 74.18 | 190.1 | 3.51 | 8.96 | 7.02 | 23.68 | 20.51 | 3.98 | 2.47 | 12.9 | 10.1 |
| | 7 | 89.54 | 160.87 | 4.42 | 7.91 | 6.39 | 23.72 | 20.17 | 3.99 | 2.23 | 13.4 | 11.7 |
| | 8 | 67.09 | 154.87 | 3.3 | 7.94 | 6.10 | 27.88 | 25.39 | 3.92 | 2.89 | 12.6 | 10.9 |
| | 9 | 75.81 | 140.64 | 4.6 | 8.66 | 7.79 | 21.41 | 19.09 | 3.67 | 2.29 | 14.1 | 12.5 |
| | 10 | 61.40 | 180.54 | 3.32 | 7.90 | 6.82 | 22.79 | 20.19 | 4.87 | 3.43 | 15.8 | 14.13 |
| S3 | 11 | 86.16 | 206.81 | 6.11 | 10.08 | 9.7 | 27.67 | 25.75 | 3.62 | 3.01 | 19.1 | 16.0 |
| | 12 | 101.14 | 276.81 | 5.44 | 9.17 | 8.08 | 30.36 | 28.59 | 4.68 | 3.17 | 17.3 | 15.1 |
| | 13 | 84.83 | 200.61 | 5.18 | 9.96 | 7.78 | 28.57 | 26.19 | 5.45 | 4.45 | 19.3 | 16.4 |
| | 14 | 97.97 | 249.91 | 6.42 | 10.92 | 9.16 | 27.45 | 25.77 | 4.12 | 3.61 | 16.9 | 13.0 |
| | 15 | 83.98 | 211.01 | 5.52 | 9.88 | 8.44 | 28.86 | 25.98 | 4.49 | 3.61 | 16.3 | 14.9 |

### *3.3. Changes in Pigments, Alkaloids, and Flavonoids*

The obtained results for Chl a, Chl b, Cars, total chlorophyll (a + b) and Chl a/b ratio, Car/Chl, alkaloids, and flavonoid contents in *P. dioscoridis* at all of the studied sites are summarized in Table 3. The results for all pigments showed a significant decrease at S1 compared to the two other sites. It should be noted that the TE accumulation was higher in *P. dioscoridis* shoots at S1 than in the two other sites. Chl b, similar to Chl a, showed a considerable reduction at S1 when compared to the rural site (S3). Carotenoids (Car) showed a considerable rise at S1, contrary to what was recorded for chl a and chl b. Car content was highest at 1.40 $\pm$ 0.04 mg/g f.w at S1 and lowest, with values of 1.28 $\pm$ 0.02 mg/g f.w, at S3.

In comparison to the control, the polluted sites showed a reduction in their total Chl content (a + b) (Table 3). The values of Chl (a + b) at S1 and S2 were 4.16 $\pm$ 0.81 and 3.85 $\pm$ 0.93 mg/g f.w, respectively, compared to the control value (4.86 $\pm$ 0.98 mg/g f.w). Meanwhile, the Chl a/b ratio showed a significant increase at S2 with a value of 2.70 $\pm$ 0.02, and at S1 for alkaloids with a value of 5 $\pm$ 0.24%. The differences in the results of the Car/Chl ratio at all three sites were non-significant (Table 3). S1 had the highest significant flavonoid value of 22.30 $\pm$ 2.438 mg/g f.w, indicating that the shoots had the highest TE accumulation at that site (Table 4).

### *3.4. Changes in Proline Content and Soluble Carbohydrate*

The results shown in Table 3 indicate that the proline content of the *P. dioscoridis* sample at the contaminated site (S1 and S2) was increased compared to the control sample (S3). The highest proline content was observed (0.78 $\pm$ 0.11 mg/g d.w) at S2 compared to S3 (0.34 $\pm$ 0.013 mg/g d.w). Generally, the results indicated that Proline content showed a higher concentration at the site that was the most highly polluted with TEs. In contrast to the proline results, the data shown in Table 3 indicates that the levels of soluble carbohydrates in plants grown in contaminated areas under TE stress were significantly reduced compared to control samples. The lowest soluble carbohydrate content was recorded at S2 with a value of 82.43 ± 9.08 mg/g d.w.

### *3.5. Nutrients (NPK) and Trace Elements (TEs) Accumulation in Plant*

Most nutrients and TEs in *P. dioscoridis* shoots and roots were significantly different between different plant organs rather than between sites ($p > 0.05$) (Table 4). The obtained results revealed that the concentrations of all examined nutrients (N, P, and K) were shown to be significantly higher in the shoots than in the roots of *P. dioscoridis*. The maximum concentrations of NPK in the shoots were detected at S1 with values of 3.24 ± 0.091 mg/kg for N, 0.444 ± 0.018 mg/kg for P, and 0.981 ± 0.061 mg/kg for K (Table 4). In the roots, N, P, and K concentrations were 2.241 ± 0.231, 0.669 ± 0.037, and 0.779 ± 0.053 mg/kg, respectively, at S1.

The obtained results, shown in Table 4, indicate that higher levels of TEs (Zn, Mn, and Cu) were accumulated in the roots of *P. dioscoridis* than in the shoots. In addition, the concentrations of Pb and Cd in the shoots were significantly higher than in the roots. In general, the largest accumulation of the TEs which were investigated was recorded at S1. The concentrations of Cd and Pb determined in shoots at the three sites were 329.0 ± 25.83, 211.0 ± 32.92, and 81.60 ± 11.76 mg/kg for Pb at S1, S2, and S3, respectively, and, for Cd 95.65 ± 9.90, 79.38 ± 11.36, and 46.09 ± 7.65 mg/kg, respectively, whereas results of Zn, Mn, and Cu showed the reverse trend. The mean values in the root and shoot ranged between 188.75 ± 16.3 and 174.0 ± 16.12 mg/kg for Cu; 125.85 ± 38.60 and 118.68 ± 28.54 mg/kg for Zn; and 295.0 ± 13.38 and 291.80 ± 17.75 mg/kg for Mn, respectively (Table 4).

### *3.6. Soil Analysis*

The data shown in Table 5 indicate the values of pH, organic matter (OM), NPK, and TE concentrations in the soil samples. Most of the studied physicochemical parameters of the soil showed the highest values at S1, followed by S2. The pH values of soil samples from the three sites were slightly alkaline (7.23–8.43). The OM values were high at S1 (6.30 ± 0.35%) and decreased at S2 (2.60 ± 0.16%) and S3 (3.20 ± 0.25%). For sites, the Pb and Cd concentration values followed the sequence S2 > S1 > S3. For the values of Cu, Zn, and Mn, the sequence S1 > S2 > S3 was observed. The maximum TE concentrations at all *P. dioscoridis* sites followed the sequence Cu > Pb > Zn > Mn > Cd.

### *3.7. BCF, TF, ECS, ECR, MAI Indices*

According to the obtained data. shown in Table 6, *P. dioscoridis* had a BCF > 1.0 for all of the examined TEs. *P. dioscoridis* had BCF values in the following order: Pb > Cd > Mn > Zn > Cu. In addition, Cu, Pb, Cd, Mn, and Zn had the opposite trend of BCF (values > 1), with TF< 1. The mean values of the TF for all of the examined TEs (except Pb and Cd at S3) were < 1 (Table 6). Cu > Cd > Zn > Pb > Mn was the order of TE translocation capability from the roots to the shoots of *P. dioscoridis*.

The maximum value of TF for Cu was observed at S1 (0.96 ± 0.08); for Pb at S3 (1.35 ± 0.35); for Cd at S3 (1.29 ± 0.04); for Zn at S2 (0.97 ± 0.093); and for Mn at S1 (0.98 ± 0.05). ECS was > 1 for Mn (S1, S2); Cd (S1, S3), and Pb (S1), while ECS values for Cu and Zn were less than one at all of the studied sites. The ECR values were >1, with the maximum values for Pb observed at S (1, 2); Cd (S1, S3); and Mn (S1, S2), while ECR values for Cu and Zn were <1 (Table 6). The highest recorded value for MAI was at S1, while the lowest was found at S3 (Figure 2).

**Table 2.** Variance analysis of the impact of the studied TE accumulation on fresh weight and dry weight of shoot parts (leaf, stem, and flower), root, leaf area (LA), specific leaf area (SLA), and leaf water content (WC) of *P. dioscoridis*.

| Accumulation | Degree of Freedom | FW. of Leaf (g) | DW. of Leaf (g) | FW. of Stem (g) | DW. of Stem (g) | FW. of Root (g) | DW. of Root (g) | FW. of Flower (g) | DW. of Flower (g) | Leaf Area (LA) ($cm^2$) | SLA ($cm^2$/g d.w) | Leaf WC (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Replication | 3 | 119.216 | 67.614 | 195.68 | 122.298 | 171.83 | 95.719 | 83.47 | 57.614 | 219.027 | 152.671 | 221.79 |
| Accumulation | 9 | 35. 45 | 28.015 | 23.0465 | 2.154 | 20.211 | 15.474 | 17.298 | 18.015 | 56.284 | 26.819 | 30.02 |
| Correlation (r-values) | 20 | 9.123 ** | 7.512 ** | 5.285 ** | 0.363 * | 7.131 ** | 7.561 ** | 6.65 * | 6.702 ** | 10.695 ** | 9.871 | 5.022 ** |
| Coefficient variation (%) | 9.83 | 9.73 | 9.09 | 7.14 | 7.38 | 11.55 | 9.93 | 6.67 | 9.39 | 9.89 | 5.64 | 6.31 |

*, **: Significant at 5 and 1% probability levels, respectively.

**Table 3.** The concentration of photosynthetic pigments (mg/g f.w), alkaloids (%), flavonoids, proline, and soluble carbohydrates (mg/g d.w) of *P. dioscoridis* samples collected from the studied sites. Data are the means of three replicates ± standard error. In each column, means with different letters are significantly different from each other ($p < 0.05$) according to Post Hoc. Tukey test.

| | Biochemical Parameters | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Chl a mg/g f.w | Chl b mg/g f.w | Car. mg/g f.w | Chl. a + b mg/g f.w | Chl. a/b Ratio | Car/Chl mg/g f.w | Alkaloides % | Flavonoids mg/g f.w | Proline (mg/g d.w) | Soluble Carbohydrates (mg/g d.w) |
| S1 | 1.38 ± 0.01 b | 1.55 ± 0.02 b | 1.41 ± 0.03 b | 2.93 ± 0.51 a | 0.89 ± 0.01 a | 0.48 ± 0.03 a,b | 5 ± 0.24 b | 22.30 ± 2.438 d | 0.52 ± 0.16 a | 90.35 ± 6.9 d |
| S2 | 1.99 ± 0.13 b | 1.78 ± 0.02 b | 1.30 ± 0.04 a | 3.77 ± 0.93 a | 1.11 ± 0.02 a | 0.34 ± 0.02 b | 4.84 ± 0.95 b | 15.39 ± 1.40 c | 0.78 ± 0.11 b | 82.43 ± 9.08 c |
| S3 | 2.87 ± 0.03 a | 2.81 ± 0.02 c | 1.28 ± 0.02 a | 5.68 ± 0.98 b | 1.02 ± 0.03 b | 0.22 ± 0.01 a | 1.84 ± 0.67 a | 18.98 ± 2.322 a | 0.34 ± 0.013 b | 113.10 ± 9.1 b |
| F-value | 11.414 | 5.893 | 5.014 | 8.976 | 5.103 | 13.990 | 2.01 | 55.911 | 6.193 | 9.414 |

**Table 4.** The concentration of TEs (Cu, Pb, Cd, Zn, and Mn) and NPK (mg/kg) in shoots and roots samples of *P. dioscoridis* were collected from the studied sites. One-way ANOVA was used. Data are the means of three replicates ± standard error. In each column, means with different letters are significantly different from each other ($p < 0.05$) according to Post Hoc. Tukey test.

| Site | Plant Organ | NPK and TEs (mg/kg) in Plant | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | N | P | K | Cu | Pb | Cd | Zn | Mn |
| S1 | Root | 2.241 ± 0.231 b,c | 0.669 ± 0.037 a | 0.779 ± 0.053 a | 160.2 ± 29.27 b | 303.20 ± 51.79 b | 86.74 ± 8.48 a | 125.85 ± 38.60 d | 295.0 ± 13.38 b |
| | Shoot | 3.24 ± 0.091 b | 0.914 ± 0.061 a | 0.981 ± 0.061 a | 154.87 ± 18.14 b | 329.0 ± 25.83 b,c | 95.65 ± 9.90 a | 118.68 ± 28.54 d | 291.80 ± 17.75 d |
| S2 | Root | 2.000 ± 0.067 a | 0.206 ± 0.032 a | 0.467 ± 0.036 a | 188.75 ± 16.3 b,c | 201.90 ± 22.94 a,b | 65.56 ± 16.27 b | 111.43 ± 31.56 b | 127.596 ± 11.79 b |
| | Shoot | 2.50 ± 0.088 a,b | 0.444 ± 0.018 a | 0.378 ± 0.040 b | 174.0 ± 16.12 a | 211.0 ± 32.92 b | 79.38 ± 11.36 a,b | 113.85 ± 14.32 a | 120.015 ± 12.02 b |
| S3 | Root | 1.850 ± 0.307 c | 0.367 ± 0.035 b | 0.529 ± 0.069 a | 72.5 ± 12.16 a,b | 60.4 ± 14.06 a,b | 35.60 ± 18.36 c,d | 91.30 ± 15.23 a | 31.367 ± 11.81 b,c |
| | Shoot | 2.65 ± 0.095 b,c | 0.438 ± 0.044 d | 0.494 ± 0.027 b,c | 60.7 ± 12.08 b,c | 81.60 ± 11.76 b,c | 46.09 ± 7.65 b,c | 87.70 ± 6.41 a | 21.558 ± 1.06 b |

**Table 5.** The concentration of TEs (Cu, Pb, Cd, Zn, and Mn), NPK (mg/kg), pH, and OM (%) in soil samples of *P. dioscoridis* collected from the studied sites. One-way ANOVA was used. Data are the means of three replicates ± standard error. In each column, means with different letters are significantly different from each other ($p < 0.05$) according to Post Hoc. Tukey test.

| Site | N | P | K | Cu | Pb | Cd | Zn | Mn | pH | OM (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 0.213 ± 0.006 a | 0.0413 ± 0.0035 c | 0.173 ± 0.0069 a | 227.29 ± 21.57 d | 223.0 ± 32.07 c | 81.67 ± 12.05 c | 184.56 ± 9.16 d | 94.24 ± 14.49 c | 8.29 ± 0.22 a | 6.30 ± 0.35 c |
| S2 | 0.190 ± 0.005 b | 0.0353 ± 0.0019 b | 0.314 ± 0.0086 d | 225.11 ± 33.73 d | 222.3 ± 21.08 a | 96.54 ± 11.03 b | 163.02 ± 11.09 c | 89.04 ± 9.31 b | 7.69 ± 0.28 b | 2.60 ± 0.16 a |
| S3 | 0.089 ± 0.004 a | 0.0277 ± 0.0029 a | 0.070 ± 0.0089 b | 97.80 ± 32.18 c | 82.0 ± 11.07 a | 21.35 ± 5.05 a | 133.00 ± 7.05 c | 38.74 ± 6.30 a | 7.28 ± 0.18 a | 3.20 ± 0.25 a |

**Table 6.** Concentration factors (CF); translocation factors (TF); enrichment coefficients for root (ECR), and shoot (ECS) of *P. dioscoridis*. Data are the means of three replicates ± standard error. In each column, means with different letters are significantly different from each other ($p < 0.05$) according to Post Hoc. Tukey test.

| TEs | Parameters | Site | | | F-Value |
|---|---|---|---|---|---|
| | | S1 | S2 | S3 | |
| Cu | CF | 1.38 ± 0.15 [a] | 1.60 ± 0.45 [a] | 1.36 ± 0.55 [a] | 142.123 |
| | TF | 0.96 ± 0.08 [a] | 0.92 ± 0.091 [a] | 0.83 ± 0.048 [a] | 237.387 |
| | ECR | 0.70 ± 0.043 [a] | 0.83 ± 0.093 [a] | 0.74 ± 0.074b [c] | 167.284 |
| | ECS | 0.68 ± 0.056 [b,c] | 0.77 ± 0.081 [a] | 0.62 ± 0.056 [a] | 132.211 |
| Pb | CF | 2.83 ± 0.85 [a,b] | 2.26 ± 0.95b [c] | 1.73 ± 0.65b [c] | 45.46 |
| | TF | 0.92 ± 0.105 [b] | 0.67 ± 0.046 [a] | 1.35 ± 0.35 [c] | 10.34 |
| | ECR | 1.47 ± 0.65 [a,b] | 1.35 ± 0.351 [a,b] | 0.73 ± 0.09 [a] | 22.13 |
| | ECS | 1.35 ± 0.35 [a,b] | 0.90 ± 0.054 [a] | 0.99 ± 0.084 [b,c] | 31.10 |
| Cd | CF | 2.23 ± 0.975 [b] | 1.50 ± 0.75 [b] | 3.82 ± 1.05 [b] | 42.52 |
| | TF | 0.90 ± 0.077 [a,b] | 0.82 ± 0.087 [a] | 1.29 ± 0.04 [a,b] | 6.77 |
| | ECR | 1.17 ± 0.095 [c] | 0.82 ± 0.15 [b,c] | 1.66 ± 0.066 [c] | 38.16 |
| | ECS | 1.06 ± 0.097 [b] | 0.67 ± 0.051 [b] | 2.15 ± 0.65 [b] | 32.87 |
| Zn | CF | 1.32 ± 0.099 [a] | 1.43 ± 0.068 [a] | 1.34 ± 0.35 [b] | 378.94 |
| | TF | 0.94 ± 0.106 [a] | 0.97 ± 0.093 [a] | 0.96 ± 0.15 [a,b] | 150.77 |
| | ECR | 0.68 ± 0.021 [a] | 0.73 ± 0.059 [a,b] | 0.68 ± 0.07 [b] | 371.46 |
| | ECS | 0.64 ± 0.053 [a] | 0.69 ± 0.057 [a] | 0.65 ± 0.043 [b] | 184.33 |
| Mn | CF | 6.22 ± 1.85 [d] | 2.78 ± 0.965 [b] | 1.36 ± 0.145 [a] | 386.59 |
| | TF | 0.98 ± 0.05 [b] | 0.94 ± 0.081 [a,b] | 0.68 ± 0.07 [a] | 32.76 |
| | ECR | 3.13 ± 0.98 [c] | 1.43 ± 0.094 [c,d] | 0.80 ± 0.105 [a] | 99.91 |
| | ECS | 3.09 ± 0.97 [c] | 1.34 ± 0.079 [b] | 0.55 ± 0.008 [b,c] | 363.10 |

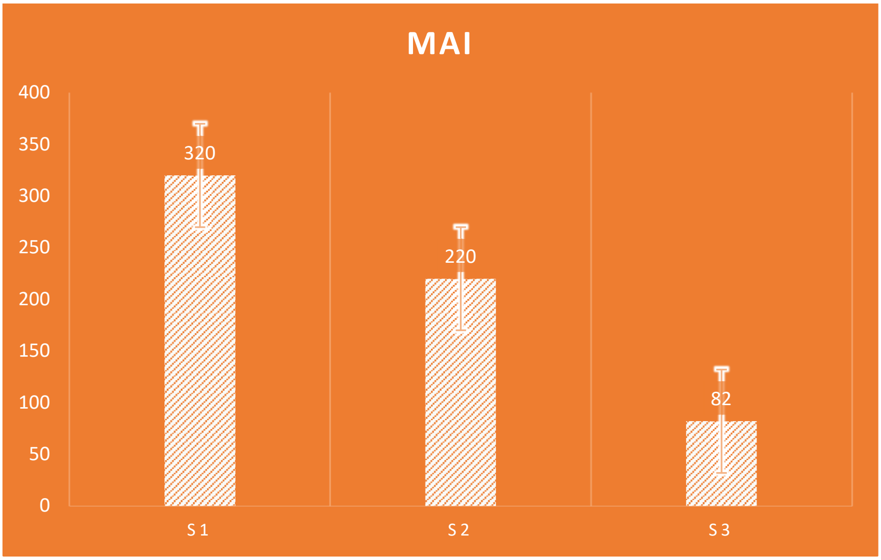


**Figure 2.** Metal accumulation index (MAI) of *P. dioscoridis* at the studied sites.

### *3.8. Plant-Soil Correlations*

For the analyzed *P. dioscoridis* tissues and soils, the Pearson correlation coefficients (r values) between the examined nutrients (NPK) and TEs are shown in Table 7. The findings revealed that various soil factors had a significant positive relationship with some nutrients and metals in the root, such as soil K (r = 0.71), soil Cu (r = 0.89), soil Cd (r = 0.83), and Cd and Zn (r = 0.77). Also, some soil variables had a significant positive correlation with some nutrients and metals in the shoot; for instance, soil N with shoot P (r = 0.59) and K (r = 0.68); soil P with shoot N (r = 0.71); and soil Cu with shoot Cd (r = 0.84) and Mn (r = 0.61).

**Table 7.** Pearson correlation coefficient (r values) between the investigated nutrients (NPK) and TEs in tissues and soils of *P. dioscoridis*.

| Plant NPK and TEs | Soil NPK and TEs | | | | | | | | Soil pH | Soil OM |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | Cu | Pb | Cd | Zn | Mn | | |
| Root | 0.31 | 0.52 | 0.45 | 0.05 | 0.01 | 0.11 | −0.73 | 0.03 | 0.51 * | 0.88 *** |
| N | 0.05 | −0.23 | 0.11 | 0.19 | 0.59 | 0.72 | 0.62 | −0.71 | 0.32 | 0.76 ** |
| P | 0.30 | 0.51 | −0.65 | −0.66 ** | 0.01 | 0.31 | 0.41 | 0.55 | 0.79 | 0.71 ** |
| K | 0.26 | 0.77 ** | −0.81 ** | 0.49 | −0.71 * | −0.23 | −0.41 | −0.24 | 0.22 | 0.60 ** |
| Cu | 0.48 | −0.42 | 0.72 | 0.71 | −0.19 | 0.83 * | 0.52 * | −0.38 * | −0.58 ** | 0.51 * |
| Pb | −0.11 | 0.22 | 0.34 | −0.71 | 0.29 | 0.21 | −0.31 | 0.41 | −0.51 * | 0.86 *** |
| Cd | −0.62 | 0.51 | −0.42 | 0.13 | −0.59 | 0.77 ** | 0.01 | 0.76 ** | −0.77 ** | 0.97 *** |
| Zn | −0.49 | 0.53 | −0.38 | 0.89 *** | 0.38 | 0.65 * | 0.23 | 0.71 * | −0.69 *** | 0.88 *** |
| Mn | −0.23 | −0.73 ** | 0.71 * | −0.59 | 0.58 | −0.51 * | −0.03 | 0.91 *** | −0.49 ** | 0.53 * |
| | | | | | Shoot | | | | | |
| N | 0.03 | 0.71 ** | −0.45 * | −0.43 | −0.41 | 0.62 | 0.32 | −0.31 * | 0.33 | 0.51 * |
| P | 0.59 * | 0.02 | 0.33 | −0.49 | −0.29 | 0.32 | 0.61 | 0.41 * | 0.66 * | 0.68 ** |
| K | 0.68 * | 0.50 | 0.73 | −0.31 * | 0.05 | −0.41 | −0.61 | −0.22 | 0.21 | 0.69 ** |
| Cu | −0.31 | −0.58 * | 0.71 | 0.36 | 0.72 | 0.63 | 0.49 | −0.03 | 0.07 | 0.91 *** |
| Pb | −0.07 | 0.43 | 0.29 | 0.50 | 0.61 | 0.11 | 0.71 | −0.91 | −0.72 * | 0.95 *** |
| Cd | 0.43 | 0.01 | −0.41 | 0.84 | 0.35 | 0.87 ** | 0.88 | −0.22 * | −0.51 * | 0.69 ** |
| Zn | −0.41 | 0.42 | 0.24 | 0.61 | 0.50 | 0.41 | 0.07 | 0.62 | −0.71 * | 0.75 ** |
| Mn | −0.03 | −0.03 | −0.65 * | −0.60 | −0.21 | 0.61 * | 0.01 | 0.86 *** | −0.64 ** | 0.61 * |

OM: Organic matter. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$

Other soil factors, on the other hand, displayed a strong negative association with root nutrients and TEs, such as soil P with root Mn (r = −0.73); soil Cu with root K (r = −0.68); soil Cd with root Mn (r = −0.51); soil Mn with root Cu (r = −0.38); and soil Mn with root P (r = −0.71). Other soil factors demonstrated a significant negative connection with shoot nutrients and TEs, including soil P with shoot Cu (r = −0.58); soil K with shoot N and Mn (r = −0.45 and −0.56, respectively); soil Mn with shoot Pb (r = −0.91); and soil Cu with shoot K (r = −0.31). The findings revealed that soil pH and OM had a significant impact on TE concentrations in *P. dioscoridis*. As a result, all of the TEs in *P. dioscoridis* tissues displayed a strong negative correlation with soil pH. Soil pH was found to have a negative correlation with root Cu, Pb, Cd, Zn, and Mn (r = −0.58, −0.51, −0.77, −0.69, and −0.49), whereas OM had a positive correlation with all of the investigated inorganic nutrients (N, P, K) of the root (r = 0.88, 0.76, and 0.71, respectively) and shoot (r = 0.51, 0.68, and 0.69, respectively). Soil OM had a positive correlation with root Pb, Cd, Zn, and Mn (r = 0.86, 0.97, 0.88, and 0.53) and shoot Pb, Cd, Zn, and Mn (r = 0.95, 0.69, 0.75, and 0.61).

## 4. Discussion

A large amount of environmental and agricultural activities, such as photosynthesis, transpiration, and field energy balance, can significantly impact LA and SLA values. Metal bioaccumulation has a deleterious influence on leaf production [47]. These findings are consistent with those of Refs. [6,48], who found that metal accumulation can reduce plant development, resulting in a drop in LA. Also, SLA is influenced by leaf growth, structure, and photosynthesis [49]. Accordingly, the lowest recorded LA and SLA values at S1 and S2 had the smallest leaf lamina expansion, which was closely associated with the significant TE accumulation in these sites. The rise in TE accumulation level and dry climate of the studied area may have caused WC (%) values to fall at all polluted sites. The low WC values of contaminated leaves appear to confirm the idea of low production [47].

Several studies [15,50] have connected reduced chlorophyll content in a variety of plant species to TE exposure. Any alteration in chlorophyll content affects plants' morphology, physiology, and biochemistry. Many researchers have discovered that metal accumulation accelerates the depletion of photosynthetic pigments [51,52]. The present findings revealed that values of Chl (a) and (b) in *P. dioscoridis* tissues were reduced in polluted areas. According to Refs. [53,54], this drop in chlorophyll concentration reflects foliar damage caused by TE contamination. These findings agree with those of Ref. [55], who found that metal pollution had a significant impact on chlorophyll levels. De Filippis and Pallaghy [56] also stated that TEs can impede the formation of chlorophyll pigments and enzymes.

The obtained results showed that, with increases in the TE concentration, there was a substantial drop in the total Chl (a + b) of *P. dioscoridis*. These results agree with many studies that revealed that TE toxicity can diminish the amount of photosynthetic pigment in many plant species [12]. The chlorophyll ratio (a/b) is a stress indicator. The ratio rose, in the current study, as the level of polluting metals increased [6]. Furthermore, numerous scientists have claimed that an increase in chlorophyll ratios was linked to increased environmental stress [57–60].

Carotenoids work as non-enzymatic antioxidants to protect plants from oxidative stress [61]. The current findings support those of [62,63], who found that increasing Cars content is an effective method to protect plants from free radical generation. *P. dioscoridis* can be a good option to recover TE-contaminated circumstances in phytoremediation because of the high content of Cars at polluted areas and its higher resilience to TE pollution.

Proline is a vital partner in structural proteins and enzymes, and it is engaged in the repair process. It is also known to have a function in the reconstruction of chlorophyll, the activation of the Krebs cycle, and the sequestering of free radicals; as well, it serves as an energy source. Proline content was found to be considerably high in *P. dioscoridis* as the TE accumulation rate rose, indicating pollution stress. Proline accumulation in plant leaves could serve as a suitable solute to maintain the osmotic balance between the vacuoles and the cytoplasm [64].

Soluble sugars, which are the plant's source of energy, are one of the most significant ingredients in the cell structure. The decrease in soluble carbohydrate content under TE stress in the current results can be considered as a defense mechanism of the plant and help in osmotic protection to perform adaptation against the inappropriate environment [65,66]. The relationship between soluble carbohydrates and photosynthesis is mostly determined by changes in the carbohydrate concentration. The current decrease in soluble carbohydrate content under TE stress when compared to control values may be due to the inhibition of biosynthesis of chlorophyll or stimulation of the respiration rate, which leads, finally, to a reduction in carbohydrate contents [67].

Many studies have indicated that the effect of a high concentration of TEs has a significant impact on the fresh and dry weight of plants [68]. According to the present results, this drop in the fresh and dry weight of *P. dioscoridis* shoots and roots is most likely due to a decrease in photosynthetic processes, which reduces carbohydrate metabolism [69,70]. Disturbance in water availability [71], suppression of nutrient uptake [70,72], and protein degradation are some of the other causes of reductions in the fresh and dry weight of *P. dioscoridis* shoots and roots.

It has been reported that, as a result of the occurrence of high levels of nutrients in the soil, the ability of hyperaccumulation of plants can be improved; this may be due to the role of NPK in the soil in enhancing the availability of TEs for plants, shown in Ref. [73]. The current findings revealed that *P. dioscoridis* has a high NPK level in the shoots and roots at S1 (with high industrial activities, and agricultural and urban activities), indicating the plant's capacity to adapt to the stress resulting from the accumulation of trace metals and pollutants through the regulation of some physiological and metabolic processes inside its cells and tissues [74].

Some plants have a remedial nature which helps plants to absorb high amounts of trace metals through the "chemical phytostabilization" mechanism. The plant roots are the main route for the transfer of elements and nutrients from the soil. Most agricultural practices, as well as their wild flora, take place within the polluted sites (S1 and S2). Large amounts of TEs have been collected in the topsoil as a result of industrial activity and intensive traffic [75]. The accumulation degree of trace metals in the soil is mainly influenced by factors such as pH, TEs level, OM % (organic carbon), and soil particle size. The findings of the current study recorded the alkaline pH values of the soil which, in turn, led to a decrease in the availability of some TEs for plant roots by enhancing the ability of colloids in the soil to absorb cations [76]. If a value of BCF above 1 indicates a higher uptake of TEs in crop/plant than in soil, then a BCF of less than 1 means a higher TE concentration in soil than in plants [43]. The highest recorded values of ECR of *P. dioscoridis* in the present study declared that this plant could be exploited for monitoring TEs (Cd, Pb, and Mn, not Cu and Zn). The significant positive correlations between Cd and Pb in soil with those in *P. dioscoridis* tissues suggest its potential use as a bioindicator and biomonitor for Cd and Pb pollution.

## 5. Conclusions

Through phytoremediation technology, wild metal hyperaccumulator plants flourishing in contaminated places could present an alternate solution for the treatment of soils enriched with TEs (trace elements), resulting from industrial and traffic activities.

Based on the current data, the photosynthetic pigments and flavonoids decreased significantly at S1, at which TEs were accumulated with high concentrations. This drop in chlorophyll concentration reflects foliar damage caused by TE accumulation. The carotenoids/chlorophyll index (Car/Chl) ratio showed non-significant variations for all studied spheres. High values of chlorophyll ratio (a/b) were also recorded in plant leaves which faced TE stress. According to the values of the bioconcentration and translocation factors (BCF > 1 and TF > 1), *P. dioscoridis* can accumulate high levels of TEs in its tissues. This suggests that *P. dioscoridis* could be a useful strategy for TEs phytostabilization. The highest recorded values of enrichment coefficient for the shoot (ECS) of *P. dioscoridis* indicated that this plant can be used as a phytoextraction strategy for Cd, Pb, and Mn, but not Cu and Zn, in contaminated areas. The concentrations of NPK in the shoot were significantly higher than in the root. However, the concentrations of most TEs were significantly higher in the roots than in the shoots. The significant positive correlations (r values) between Cd and Pb in soil with those in *P. dioscoridis* tissues suggest its potential use as a bioindicator and biomonitor for Cd and Pb pollution. Future studies are required to evaluate the potential of wild species, particularly *P. dioscoridis*, under man-made environmental stressors for phytoremediation purposes.

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## Abbreviations

| | |
|---|---|
| TEs | Trace Elements |
| Car/Chl | Carotenoids/Chlorophyll |
| TF | Translocation factors |
| ECR | Enrichment coefficient for root |
| ECS | Enrichment coefficient for shoot |
| MAI | Metal accumulation index |
| ROS | Reactive oxygen species |
| LA | Leaf area |
| SLA | Specific leaf area |
| WC | Water content |
| RWC | Relative water content |
| FW | Fresh weight |
| DW | Dry weight |
| TW | Turbid weight |
| NPK | Nitrogen, Phosphorus, Potassium |
| AQ | Aqua regia |
| BCF | Bioconcentration factors |
| EC | Enrichment coefficients |

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# Construction of Control Charts to Help in the Stability and Reliability of Results in an Accredited Water Quality Control Laboratory

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**Abstract:** Overall, laboratory water quality analysis must have stability in their results, especially in laboratories accredited by ISO 17025. Accredited parameters should be strictly reliable. Using control charts to ascertain divergences between results is thus very useful. The present work applied a methodology of analysis of results through control charts to accurately monitor the results for a wastewater treatment plant. The parameters analyzed were pH, $BOD_5$, COD, total suspended solids, and total phosphorus. The stability of the results was analyzed from the control charts and 30 analyses performed in the last 12 months. From the results, it was possible to observe whether the results are stable, according to the rehabilitation factor that cannot exceed WN = 1.00 and the efficiency of removal of pollutants that remained above 70% for all parameters. The method of determining the technological reliability and stability of the treatment station using control charts is an efficient tool for detecting any instability in the results. These results help to monitor the results of the analyses more clearly and thus enable a rapid response to possible disturbances and maintain the quality of the analysis control, as well as determining the accreditation entities.

**Keywords:** water quality; control charts; reliability; wastewater treatment

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## 1. Introduction

Quality management in accredited laboratories consists of a set of actions based on the international regulatory standard ISO 17025. It is seen as fundamental to maintaining the suitability of its services and products. Organizations are increasingly looking for improvement in their procedures and have tools contributing to achieving their goals. Using statistical controls, continuous improvement, training, and participation reduce the process's variability and consequently increases quality and productivity. Some tools help ensure quality control. Some examples are check sheets, histograms, and control charts [1,2]. For Samohyl [3], quality is ensured by minimizing variations in the characteristics of products and procedures.

Control charts or charts are one of the main statistical tools used to control and monitor processes. They signal the presence of accidental causes and special causes in a process [4]. According to Corrêa [5], every process has variation, and a natural or common cause is within the control limits. In contrast, so-called special causes need more attention because they indicate values outside the control limits and therefore need rapid correction. Using control charts to manage routine analyses allows easy detection of negative trends in analytical work, enabling quick corrective action, reducing out-of-specification results, and consequently avoiding non-compliance [6]. They can be applied in several areas and are used worldwide. A study carried out by Razif [7] proves that the use of control charts contributed to faster detection of anomalies in a daily cycle of analysis and showed similarities in the characteristics of the water quality data of the Surabaya river in Indonesia between 2014 and 2015 for several parameters such as $BOD_5$, COD, and TSS.

In an analogous study in Brazil using control charts in conjunction with other statistical tools, it was possible to identify the problem in the domestic sewage treatment plant. The treatment did not produce an effluent with characteristics that meet the specifications or release standards of the environmental legislation, indicating the need for restructuring and correction of the efficiency of the process [8].

The International Standard ISO: 7870-1, 2019 addresses the objectives regarding control charts, among the main ones being: indicating if the process is stable, comparing information from samples that represent the current state of the process against the control limits that reflect this variability; estimating the magnitude of the variability inherent to the process; and aiming to determine if the variability of the process has remained stable or if there are oscillations. In a study by Liz and Piotr (2022) [9], they concluded that control charts could be an effective tool for assessing the operation of a sewage treatment plant, allowing the detection of any disturbances during the sewage treatment process in the tested facility. Thus, they enable operators to take appropriate action to remove them quickly and ensure the natural reservoir's water quality. The Shewhart-type control chart is the most used and has broad applicability. In building this model, a preliminary period of subsequent sample analysis is needed to determine the control limits [10]. After this analysis period, statistical treatment is applied to obtain the control charts.

According to Zan et al. [11], control charts are used to monitor whether the process is controlled or not. They have long been used for quality monitoring in the manufacturing process. If only random causes affect the operation, it is considered that the production process is natural or normal [12]. At this time, the control chart tends to fluctuate randomly in the symmetrical coordinate system. The traditional control chart easily detects the abnormity beyond the boundary. Still, it is challenging to identify the abnormity range that usually requires human judgment and is easily affected by various factors.

The problem of water pollution in urban areas is essential and current due to progressive urbanization, aging of ecological infrastructure, and high population density [9,13]. The Member States of the European Union, in agreement with the Water Framework Directive (WFD), are obliged to use and protect their water resources rationally. These include the proper treatment of wastewater.

This study aimed to apply a methodology of analysis of results through control charts, aiming at accurately monitoring the results for a wastewater treatment plant from a slaughterhouse in a specific region of Alentejo in Portugal. The parameters analyzed were pH, biological oxygen demand for five days ($BOD_5$), chemical oxygen demand (COD), total suspended solids (TSS), and total phosphorus (TP).

According to Reilly et al. [14], slaughterhouse wastewater presents a biological risk to humans and other animals due to the presence of pathogens, pharmaceuticals, and toxic chemicals used for plant cleaning [15]. This harmful potential means that the disposal of slaughterhouse and dairy waste is often subject to local legislation which has been put in place to protect public health [16]. For example, COD in slaughterhouse wastewater often requires a 95% reduction, with similar levels of treatment being required for TP before final discharge into the environment [15]. Currently, the UK dairy processing and slaughterhouse industries use technologies such as chemical dosing, reverse osmosis, anaerobic digestion, dissolved air floatation, and membrane bioreactors to treat their wastewater. They have been obtaining good results [17–19].

The construction of control charts will help guide analysts when there are results outside the control lines, making it possible to reassess the results faster if necessary. This method will assist in managing the quality of the results of the water analysis laboratory.

## 2. Materials and Methods

### *2.1. Description of the Study*

The School of Agriculture has a water quality control laboratory accredited by ISO 19025, where water quality is analyzed. This laboratory is located in Beja, Portugal. The technological process of the wastewater treatment plant analyzed includes mechanical, biological, and chemical treatment of wastewater. The values of pollution indicators for sewage discharged into the municipality to the slaughterhouse may not exceed the following values: pH—19, $BOD_5$—500.0 mg $O_2 \cdot L^{-1}$, COD—1500.0 mg $O_2 \cdot L^{-1}$, TSS—1000.0 mg$\cdot L^{-1}$, Pt– 25 mg $P \cdot L^{-1}$ these values are accorded between the company and the municipality.

The objective was thus to create control charts for the pH, $BOD_5$, COD, total suspended solids, and total phosphorus parameters in analyzing a wastewater treatment plant from a slaughterhouse in Alentejo for 18 months (2021–2022).

## 2.2. Methods

The methodology was made according to Figure 1. The laboratory receives the wastewater samples, analyzes them creates a database. The work was applied from this step forward, where the data was analyzed, and the control charts were created.

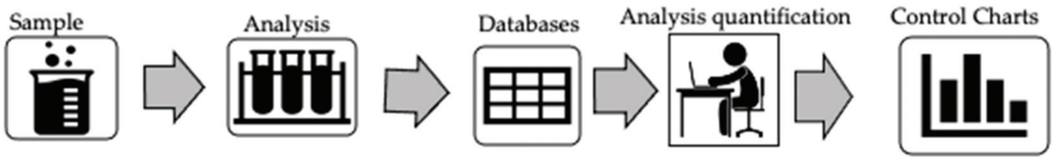


**Figure 1.** Process method.

The creation of the control charts is structured with an upper control line (UCL), a lower control line (LCL), the process means or target (CL), and the observed points. This statistical tool shows the evolution over time of a characteristic, allowing the identification of the purpose of variations and assisting in a continuous improvement of the process to produce itself according to the specifications keeping the process under statistical control. Statistical control is ensured through the lines of the control limits that allow real-time analysis of the progress of the process.

This represents the statistic related to the variable of interest in case one or more points exceed the control limits, indicating that the process has a problem [20].

For pollution indicators in treated sewage, control charts were with the boundaries of the helplines, and the control lines and the center line were determined considering the tree-sigma rule for the normal distribution N ($\mu$, $\sigma$) [9,21,22].

Lower control line (*LCL*):

$$LCL = \mu - 3\sigma \quad (1)$$

Lower warning line (*LWL*):

$$LWL = \mu - 2\sigma \quad (2)$$

Lower helpline (*LHL*):

$$LHL = \mu - 1\sigma \quad (3)$$

Centre line (CL):

$$CL = \mu \quad (4)$$

Upper helpline (*UHL*):

$$UHL = \mu + 1\sigma \quad (5)$$

Upper warning line (*UWL*):

$$UWL = \mu + 2\sigma \quad (6)$$

Upper control line (*UCL*):

$$UCL = \mu + 3\sigma \quad (7)$$

where: $\mu$ = average of the analyzed values, and $\sigma$ = standard deviation of the analyzed variable.

To analyze the technological reliability and stability of the wastewater treatment station in Alentejo, Portugal, with the use of control charts, some specifics were necessary; the coefficient of technical reliability was used, as in other authors [9]:

$$WN = \frac{x_{sr}}{x_{dop}}\,[-] \quad (8)$$

where $WN$ = plant reliability factor [−], $x_{sr}$ = average value of the analyzed pollution index in treated sewage [mg·dm$^{-3}$], and $x_{dop}$ = permissible value of the analyzed pollution index in treated sewage [mg·dm$^{-3}$].

To determine the effectiveness of wastewater treatment, it was calculated according to the following formula:

$$\eta = \frac{S_s - S_0}{S_s} \times 100\% \quad (9)$$

where: η = reduction of a particular pollutant index in treated sewage [%], Ss = value of the pollution index in raw sewage [mg·dm$^{-3}$], and So = value of the pollution index in treated sewage [mg·dm$^{-3}$].

To verify interruption or instability of the effluent treatment process from control charts, we can use the following parameters according to Andraka [23]: eight consecutive points on one side of the central line, one point outside the control limits, two of the three points outside the ±2σ warning lines and four of five consecutive points beyond the ±1σ extension lines [9].

Control charts have three fundamental objectives: reducing variability, monitoring, and estimating process quality parameters [24]. In constructing control charts, it is essential and valuable to distinguish the two phases of implementation and construction.

In phase 1, a set of process data is analyzed retrospectively to understand the variation of the process over time, evaluate the stability of the process, and model the performance of the process under control. This last step is usually carried out by estimating the parametric model in phase 2, in which the process has been previously estimated. Phase 1 thus corresponds to a retrospective check of the process where the experimental control limits are calculated, while phase 2 concerns monitoring the process itself [25].

Phase 2 begins after collecting a set of process data under stable conditions and is representative of the performance of the process under control. In phase 2, a control chart is used to monitor the process, comparing the sample statistics for each successive sample as extracted from the process with the control limits [26].

## 3. Results

The results show the control charts for the inlet and outlet effluents of an existing wastewater treatment plant in a slaughterhouse in Alentejo, Portugal.

Figures 2 and 3 show the inlet and outlet effluent behavior for the pH parameter. The control charts show the variation during the 30 days of treatment for wastewater.

It can be seen that after treatment, the results are stabilized; this is the possible interpretation of the analysis definition of the control lines. Figure 4 shows the COD inlet results; compared to Figure 5, the COD outlet shows an improved system. For Figure 5, there is a first point close to the LWL, but it is not necessary to take control because the next point is far away from the LWL. Only two points cross the control lines, and this behavior does not jeopardize the treatment outcome.

Analyzing the results for Figures 6 and 7. it is possible to see the same stability of the results at the outlet of the treated effluent with only one point crossing the UCL control line. Due to all the results obtained having this same point outside the standard, it is believed that the treatment was ineffective on this day.

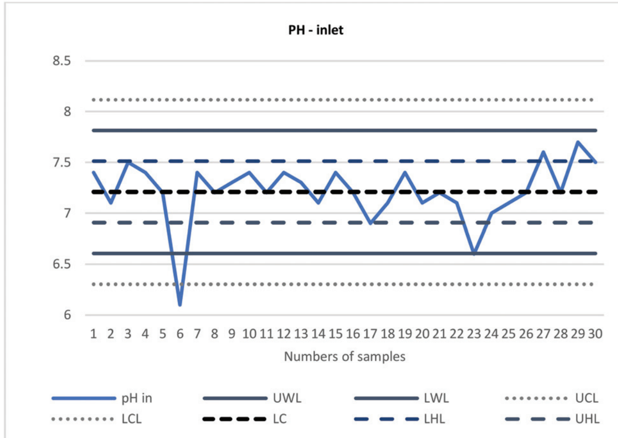


**Figure 2.** pH inlet.

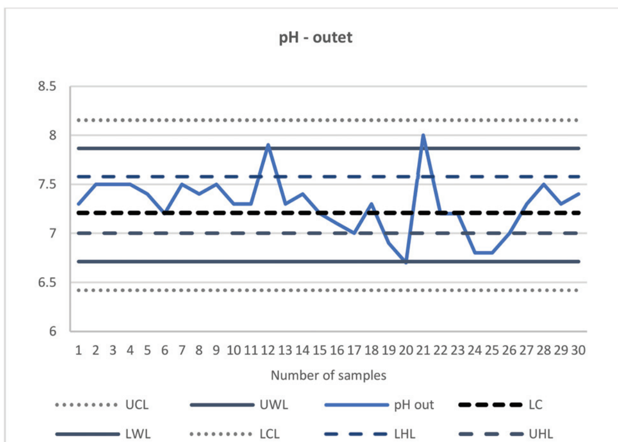


**Figure 3.** pH outlet.

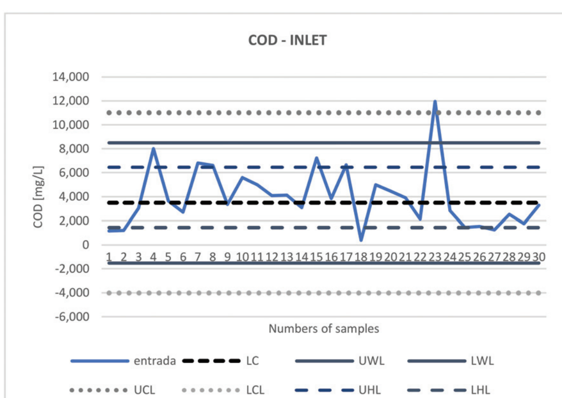


**Figure 4.** COD inlet.

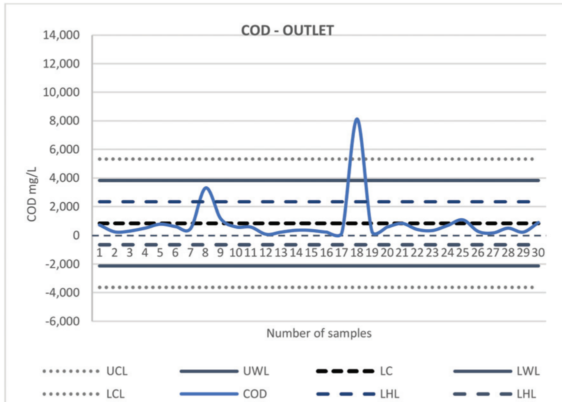


**Figure 5.** COD outlet.

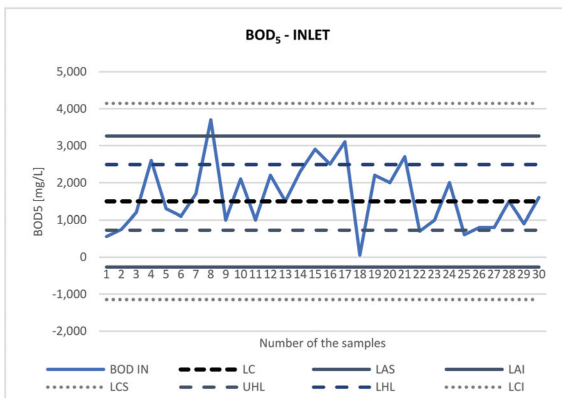


**Figure 6.** $BOD_5$ inlet.

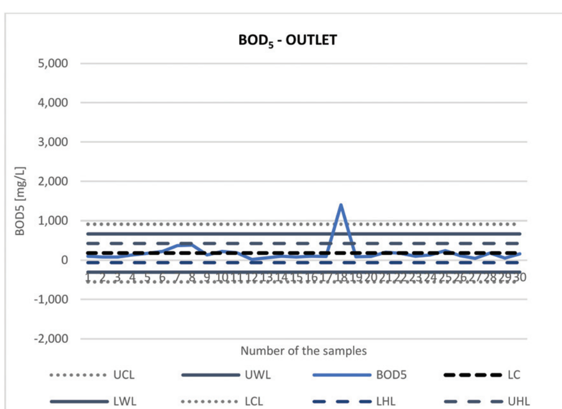


**Figure 7.** $BOD_5$ outlet.

For total phosphorus results, Figures 8 and 9 show similar results. The resulting line remains stable and only crosses the UHL line once; the results stay close to the LC control line across all samples.

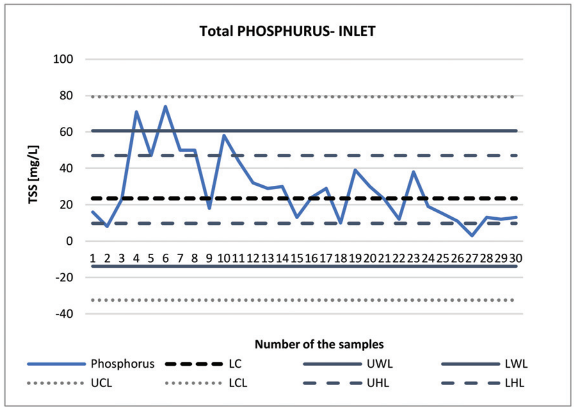


**Figure 8.** Total phosphorus inlet.

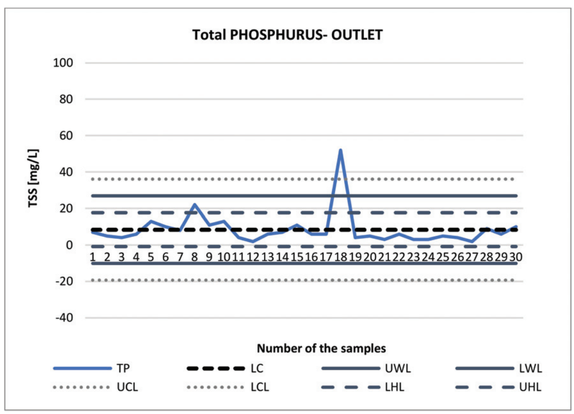


**Figure 9.** Total phosphorus outlet.

For the TSS inlet chart (Figures 10 and 11) as a sample to reach the UWL line when observing the TSS outlet chart, it can be noted that the post-treatment results are stable, except on three occasions. In this situation, it may alert the company to a possible problem in the treatment in that specific period.

All control charts obtained were analyzed, and most points are under statistical control in Figures 2–11. In accordance with Montgomery [26], only rule 1, the presence of special causes of variation, was evaluated, and there was only one particular cause. With the process under statistical control in phase 1, it passes to phase 2, which consists of monitoring the process.

The purpose of using the rules is to increase the sensitivity of control charts. However, care must be taken when using a set of rules, as an excessive number of false alarms may occur. The higher the number of rules to be used, the greater the number of false alarms [26].

Table 1 shows the technological reliability coefficient against the average efficiency of the analyzed pollutants removal in the sewage treatment plant. It can be seen that the efficiency of reduction from treatment is good enough to reach more than 70% in all parameters analyzed, with better results for the $BOD_5$ indicator, reaching 89%.

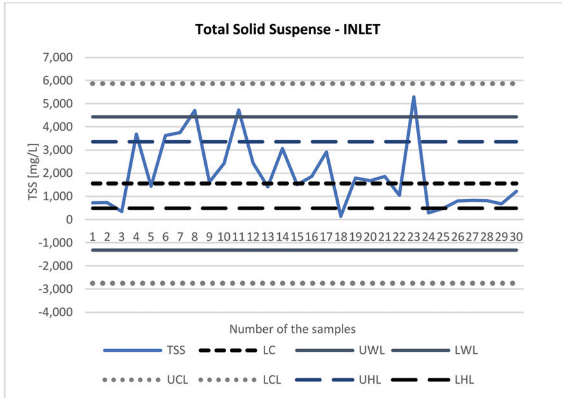


**Figure 10.** Total suspended solids inlet.

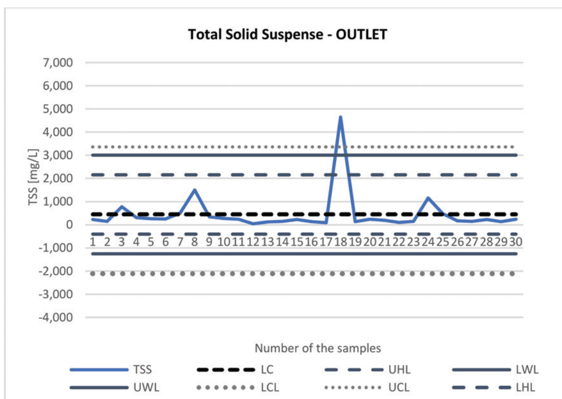


**Figure 11.** Total suspended solids outlet.

**Table 1.** Value of the technological reliability coefficient against the average efficiency of the analyzed pollutant removal in the sewage treatment plant in the Alentejo slaughterhouse.

| Indicator | $BOD_5$ | COD | TSS | TP |
|---|---|---|---|---|
| Reliability coefficient WN | 0.37 | 0.57 | 0.45 | 0.84 |
| Reduction Efficiency η (%) | 89 | 78 | 76 | 70 |

Explanations: $BOD_5$ = biochemical oxygen demand, COD = chemical oxygen demand, TSS = total suspended solids, TP = total phosphorus.

The $BOD_5$ parameter showed the lowest rehabilitation coefficient (WN) of 0.37 and, consequently, the most excellent technological reliability, which indicates a very satisfactory result for this parameter. For COD and TSS parameters, the rehabilitation coefficient showed results of 0.57 and 0.45, respectively, indicating values that can be considered reasonably good. In the case of TP, the indicated value is within the legislation in force. However, it is the highest value for the rehabilitation coefficient and consequently has the lowest treatment efficiency among the analyzed parameters since the indicators are inversely proportional. A study by Mlyński [27] used the indicator to prove the technological reliability of the treatment plant, where it obtained results below 1. However, this was slightly higher when compared to the results obtained in the present study.

## 4. Discussion

Although there were some lower deviations in the LC, most of the results were stable after the treatment, which can be seen from the construction of the control charts.

The graphs demonstrate stability after water treatment, except for occasional events in a given period. These points that suffered oscillation may indicate a lower treatment efficiency because this anomaly is in the same period and different parameters such as COD and $BOD_5$. For the TSS input graph as a sample to reach the UWL line by looking at the TSS output graph, it can be noted that the post-treatment results are stable, except for three points that, in this situation,, may alert the company to a possible problem in the treatment in that specific period. Another potential cause of this difference in results may be related to the error in sample collection.

In sample 18, all parameters were altered beyond the control lines UCL, UWL, and UHL, except for the parameter pH. This behavior leads us to believe that the wastewater treatment plant had some technical problems that led to the inefficiency of treatment or stoppage of the process on this day. It is verified that only with this sample we obtained this change. In the previous and subsequent samples, the results were satisfactory within the control lines, as expected. According to Nagendra and Rai [28], the chart series size, sample size, and sampling interval are the three main factors in detecting changes efficiently. Thus, for further investigation of the cause of this variation, a larger number of samples is required. In a similar study Moore [29] suggests that in relation to the Shewhart chart of averages ($x^-$), the errors depend on the degree of non-normality and the sample size (or subgroup). These errors can be reduced by using a larger sample size.

Studies related to wastewater treatment from slaughterhouses indicate the need for efficiency in treatment due to environmental risks and human health. When comparing the results obtained by Really et al. [14] in their studies for COD (75%) and $BOD_5$ (85%), the results obtained in this study show a good removal efficiency for values of 78% and 89%, respectively. These data assist in analyzing results compared to the values established in the decrees of laws in force for Portugal, such as 236/98 [30].

According to Decree-Law No 236/1998 [30], phosphorus in wastewater may have a concentration of 10 mg P/L in the forms of orthophosphates, polyphosphates ($P_2O_7$), and organic phosphorus [31]. Wastewater treatment is carried out to avoid risks to public health, pollution of water resources, and the environment in general. It is essential to be able to control these results. The work performed by [32] created control charts similar to this work and obtained values of 95% for removal efficiency and 0.49 for the rehabilitation coefficient for TP. The values are better than those found in Table 1 for the TP, and a justification for these results is the origin of the residual water. Although there is a similarity in the construction of the control charts, we cannot compare the results since they are wastewater from different sources.

These results help in the analysis of data in the laboratory, thus creating a greater control, so when a result is outside the line control (LC) in the respective control chart, it can already be said that there was an error in the treatment process, facilitating the search for corrections.

## 5. Conclusions

The study's main objective was based on the application of statistical control of the process of analyzing wastewater from a food industry company, more specifically in the meat sector (a slaughterhouse). From the experimental point of view, it started by diagnosing the work of data control from the results of the construction of control charts to identify the main problems and situations to be corrected and monitored.

Most of the results of the studied parameters in question oscillated around the central line and did not show any crossing of the control lines or grouping of samples below or above the characteristic lines.

The control charts were effective for what was proposed, and variations could be observed in the analyzed period. These results confirm that the treatment is stable according to the rehabilitation coefficient and treatment efficiency results.

It can be observed that on the 18th day of collection, all parameters exceeded the UWL. This behavior is due to a possible isolated failure of treatment. It can be observed in all control charts constructed, thus concluding the objective of the work where the rapid detection of variations in small scales allows the identification of such causes of variability. However, it is possible to state that all points are under statistical control, and this chart can then be used in the laboratory routine.

**Author Contributions:** Conceptualization, F.M.O.d.S. and K.S.S.; methodology, F.M.O.d.S. and M.A.A.; validation, F.M.O.d.S., K.S.S. and M.A.A.; formal analysis, M.I.C., M.R., I.S. and M.J.I.; investigation, F.M.O.d.S. and K.S.S.; data curation, M.I.C., M.R., I.S. and M.J.I.; writing—original draft preparation, F.M.O.d.S.; writing—review and editing, F.M.O.d.S. and K.S.S.; supervision M.A.A. All authors have read and agreed to the published version of the manuscript.

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## Abbreviations

| | |
|---|---|
| $BOD_5$ | Biological oxygen demand |
| CL | Centre line |
| COD | Chemical oxygen demand |
| LCL | Lower control line |
| LHL | Lower helpline |
| LWL | Lower warning line |
| TP | Total phosphorus |
| TSS | Total solid suspense |
| UCL | Upper control line |
| UHL | Upper helpline |
| UWL | Upper warning line |
| WFD | Water framework directive |

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# Real Estate Values and Urban Quality: A Multiple Linear Regression Model for Defining an Urban Quality Index

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**Abstract:** Urban quality, real estate values and property taxation are different factors that participate in defining how a city is governed. Real estate values are largely determined by the characteristics of urban environments in which properties are located and, thus, by quality of the location. Beginning with these considerations, this paper explores the theme of urban quality through a study of property values that seeks to define all physical (and thus measurable) characteristics that participate in defining urban quality. For this purpose, a multiple linear regression model was developed for reading the residential real estate market in the city of Pescara (Italy). In addition to the intrinsic characteristics of a property (floor area, period of construction/renovation, level, building typology and presence of a garage), input also included extrinsic data represented by the Urban Quality Index. Scientific literature on this theme tells us that many independent variables influence real estate prices, although all are linked to a set of intrinsic characteristics (property-specific) and to a set of extrinsic characteristics (specific to the urban context in which the property is located) and, thus, to the quality of urban environments. The index developed was produced by the analytical and simultaneous reading of four macrosystems with the greatest impact on urban quality: environment, infrastructure, settlement and services (each with its own subsystems). The results obtained made it possible to redefine proportional ratios between various parts of the city of Pescara, based on a specific Urban Quality Index, and to recalculate market property values used to calculate taxes in an attempt to resolve the inequality that persists in this field.

**Keywords:** Urban Quality Index; real estate; real estate taxation; spatial analysis; multiple linear regression; sustainable planning; governance instrument

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## 1. Introduction

The evolution of the urban environment through dynamic processes of innovation contributes to the transformation of the original territorial dimension of a city. From an economic-estimative point of view, it is possible to identify—and monitor—the impact of these changes by observing variations in the real estate market.

Changes to the structure of the city [1], the introduction of new infrastructures or facilities in an urban area or further variations to the urban fabric resulting from political-administrative decisions [2,3] and/or spatial management are all factors with a positive or negative influence on the formation of real estate prices [4]. They can also modify the functional aspects of spaces and, as a reflection, the quality of life for residents.

Dynamic conditions and the need for administrations to produce development plans [5] and adopt approaches that confirm changes taking place return the city to the centre of debate: to understand the scarcity and abundance of the characteristics of which the urban environment is a global expression in order to select and implement appropriate strategies for pursuing a sustainable increase in urban quality [6].

*Typical problems of large cities such as the degradation of neighbourhoods, the increase in road traffic, socio-economic deprivation, physical and mental health inequalities,* *have become central political issues in most EU countries. This is reflected in the local environmental quality and European and governmental strategies of individual states with respect to housing, spatial planning and national and local environmental policies [6].*

Consequently, every decision taken within the urban environment has the ability to increase or diminish the value—qualitative and economic—of the environment with which it interacts, with further considerations of the fact that interventions involving settlements, or the conservation of urban natural elements, are not always associated with economic benefits [7]. The entity of their value can be quantified by studying the variation in property values situated in proximity to interventions (land value recapture), and this includes the work of architecture, improvement in services, creation of public space or rehabilitation of environmental resources.

The case study is located in the Abruzzo region, where the inland areas are affected by demographic decline exacerbated by the consequences of the 2009 earthquake. While this has resulted in a stagnation of real estate values [8], coastal areas—where the city of Pescara is located—have a much more dynamic real estate market. As with indicators that, on a large scale, make it possible to *detect changes in land use to allow for the implementation of appropriate control and planning actions* [9], the intention, for the Pescara real estate market, was to create an articulated variable at the urban level—the Urban Quality Index—that considers a series of peculiarities of the urbanised environment and the sum of services innervating it in relation to market real estate values [10,11]. The principal challenge involved retracing and surveying measurable physical and univocally interpretable aspects within the urban environment and verifying their statistical significance—market appreciation—by using a multiple linear regression model. As is known, multiple regression is used to explain the entity of a dependent variable (in our case market value) by using a set of independent variables clearly held to influence the entity of the dependent variable [12]. Despite their relevant incidence, these independent variables—the characteristics of the city—can be very difficult to identify.

The concept of urban quality was, thus, defined in relation to the appreciation manifested by the real estate market for property location and using a unique variable to define different levels of quality in diverse parts of the city.

The effects of social, economic and cultural dynamics that, certainly, *play a decisive role in the decision-making processes on urban strategies* [13] and the indicators which more generally define the quality of life of citizens such as the level of access to health or social services [14,15], while not directly explicated in the indicator, structured atop an appropriate subsystem used to quantify their presence can nonetheless be said to have been considered as they are directly connected with spaces-services (public gathering spaces, public and private offices, places offering services to people or the community, etc.) and are physically identified and quantified.

In Italy, property values are currently determined by the Cadastral Registry—now the Revenue Agency (*Agenzia delle Entrate ex Agenzia del Territorio*). Calculations consider numerous variables, including both intrinsic and extrinsic. Nonetheless, the scheme for defining cadastral income based on an obsolete structure and organised by rigid schemes is unable to capture urban, typological and socioeconomic changes to the city. To date, revisions and adaptations have focused exclusively on the fiscal-monetary side of estimation tariffs and introducing percentage multipliers to correct the distortive effects of inflation, and it is unable to capture urban, typological and socio-economic changes in the city.

The results of this study make it possible to affirm that an increase in the values identifiable in diverse areas of the city must be redistributed in a balanced manner in order to permit a general increase in property values. In light of emerging data, this translates into a higher quality of both the urban habitat and services in proximity to properties, with a consequent benefit to users and an effective administrative tool for reading the territory that assists the decision maker in choosing the policies to be implemented, as has happened, for example, in recent years in Italy, with a view toward decommissioning, adaptively reusing or redeveloping public building stock [16].

## 2. Materials and Methods

The definition of the Urban Quality Index is triggered by a reading of the urbanised fabric. This process began by subdividing the municipal territory into homogenous zones (in accordance with Decree of the President of the Republic dated 23 March 1998 n. 138 138/98) and identifying all of their characteristic elements; successively, these elements were related to corresponding values referred to the entire municipal territory.

The surveying process followed the indications contained in the bill dated 15 June 2012 in matters of taxation and developed in accordance with the following operative criteria:

Territorial segmentation: In reference to municipal territory, a perimeter was established to form microzones as defined in the Decree of the President of the Republic dated 23 March 1998 n. 138 by utilising market values from 2014.

Utilisation of normal values: As defined in art. 9 of the Consolidated Tax Act (TUIR *Testo Unico delle Imposte sui Redditi*), these values are intended as average prices, for comparable goods and services, under free market conditions. Specifically, they indicate the market value of the property and represent the estimated price of a good during a free sales negotiation referred to the date of valuation.

Use of statistical functions: The representation of the urban territory as a set of variables, with a more or less evident corelation. Given the subsistence of a criteria of objectivity, the study of variables is linked to the use of statistic-analytical models and the statistic dependence of a dependent variable on multiple independent variables is referred to as multiple regression analysis.

### *2.1. Territorial Investigation*

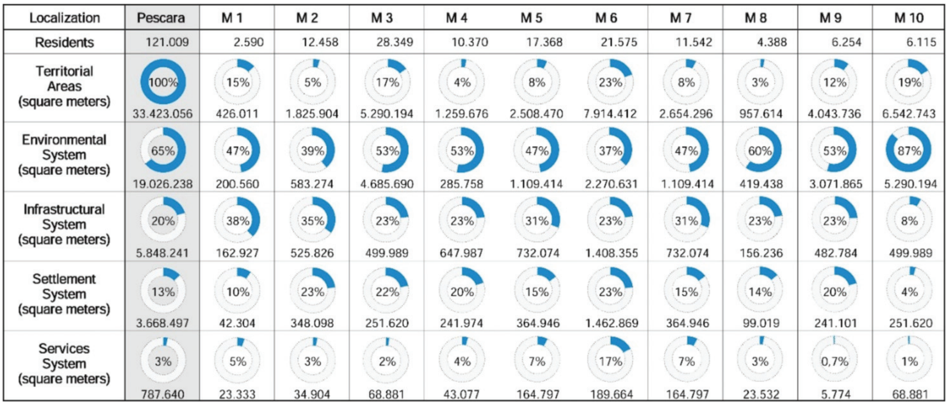
The first phase involved the gathering of information and data that represent the urban situation: This process made use of maps from *WebGIS Regione Abruzzo*, *Carta Tecnica Regionale Numerica* (C.T.R.N.), *DataBase Territoriale Regionale* and the Cadastral Maps conserved by the Revenue Agency. In addition to information provided by institutional sources, a "virtual" survey was also carried out by using the internet and geographic software (Google Maps, Google Street View and Google Earth), together with a direct survey, and both were useful for comparing the state of the art with maps to verify eventual anomalies and quantitively and qualitatively implement available information.

Spatial data gathered were aggregated in a Geographic Information System (GIS) using Open Source QGIS software with which it was possible to weigh geographical data with statistical analysis [17] through normalization operations, obtaining empirical models that allow the reading of urban phenomena that contribute to the definition of quality-quantitative indices. Indicators were subsequently used for the elaboration of a multiple linear regression model on SPSS Statistical Analysis Software.

Four reference macrosystems were identified to define the Urban Quality Index: Environmental System, Infrastructural System, Settlement System and Services System, each with its own set of subsystems that are univocally quantifiable and representative of the variation in quality of each macrosystem.

### *2.2. Framework Summary*

The analysis of the four macrosystems generated a framework for interpreting the entire municipal territory and is described in a summary chart (Figure 1) listing the number of residents and territorial area of each microzone and its relationship with the areas of the four macrosystems identified.



| Localization | Pescara | M 1 | M 2 | M 3 | M 4 | M 5 | M 6 | M 7 | M 8 | M 9 | M 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Residents | 121.009 | 2.590 | 12.458 | 28.349 | 10.370 | 17.368 | 21.575 | 11.542 | 4.388 | 6.254 | 6.115 |
| Territorial Areas (square meters) | 100% 33.423.056 | 15% 426.011 | 5% 1.825.904 | 17% 5.290.194 | 4% 1.259.676 | 8% 2.508.470 | 23% 7.914.412 | 8% 2.654.296 | 3% 957.614 | 12% 4.043.736 | 19% 6.542.743 |
| Environmental System (square meters) | 65% 19.026.238 | 47% 200.560 | 39% 583.274 | 53% 4.685.690 | 53% 285.758 | 47% 1.109.414 | 37% 2.270.631 | 47% 1.109.414 | 60% 419.438 | 53% 3.071.865 | 87% 5.290.194 |
| Infrastructural System (square meters) | 20% 5.848.241 | 38% 162.927 | 35% 525.826 | 23% 499.989 | 23% 647.987 | 31% 732.074 | 23% 1.408.355 | 31% 732.074 | 23% 156.236 | 23% 482.784 | 8% 499.989 |
| Settlement System (square meters) | 13% 3.668.497 | 10% 42.304 | 23% 348.098 | 22% 251.620 | 20% 241.974 | 15% 364.946 | 23% 1.462.869 | 15% 364.946 | 14% 99.019 | 20% 241.101 | 4% 251.620 |
| Services System (square meters) | 3% 787.640 | 5% 23.333 | 3% 34.904 | 2% 68.881 | 4% 43.077 | 7% 164.797 | 17% 189.664 | 7% 164.797 | 3% 23.532 | 0,7% 5.774 | 1% 68.881 |

**Figure 1.** Summary chart.

## 2.3. Evaluation Model

The evaluative study of the data gathered began with the elaboration of a model capable of capturing the underlying relations of urban phenomena; the observation of a large number of cases permitted the elaboration of a multiple linear regression model. The equation of linear regression is described as follows:

$$\hat{Y} = b_0 + b_1 * x_1 + b_2 * x_2 + b_3 * x_3 + b_4 * x_4 + b_5 * x_5 + b_6 * x_6 \quad (1)$$

where $x_1$ = Urban Quality Index; $x_2$ = gross floor area; $x_3$ = building age coefficient; $x_4$ = building typology (single unit in a detached home); $x_5$ = garage; $x_6$ = floor level, while the value $b_i$ represent the non-standardised coefficients to which the model attributes a value–an increase or decrease–as a function of the identified statistical unit (€/m$^2$). The results obtained from the product of the coefficients and their respective variables describe the level of appreciation, in economic terms, for the characteristics analysed by users (citizens).

This statistical approach allowed the identification and quantification of the elements, correlated with one another, and permitted the reproduction of phenomena observed in a simplified manner, free of superficial aspects.

The trends and expectations of the user-citizen who prefers urban zones over others are confirmed in the formation of real estate prices. In fact, aside from the intrinsic characteristics of each property, the values of real estate transactions also reflect the combined characteristics of the urbanised environment. This highlights the close interdependence between market value and urban quality [18]. In virtue of this relation, the choice was made to develop the Urban Quality Index as a direct expression of market property, "Estimative market analysis focuses on clarifying typical trends by identifying and studying prices and characteristics considered influential; these characteristics are generally aimed at summarising how operators perceive the formation of a market price" [19].

### 2.3.1. Identification and Construction of Variables

The multiple regression model was used to determine a function capable of expressing the relationship between a dependent variable and independent variables. The dependent variable selected for the present case study was the unit value (€/m$^2$) of transacted properties. Data collected to prepare the evaluative framework included transactions involving category A (residential) properties, excluding category A10 (offices), registered in the city of Pescara for the year 2014. The reference sample included 205 cases with sufficient variability (Figure 2) of intrinsic characteristics in terms of area, typology, era of construction and state of conservation. This heterogeneity of characteristics and the consequent unit rates of sale are an indicator of how these observations describe a representative and statistically significant framework of the urban territory.

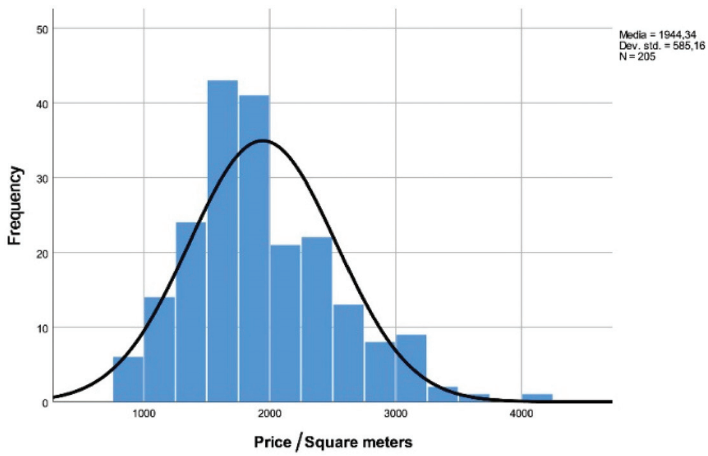



**Figure 2.** Normal distribution of the sample analysed.

The data elaborated refer to a suitable variability (normal distribution Kolmogorov–Smirnov Sign $p$-value 0.000081 and Shapiro–Wilk $p$-value 0.000141) in the properties analysed: They present areas between 30 $m^2$ and 253 $m^2$ built between 1939 and 2014. Roughly 36% of the properties feature a garage; 6% belong to the typology "properties in detached or semi-detached homes"; 9.8% of the units analysed are situated on the ground floor; 49.3% are situated on the first or second floor; 28.8% are situated on the third or fourth floor; and 12.2% are situated on or above the fifth floor. Prices range from between €830/$m^2$ and €5356/$m^2$, for an average value of €1944/$m^2$, to a standard deviation of 585.16. The construction of the model considers intrinsic and extrinsic characteristics [20] grouped in homogeneous clusters in order to simplify the input of data and to represent the explanatory variables ($x_n$) in the regression equation.

With reference to surveyed property prices (on a monthly basis), there is no significant temporal trend in property prices: after the negative peak in 2008/2009, property prices in Italy remained stable except for the property market segment of the highest quality. The data collected for the elaboration of the model (2014) refer to a year of absolute stagnation in prices and therefore it was not necessary to elaborate time trend lines (also because the sample of properties is not homogeneous both for intrinsic and extrinsic characteristics). From a partial analysis of the data, there is no significant price trend that could lead to conclusions different from those elaborated: in urban area B1 (Figure 3), for example, there was substantial stability in average property prices.

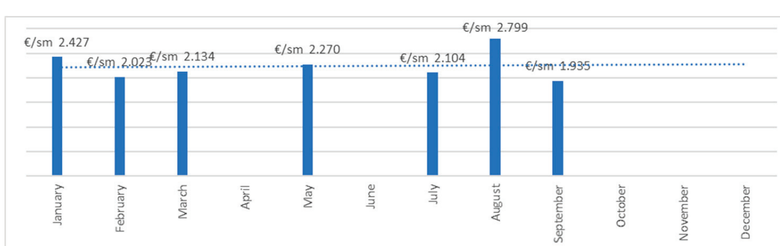



**Figure 3.** Trend of average market prices in urban area B1.

2.3.2. Intrinsic Variables

Intrinsic characteristics, linked to the material and architectural properties of real estate units [21], can be easily identified from the information listed in deeds of sale. They permit an understanding of the location, use, dimensions ($m^2$) and state of maintenance of each single unit and/or building. Additional aspects, to which particular attention was paid during the processing of the data, were related to verifying criteria for measuring—to some degree quantifiable—the direct proportionality between the parameters and the value of the statistical unit expressed in €/$m^2$ and the absence of phenomena of self-correlation [22] among the selected parameters.

The specific elements of the different properties were based on the consideration of five essential aspects with the greatest impact on pricing:

1. Total floor area: commercial floor area, including balconies and other accessory areas;
2. Period of construction or renovation of the unit or building: these data provide an indication of a drop in value imputable to the passage of time and, therefore, represent, to all effects and purposes, the aging coefficient;
3. Floor level: a proportional increase in property value was assigned to higher floor levels by considering the advantages—in terms of natural light, views, privacy, greater protection against atmospheric and acoustic pollution—offered by upper storeys with respect to lower ones. The qualities attributed to the "ground floor" were considered inferior to those recognised for levels above; this characteristic was assigned the value "0";
4. Building typology: There is a differentiation between properties in multi-family buildings and those in single-family constructions (single-family or two-family detached and semi-detached homes). For this reason, it was considered useful to introduce a dichotomic variable that would express this differential by assigning the value of "1" to units in detached/semi-detached homes and "0" to those in other building typologies;
5. Garage: This element, which has a notable influence on the formation of property value, was identified with the associated presence of a garage intended as both covered and exclusive. This aspect was evaluated in the model by introducing a dichotomic variable: "1" when a garage is present and "0" when absent.

2.3.3. Extrinsic Variables: Building the Urban Quality Index

The definition of the extrinsic variable involved elaborations of the four macrosystems—environment, infrastructure, settlement and services (each broken down into subsystems) (Figure 4)—obtaining values in an ordinal scale [23] for which its sum expresses the Urban Quality Index ($U_{QI}$).

$$U_{QI} = \sum_{i=1}^{n} I_i \quad (2)$$

In order to permit a comparison between the elements that participate in the formation of the Urban Quality Index in the 10 microzones of the city of Pescara, it was necessary to introduce a procedure of normalisation. For each characteristic observed, the characteristic that represented the most important presence or feature was attributed a value of "1" and utilised as a benchmark for scaling values in the other microzones. This approach was necessary to make a comparison among the values obtained in a single microzone and those necessary to describe the entire municipal territory.

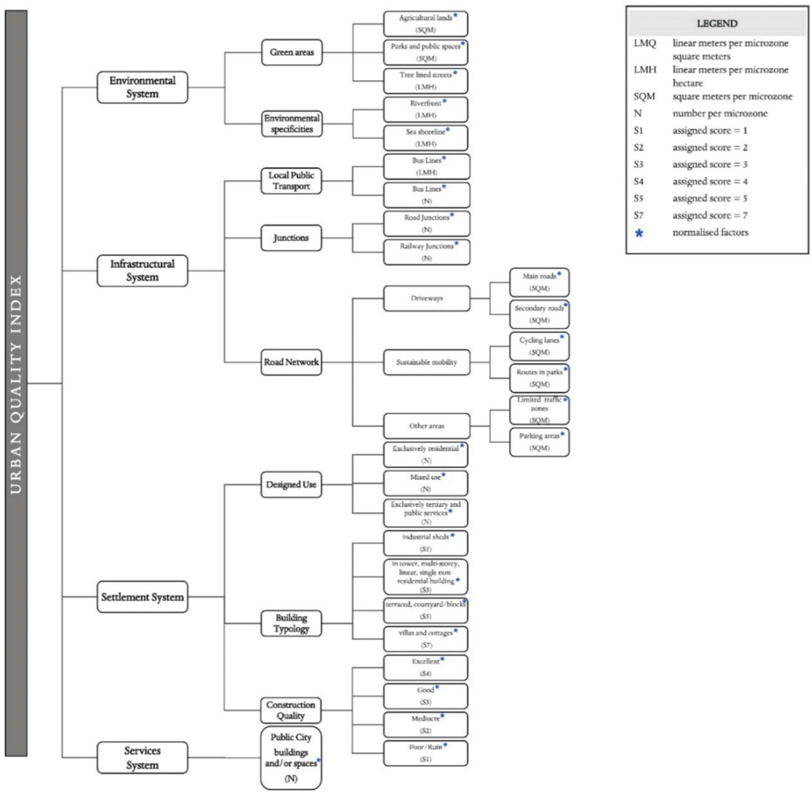



**Figure 4.** Schematic diagram of the process used to calculate the Urban Quality Index ($U_{QI}$).

Environmental System

This system represents the quantity, in square and linear metres, of natural areas for which its influence on the quality of public spaces and the landscape is considered an improvement [24]. The Environmental System was then subdivided and analysed in 2 subsystems:

1. Green/landscaped areas
    - Parks and Public spaces (*PP*);
    - Peripheral Agricultural Lands (*AL*) (cultivated, uncultivated and forests);
    - Tree-Lined streets (*TL*): given the particularity of the city of Pescara, the analyses also examined other elements of environmental value, such as the River Front (*RF*).

Table 1 shows how to define the Reference Value Calculation and the Normalised Value Calculation.

**Table 1.** Environmental macrosystem: division into subsystems of green areas.

| Subsystem | Reference Value Calculation | Normalised Value Calculation |
|---|---|---|
| **Agricultural Lands** | $AL_{Mi\ (\%)} = \frac{AL_{Mi\ (mq)}*100}{M_{i\ (mq)}}$ | $\widetilde{AL}_{Mi} = \frac{AL_{Mi\ (\%)}}{max_{AL_M\ (\%)}}$ |
| **Parks and Public spaces** | $PP_{Mi\ (\%)} = \frac{PP_{Mi\ (mq)}*100}{M_{i\ (mq)}}$ | $\widetilde{PP}_{Mi} = \frac{PP_{Mi\ (\%)}}{max_{PP_M\ (\%)}}$ |
| **Tree-Lined street/avenue** | $TL_{Mi} = \frac{TL_{Mi\ (lm)}}{M_{i\ (ha)}}$ | $\widetilde{TL}_{Mi} = \frac{TL_{Mi}}{max_{TL_M}}$ |

2. The specific environments of the city of Pescara

- The River Front (*RF*): considering the presence of the river in terms of real estate appreciation and both for its environmental qualities and for the aesthetic, recreational and socio-cultural functions it represents [25];
- The Sea Shoreline (*S*): This latter environment was constructed by analysing 190 properties in the microzones along the coast to identify and measure the influence of this characteristic on the formation of prices. These analyses, conducted using an ad hoc multiple linear regression model, made it possible to define the area within which the influence of the waterfront has a significant effect on real estate market value within a limit of 250 metres from the coastline.

All measurements (in square and linear metres) were compared to the territorial area of the *i*-th microzone. Successively, the benchmark for normalisation (the maximum value) was identified among the values obtained in the same category. The sum of the normalised values expresses a part of the Urban Quality Index ascribable to the Environmental System. Table 2 shows how to define the Reference Value Calculation and the Normalised Value Calculation.

**Table 2.** Environmental macrosystem: division into the own subsystems of the City of Pescara.

| Subsystem | Reference Value Calculation | Normalised Value Calculation |
|---|---|---|
| Riverfront | $RF_{Mi} = \frac{RF_{Mi\ (lm)}}{M_{i\ (ha)}}$ | $\widetilde{RF}_{Mi} = \frac{RF_{Mi}}{max_{RF_M}}$ |
| Sea shoreline | $S_{Mi} = \frac{S_{Mi\ (lm)}}{M_{i\ (ha)}}$ | $\widetilde{S}_{Mi} = \frac{S_{Mi}}{max_{S_M}}$ |

Infrastructural System

The Infrastructural System includes the areas, paths and number of services subordinate to public transport, private vehicles or for use by bicycle/on foot. The Infrastructural System was then subdivided and analysed in 3 subsystems:

1. The Road Network (RN) that in turn includes: 1.a. Vehicular roads or:
   - ○ Main Roads (*MR*);
   - ○ Secondary Roads (*SR*).

   Table 3 shows how to define the Reference Value Calculation.

**Table 3.** Infrastructural macrosystem: division of the subsystem "Road Network".

| Subsystem | Reference Value Calculation |
|---|---|
| Main roads | $MR_{i\ (\%)} = \frac{MR_{i\ (mq)} * 100}{\Sigma[MR_{i\ (mq)}]}$ |
| Secondary roads | $SR_{i\ (\%)} = \frac{SR_{i\ (mq)} * 100}{\Sigma[SR_{i\ (mq)}]}$ |

2.a. Sustainable Mobility or:

- ○ Cycling Lanes (*CL*);
- ○ Routes in Parks (*PR*).

Table 4 shows how to define the Reference Value Calculation.

**Table 4.** Infrastructural macrosystem: division of the subsystem "Sustainable Mobility".

| Subsystem | Reference Value Calculation |
|---|---|
| Cycling Lanes | $CL_{i\ (\%)} = \frac{CL_{i\ (mq)} * 100}{\Sigma[CL_{i\ (mq)}]}$ |
| Routes in Parks | $PR_{i\ (\%)} = \frac{PR_{i\ (mq)} * 100}{\Sigma[PR_{i\ (mq)}]}$ |

3.a. Other Vehicular Areas:

- ○ Limited Traffic Zones (*LTZ*);
- ○ Parking Areas (*PK*): qualifying elements in square metres of the presence for the *i*-th microzones and expressed as a percentage of the total of their respective categories in the 10 microzones.

Table 5 shows how to define the Reference Value Calculation.

**Table 5.** Infrastructural macrosystem: division of the subsystem "Other Vehicular Areas".

| Subsystem | Reference Value Calculation |
| --- | --- |
| Limited Traffic Zones | $LTZ_{i\ (\%)} = \frac{LTZ_{i\ (mq)}*100}{\Sigma\left[LTZ_{i\ (mq)}\right]}$ |
| Parking Areas | $PK_{i\ (\%)} = \frac{PK_{i\ (mq)}*100}{\Sigma\left[PK_{i\ (mq)}\right]}$ |

2. Road-based Local Public Transport (*LPT*) (the city of Pescara does have a rail-based transport network) was analysed in relation to two factors:
   - The length in linear metres of urban bus lines (Bus Lines $_{(1)}$—BL $_{(1)}$) in the *i*-th microzone in relation to the territorial area of the same microzone (in hectares);
   - The number of lines (Bus Lines $_{(2)}$—BL $_{(2)}$) traversing each single microzone.

The benchmark for normalisation was identified in an obvious availability of transport services (*max*) among all of the values obtained in the same category. Table 6 shows how to define the Reference Value Calculation and the Normalised Value Calculation.

**Table 6.** Infrastructural macrosystem: division of the subsystem "Local Public Transport".

| Subsystem | Reference Value Calculation | Normalised Value Calculation |
| --- | --- | --- |
| Bus Lines $_{(1)}$ | $BL_{(1)Mi} = \frac{BL_{Mi\ (lm)}}{M_{i\ (ha)}}$ | $\widetilde{BL}_{(1)Mi} = \frac{BL_{(1)Mi}}{max_{BL_{(1)M}}}$ |
| Bus Lines $_{(2)}$ | $BL_{(2)Mi} = \frac{BL_{Mi\ (n)}}{M_i}$ | $\widetilde{BL}_{(2)Mi} = \frac{BL_{(2)Mi}}{max_{BL_{(2)M}}}$ |

3. A survey of Junctions (*J*) or points of access to principal networks:
   - Rail Way Junctions (*RWJ*);
   - Road-based mobility (Road Junctions—*RJ*): considering their presence, in absolute numbers, in the *i*-th microzone.

The benchmark for normalisation was identified in an obvious availability of transport services (*max*) among all of the values obtained in the same category. Table 7 shows how to define the Reference Value Calculation and the Normalised Value Calculation.

**Table 7.** Infrastructural macrosystem: division of the subsystem "Nodes".

| Subsystem | Reference Value Calculation | Normalised Value Calculation |
| --- | --- | --- |
| Road junctions | $RJ_{Mi} = \frac{RJ_{Mi\ (n)}}{M_i}$ | $\widetilde{RJ}_{Mi} = \frac{RJ_{Mi}}{max_{RJ_M}}$ |
| Railway junctions | $RWJ_{Mi} = \frac{RWJ_{Mi\ (n)}}{M_i}$ | $\widetilde{RWJ}_{Mi} = \frac{RWJ_{Mi}}{max_{RWJ_M}}$ |

Settlement System

Developing the construction index of the Settlement System (*SS*) required a detailed analysis of all 17,603 buildings present in the city of Pescara.

The following factors were calculated:

- Total floor area;
- The construction/maintenance quality of buildings or Building Quality Score (*BQS*);
- Building Typology Score (*BTS*);
- Building Designed Use (*BDU*).

For the two sub-indexes, Building Quality Score and Building Typology, reference was made to a previous study by the authors from 2012 [26]. Part of this study fixed the principles for assigning points with respect to elements linked to a state of maintenance, while another part, after processing a series of interviews with residents of the city of Pescara, defined a system of points based on appreciation for building typologies.

Regarding construction/maintenance quality, the direct observation of building façades made it possible to verify the presence of prized materials and/or detailing or, vice versa, of deteriorations, all of which have a powerful impact on the perception of a building and, as a reflection, on its surroundings [27].

The assignment of points ($QS(n)$)—from 1 to 4 (in order of growing appreciation)—made it possible to measure the overall level of quality within the *i*-th microzone in percentage terms with respect to the maximum number of points in the microzone itself.

The maximum ideal score ($QS(max)$) was obtained by hypothesising an ideal situation defined by the exclusive presence of properties in an optimum state and assigned the highest value of 4. Table 8 shows how to define the Reference Value Calculation and the Normalised Value Calculation.

**Table 8.** Settlement macrosystem: subsystem of the Building Quality Score.

| Subsystem | Reference Value Calculation | Normalised Value Calculation |
|---|---|---|
| Building Quality Score (Construction Quality Score) | $BQS_{Mi\ (\%)} = \frac{[B_{Mi} * QS_{(1,\ 2,3,4)}] * 100}{max_{SQ}} \Leftrightarrow max_{SQ} = B_{Mi} * 4$ | $\widetilde{BQS}_{Mi\ (\%)} = \frac{BQS_{Mi\ (\%)}}{max_{BQS_M\ (\%)}}$ |

For the Building Typology subsystem, in terms of building design [28], 8 typologies were noted, and points were assigned based on the results obtained during interviews with citizens. The points ($TS(n)$) were assigned as follows:

- Industrial warehouses (score = 1);
- Towers, multistorey and isolated non-residential towers (score = 3);
- Row housing, block housing or courtyard hosing (score = 5);
- Detached and semi-detached homes (score = 7).

The points calculated make it possible to measure the presence of determinant typologies within the *i*-th microzone as a percentage of the maximum points possible in a specific microzone. The maximum ideal score ($TS(max)$) was obtained by hypothesising a situation defined by the exclusive presence of detached and semi-detached homes and assigned the highest score of 7. Table 9 shows how to define the Reference Value Calculation and the Normalised Value Calculation.

**Table 9.** Settlement macrosystem: subsystem of building typologies.

| Subsystem | Reference Value Calculation | Normalised Value Calculation |
|---|---|---|
| Building Typology Score (Building Typology Score) | $BTS_{Mi\ (\%)} = \frac{[B_{Mi} * TS_{(1,\ 3,5,7)}] * 100}{max_{TS}} \Leftrightarrow max_{TS} = B_{Mi} * 7$ | $\widetilde{BTS}_{Mi\ (\%)} = \frac{BTS_{Mi\ (\%)}}{max_{BTS_M\ (\%)}}$ |

The benchmark selected for normalisation was the highest possible score (*max*) among the values obtained in the same category.

The sub-index of Building Use was constructed by identifying the use of each unit inside a single building. Three building categories were established:

- Exclusively Residential Buildings (*RB*);
- Mixed-Use Buildings (*MB*);
- Buildings used exclusively for tertiary activities or as public offices (Services Buildings) (*SB*).

The survey examined the number of buildings present in the territory, classified in one of the three categories, as a percentage of the total number of buildings in the *i*-th microzone (Total Buildings) ($TotB_{Mi}$). Table 10 shows how to define the Subsystem and the Reference Value Calculation.

**Table 10.** Settlement macrosystem: subsystem of Building Uses.

| Subsystem | Reference Value Calculation |
|---|---|
| Exclusively Residential Buildings | $RB_{Mi(\%)} = \frac{RB_{Mi\ (n)}}{TotB_{Mi}}$ |
| Mixed-Use Buildings | $MB_{Mi(\%)} = \frac{MB_{Mi\ (n)}}{TotB_{Mi}}$ |
| Exclusively Tertiary and Public Services Buildings | $TB_{Mi(\%)} = \frac{TB_{Mi\ (n)}}{TotB_{Mi}}$ |
| Total Buildings | $TotB_{Mi\ (n)} = \left(RB_{Mi\ (n)} + MB_{Mi\ (n)} + TB_{Mi\ (n)}\right)$ |

Property values provided by the Real Estate Market Observatory (OMI) demonstrate how average real estate values (for residential buildings) in Microzone n. 4 were the highest in the entire municipal territory: these data resulted in the selection of a benchmark based on the combination of uses present in Microzone n. 4 (30% exclusively residential, 59% mixed-use and 11% tertiary, plus public and private offices).

These values were then used to normalise the values measured in the other microzones.

Services System

The presence of public and private services (Public/Private services System) ($PP_S$) offered to citizens was considered a positive factor. The survey divided the services present in the city of Pescara into the following categories:

- Basic education (nurseries, kindergartens, schools and junior high schools) and higher education (high schools, universities and research centres);
- Hospitals, care facilities and healthcare structures;
- Libraries, museums, cinemas, theatres, auditoriums and exhibition halls;
- Places of worship;
- Facilities for sport, free time, shopping and private services (large and small shops, restaurants, bars, markets, hotels, artisans' shops, tertiary, banks and agencies), public squares and spaces of public gathering.

The resulting values express the relationship between the number of services present in the *i*-th microzone without considering the radius of influence proximity can have on the formation of real estate prices, although it can reasonably be considered positive [29]. Table 11 shows how to define the Reference Value Calculation and the Normalised Value Calculation.

**Table 11.** Macrosystem of services.

| Sistema | Reference Value Calculation | Normalised Value Calculation |
|---|---|---|
| Public/Private Services System | $PP_{S\ Mi} = \frac{PP_{S\ (n)}}{M_i}$ | $(PP)o\_(Mi\ ) = PP\_(S\ Mi\ )/max\_(PP\_(S\ M\ (n))\ )$ |

The benchmark for normalisation was the maximum number of services (*max*) from a comparison of values in all microzones (Figure 5).

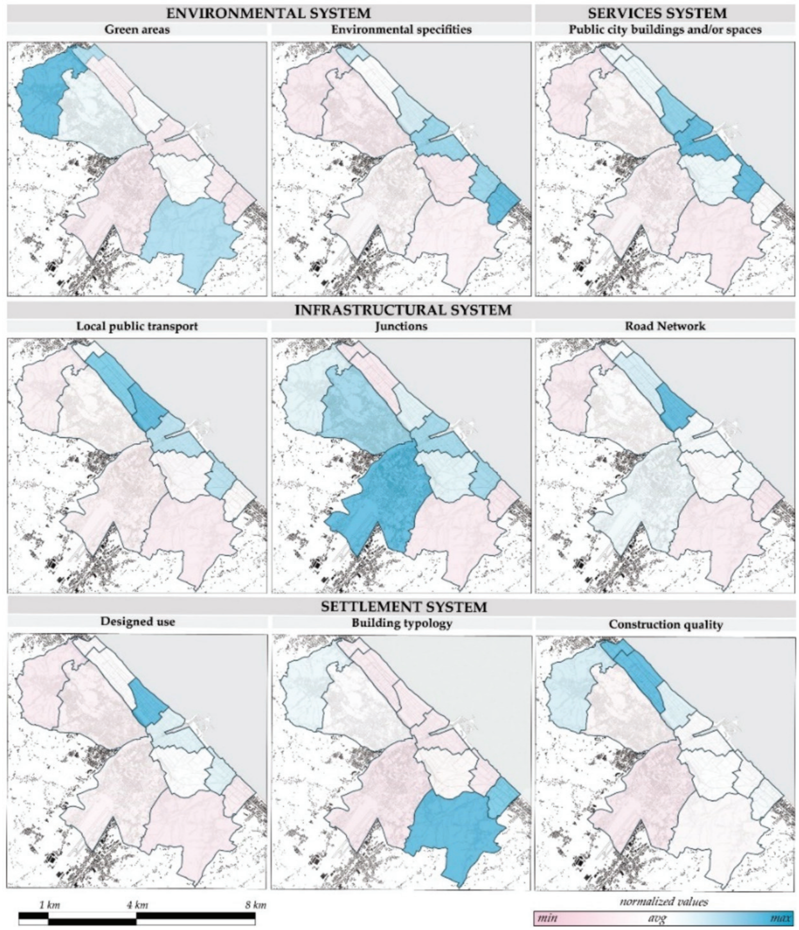



**Figure 5.** Representation of the normalised values for the subsystems.

Thus, by applying Formula (1) to the values obtained for each of the systems studied, it was possible to explicate the variable of urban quality for each of the 10 microzones in the city of Pescara (Figure 6).

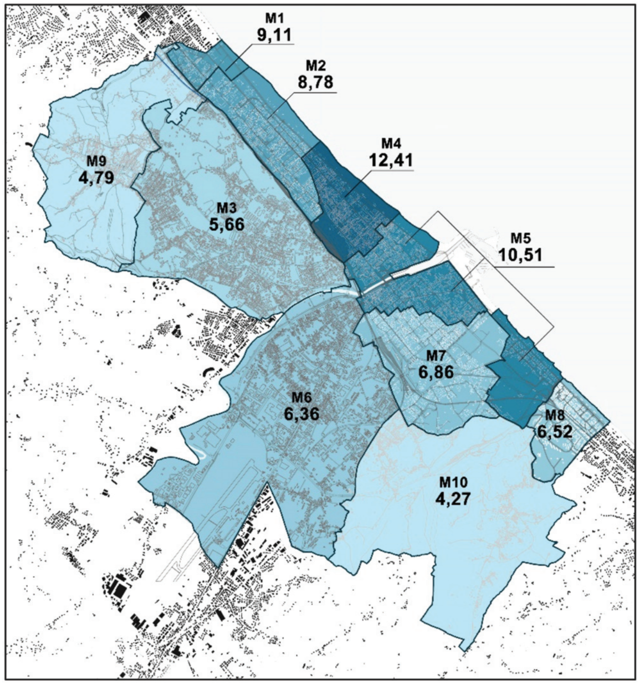



**Figure 6.** Urban Quality Index (UQI) aggregated in the 10 microzones of the City of Pescara.

## 3. Results

All data were processed and modelled using SPSS Statistics software; the results demonstrate how the variables inserted, particularly those relative to urban quality, are both effective and significant and prove that the model can be considered very reliable.

The determination coefficients R-squared ($R^2$ = 0.866) and R-squared adjusted (Adjusted $R^2$ = 0.862) are very high, demonstrating how the proportion of variance in the dependent variable (price per square metre) is explained by the independent variables.

The correlation test showed a high correlation between the variable "Price Square meters" and the variable "Urban Quality Index" (Pearson coefficient 0.457).

The Analysis of Variance (ANOVA) demonstrates how the statistical significance of the regression model less than 0.05 provides an overall indication that the model has a significant capacity to statistically forecast the resulting variable.

The Table of Coefficients (Table 12) lists the values of the marginal prices implicit of all the characteristics/variables considered. As shown, the implicit marginal price relative to the Urban Quality Index affects the formation of the price of each single unit by €189.978/$m^2$ (square metres of Gross area). Furthermore, the relative standardised coefficient of regression (β) demonstrates how the Urban Quality Index is the first among all of the variables identified that contributes to the definition of the model.

**Table 12.** Table of coefficients [a].

| Model | | Non-Standardised Coefficients | | Standardised Coefficients | $t$ | $p$-Value |
|---|---|---|---|---|---|---|
| | | B | Standard Error (SE) | Beta (β) | | |
| 1 | (Costante) | 1089.030 | 72.111 | | 15.102 | $8.6649 \times 10^{-35}$ |
| | Urban Quality Index | 189.978 | 6707 | 828 | 28.325 | $1.4355 \times 10^{-71}$ |
| | Gross Floor Area | −3852 | 481 | −224 | −8010 | $9.6296 \times 10^{-14}$ |
| | Building Age Index | −308.356 | 14.203 | −654 | −21.711 | $2.8602 \times 10^{-54}$ |
| | Building Typology | 461.572 | 66.764 | 193 | 6914 | $6.3518 \times 10^{-11}$ |
| | Garage | 346.767 | 35.366 | 297 | 9805 | $9.437 \times 10^{-19}$ |
| | Floor Level | 56.682 | 7627 | 207 | 7432 | $3.1419 \times 10^{-12}$ |

[a] Dependent variable: price square meters.

## 4. Discussion

The statistical indicators demonstrate the legitimacy of the model constructed. The index of determination $R^2$—in this study, it is equal to 0.863—assigns the model a predictive capacity. In other words, the explanatory variables show a good ability to predict the value of the dependent variable since the Analysis of Variance has a $p$-value equal to $1.9706 \times 10^{-83}$ while the $t$-tests (Table 12) confirm the significance of the entire model and the individual variables used.

Finally, the percentage error, intended as the ratio between standard error and the average values of the dependent variables (representing the percentage shift of data from the regression line), is equal to 11% and, thus, is amply below the critical values expressed in literature.

Other than the correct identification and quantification of an index capable of fully defining the elements that bring urban quality, the present research also shows how the model can be further developed for different purposes, the least of which is linked to taxation.

The following figure (Figure 7) shows the difference between the real value (listed in deeds), the value calculated using the model and the fiscal value (or cadastral value, that is, the value used to calculate diverse taxations) for the sample analysed. In particular, the real value and the predicted value, although different, develop according to a similar trend, while the taxable value appears to be wholly separate from market dynamics and has a largely divergent trend with respect to real values. In all cases except one, cadastral values were significantly lower than both real values and those calculated using the model. It is, therefore, evident that the city of Pescara (similarly to many Italian cities) suffers from considerable forms of fiscal inequality.

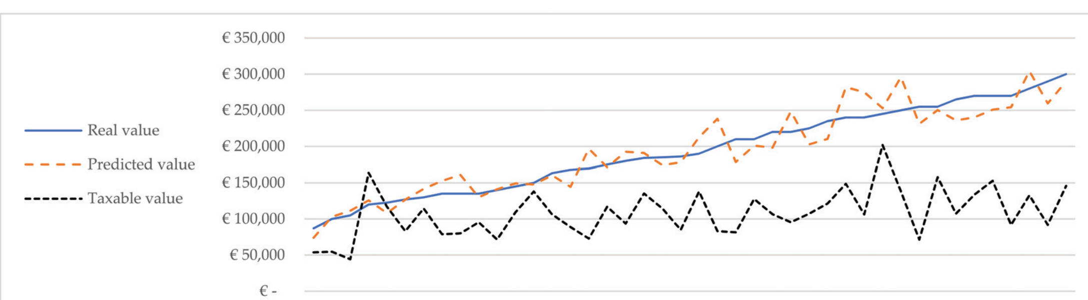



**Figure 7.** Comparison between real value (from deeds of sale), predicted value (using the model) and cadastral value.

In light of these economic-fiscal considerations, an Urban Quality Index constructed in this manner may represent an innovative tool for political decision makers and/or public administrations in rebalancing taxation and, at the same time, proposing a more balanced and sustainable form of planning.

Composed of a consistent quota of environmental factors—planted and landscaped areas, infrastructures and services—in addition to qualitative factors intrinsic to urban properties and given the notable significance assigned by the regression model to this index, the $U_{QI}$ becomes a detector of criticalities and shortcomings in the consolidated urbanised fabric and indicates a possible approach to rebalancing existing disparities and managing future actions of planning.

To cite an example, an increase in property values in the presence of a garage reveals how urban movements make widespread use of private vehicles. This reading of the urban environment may suggest that local governments intervene by improving the system of public transport, triggering an improvement to the index and, consequentially, to the quality of services—and the urban environment in general—utilised by citizens.

## 5. Conclusions

The index developed by the model based on a reading of property values has permitted the definition of all of the physical (and thus measurable) characteristics that participate in the definition of urban quality. The model is objective, replicable and scalable:

- Objective, because it is structured by quantitative elements devoid of any form of subjective alteration;
- Replicable, because the systems considered comprise the structural components of the city;
- Scalable, because the essential elements of the city can be found at diverse scales.

The model considers a set of elements that affect market values, beginning with the Urban Quality Index defined within the "institutional polygons" represented by micro-zones. As imaginable, the model expresses different levels in different parts of the city of Pescara.

The other quota of variability explained by the model results from the specific characteristics of each real estate unit (floor area, era of construction, level, building typology and presence or not of a garage).

After verifying the statistical acceptability of the model by using statistical and estimative tests, two aspects emerge powerfully and clearly from its use: The first is linked to the Urban Quality Index. It is worth underlining that this elaboration is triggered by, belongs to and is circumscribed exclusively to the appreciation manifested by the real estate market in relation to the location of a building. In this regard, it is possible to consider the following: if this index considers a series of urban characteristics, for which its density must be read in positive terms and if the *t*-test of significance of the variable constructed in this manner is the highest among the variables input into the model, then it is possible to recognise that this index has the ability to describe and interpret parts of the city that are of use to the decision-making processes and that characterise urban policies.

Further specific aspects could be considered for the refinement of the assessment such as air pollution due to the high rate of urbanisation—and population—the high density of means of transport or the proximity of industrial settlements to urban areas [30] criticalities linked to the presence of publicly owned areas and buildings, mostly industrial complex [31] and abandoned military barracks [32], that occupy large urban portions and the potential they would offer in terms of urban quality by undertaking appropriate recovery plans on these assets [33]. Assessments, with modern computational methodologies of estimation, their market value or their recovery value [34] or, again, knowing detailed information on the energy characteristics of the buildings—in light of the energy efficiency incentives undertaken by the Italian State and the plans for the following decade [35]—and its appreciation in economic terms should all be undertaken [36].

The second aspect is linked to physicality: The difference between predicted value (aligned with the value listed in deeds of sale) and taxable value (cadastral value) suggests a profound reflection of the inappropriateness of the current taxation system, which calculates value using procedures considered improper and "completely disconnected from real market values" [37].

Thus, the proposed model would consent to a mass appraisal capable of producing property values that more correctly reflect the real situation and, in turn, consenting greater fiscal equity among taxpayers, while helps in stimulating the real estate market [38].

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# Does Google Trends Show the Strength of Social Interest as a Predictor of Housing Price Dynamics?

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**Abstract:** A recently emerged sustainable information society has ceased to be only a consumer and has become a web-based information source. Society's online behaviour is tracked, recorded, processed, aggregated, and monetised. As a society, we are becoming a subject of research, and our web behaviour is a source of information for decision-makers (currently mainly business). The research aims to measure the strength of social interest in the housing market (Google Trends), which will then be correlated with the dynamics of housing prices in Poland in the years 2010–2021. The vector autoregressive model was used to diagnose the interrelationships (including Granger causality) and to forecast housing prices. The research showed that web searching for the keyword "dwelling" causes the dynamics of dwelling prices and is an attractive alternative to the classical variables used in forecasting housing market prices.

**Keywords:** sustainable information society; housing market; Granger causality

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## 1. Introduction

The human being functions in a complex and multidimensional socio-economic reality. General principles, rules or patterns of behaviour passed down from generation to generation in new conditions of the human environment (organisational, economic, informational) may be ineffective in the current reality. The evolution of society from hunting, agricultural and industrial to information society has changed the paradigms of thinking and required adaptation to the current conditions of functioning of societies. Almost 20 years ago, Hilty [1] recognised that sustainable development and the emerging information society are two significant visions that characterise the beginning of the 21st century.

Human economic activity, which has significantly disturbed the balance of the ecosystem, provided the basis for introducing the concept of sustainable development, which promotes a balance between socio-economic development and the natural environment. Combining the (equally important) relationships between economy, environment and man in one concept depart from traditional concepts, where these issues were treated separately (ceteris paribus). Sustainability is a concept [2,3] to improve and sustain a healthy economic, ecological and social system for human development. The best-known definition of sustainable development is proposed in the Brundtland Commission Report [4]. The report defines sustainable development as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs [2]. More detailed concepts of 'sustainability' and 'sustainable development' are presented in several studies [5–11].

Hilty [1] believed that at the beginning of the new millennium, we are on the cusp of an information-intensive economy, in which nothing can be done without heavy use of Information and Communication Technology (ICT). The memorandum "Sustainable Information Society" [12] has provided that ICT will penetrate his everyday life and affect people, society and the environment. However, the ever-broader usage of ICT does not automatically favour a sustainable, environmentally fair development. The memorandum stated [12] that:

- Internet may offer excellent opportunities to develop into a society;
- ICT offers great opportunities which could be distributed very unevenly in society;
- It is becoming increasingly difficult to establish a relationship between cause and effect in the digital world;
- ICT alone does not cause a reduction in the use of natural resources by production and consumption;
- ICTs offer great potential for sustainable development, but the opportunity to reorient our activities toward a sustainable information society can be lost without discussion.

Today, in 2022, we are fully aware that the new society, which does not remember the times without the Internet, cannot imagine the world without the possibilities offered by modern information and communication technologies (ICT). It can be said that the present society, accepting the general idea of sustainable development, is now transforming itself into a modern and sustainable information society.

According to Thomas [2], sustainable development is focused on the ability of humans to meet human needs. If we become a sustainable information society, the question will bewhether this social development is equally applicable to housing markets, which meet basic human needs. Home (in the Markov hierarchy of needs) offers a feeling of safety [13], a sense of belonging [14], is a factor in the health of societies [15] and is also considered a significant human right [16]. Housing is one of the areas of the economy that has a significant effect on the level of satisfaction of social needs, dynamics of economic processes and effectiveness of developmental activities. Interconnections of housing development and the economy indicate that the former plays a significant role in elevating the country's social, economic, and spatial cohesion [17–19]. Housing is a particular type of commodity [20] because it is a spatially stationary commodity, highly durable, costly, heterogeneous and physically changeable. Sustainable housing significantly influences the satisfaction of social needs and the efficiency of development activities. Improved housing increases the quality of life and contributes to the achievement of several sustainable development goals (SDGs), including those addressing health (SDG 3) and sustainable cities (SDG 11) [21].

A sustainable information society cannot exist without information about the housing market. The primary source of housing market data is the range of government, local government and private institutions that collect, process, aggregate and share it. The information that the public needs in buying a property, thanks to the development of ICT, can now be accessed directly on the internet. Thus, a prospective homebuyer, without leaving his/her home and using tools such as a laptop or smartphone, can analyse: the prices of similar properties, the surroundings of the real estate, the air pollution level, the sunshine level, the security level of the neighborhood (robberies, thefts) and even the traffic jam level in the vicinity of the chosen property. On the one hand, ICT allows society to obtain information about the market, but on the other hand, thanks to ICT, the same society (each person individually) becomes a provider and subject of data analysis (often unconsciously). Society's web behaviour leaves a footprint that, when processed and aggregated, becomes data. As a result, the actions of one part of society in the sphere of information acquisition generate the possibility of analysing their behaviour for another part of society. Based on such data it is possible to conclude the current needs of society in terms of housing. An instrument to measure public sentiment can be Google Trends.

Internet search trend analysis is becoming increasingly popular in business and science to understand social awareness [22–25]. According to Yang [26], the activity of internet users at a given point in time is assumed to reflect collective behaviour and shows the interests, concerns and intentions of the observed population. As a freely accessible tool, Google Trends provides information on trends of keywords that people search for on Google [27]. It could be said that Google has dominated the search market. Therefore, it can be a valuable tool for assessing the popularity or public interest of a given product, topic or event. Presenting the absolute number of searches for a given type of topic would generate difficulties compared to other keywords. Therefore, Google Trends provides the relative search volumes of search terms on the web, by estimating the search volume for all searches for a given time and location. The relative search volume index (RSV) is generated by normalising the search results by the highest proportion of queries in the created time series. The wide applications of Google Trends in science and business are outlined in many scientific studies [28–32].

This paper shows social interest in the housing market in Poland (2010–2021) using Google Trends. In the sustainable information society era with widely available ICT tools, an individual searches for information about dwellings, houses or land just on the web. Measuring the significance of such interest in time may help diagnose the future, i.e., in forecasting the dynamics of housing prices. It seems reasonable to assume that the increased social interest in real estate on the web results after some time in a reaction through the purchase of a dwelling or a house. Of course, it is necessary to distinguish the potential interest of the real, just as the offer price of the transaction price is distinguished.

The research concerns internet searches for the word “flat” in Polish, which is a rather small percentage of similar research, where the English language dominates. The Polish residential market is currently very attractive to investors from all over the world. This is due to Poland’s stable and growing economy, still lower prices than in Western Europe and a stable upward trend in residential prices. Currently, there is a remarkable increase in individual investment in housing to protect against the loss of capital, due to the National Bank of Poland’s low interest rate policy. In such a situation, the presented research is very timely and helpful in the evaluation of investment decisions. The presented research may contribute to the discussion on potential drops in residential prices in Poland, an essential element of investors’ risk minimisation policy. Investros’ beliefs in the continuation of price increases is currently dominant. The important question, then, is whether such an assumption is still possible. This research allows us to partially change the prevailing assumptions on the housing market.

The adopted time horizon (2010–2021) of the research allows analysis of opposing phases of residential market activity in Poland. In the first phase of this period (2010−2013), we observed a decrease in housing prices after peaks reached in 2007−2008. This was a consequence of global megatrends connected with the so-called mortgage crisis. In the second phase of the analysis period (2013−2021), we observed a strong upward trend in residential prices, which was not stopped even by the appearance of the COVID-19 pandemic in Poland in March 2020. You can read more about the housing market in Poland in the extensive literature on the subject [33–41]. The use of Google Trends in such distinct phases (price decreases and increases) allows us to take a more in-depth look at the public’s actual behaviour in the housing market.

In this study, the vector autoregressive model VAR was used together with the analysis of Granger causality. All computations and their visualisation were carried out in the R software.

## 2. Materials and Methods

### *2.1. Study Area and Data Description*

The research was conducted on the Polish housing market in 2010–2021. The National Bank of Poland (BaRN) database was the source of data on housing prices. The research assumes average quarterly prices per square meter of a flat (Secondary Residential Market) weighted by the city’s residential market resources, averaged for the seven largest Polish cities (Gdańsk, Gdynia, Kraków, Łódź, Poznań, Warsaw and Wrocław). Data on public interest in housing were obtained from the Google Trends website. The options available on this website are insufficient for a more precise and accurate keyword search. Therefore, data collection has been carried out using the “gtrends” package in R software. First, the search had to be conducted in Polish, as the research concerned a Polish society. It has been assumed that the keyword is “mieszkanie”, which means a dwelling, a flat or an apartment in Polish. Secondly, the script in R allows you to select a search category to minimise errors.

In the case of this work, code 1080 (Real Estate Listings) was chosen, which allows us to search for terms correlated with housing listings in real estate companies.

### 2.2. Methodology

Autoregressive vector models (VAR) explain the endogenous variables solely by their history and could include certain exogenous variables, such as trends and seasonal dummies, but they do not have to classify variables as endogenous or exogenous [42]. VAR models are a bridge between traditional econometrics and time series models. They are multiequation models whose expansions may be consistent with even incredibly detailed economic theory. At the same time, they make full use of information on processes that generate variables [43]. The basic form of the VAR model is:

$$x_t = A_0 D_t + A_1 x_{t-1} + A_2 x_{t-2} + \ldots + A_k x_{t-k} + e_t \tag{1}$$

where:

$x_t$—vector of observations on the current values of all n variables model $x = [x_{1t}\ x_{2t}\ x_{3t} \ldots\ x_{nt}]^T$,
$D_t$—vector of deterministic components of equations,
$A_0$—matrix of parameters with the vector variables $D_t$, not containing zero elements,
$A_i$—matrix of parameters with lagged variables of vector $x_t$, not containing zero elements,
$e_t$—vectors of stationary random disturbances $e_t = [e_{t1}\ e_{t2}\ e_{t3} \ldots\ e_{tn}]^T$.

As opposed to structural models, the VAR model allows a broad analysis of system linkages without maintaining the "ceteris paribus" principle. They do not explicitly require the identification of endogenous exogenous variables [44], no causal relationships between vector variables are excluded and no restrictions are imposed by design [45,46]. This assumes that every variable affects every other variable in the system. VAR models are helpful in many contexts [45,47–50]:

- forecasting a set of related variables where no unambiguous interpretation is required;
- examining if one variable is predictive of another (Granger causality tests basis);
- impulse response analysis, which looks at the response of one variable to a sudden but instantaneous change in another variable;
- decomposition of the forecast error variance, in which part of the variance of the forecast of each variable is attributed to the influence of the other variables.

## 3. Results

The time horizon of the research (Q1 2010−Q4 2021) resulted from the availability of data on housing prices, as data for Q4 2021 were not available until February 2022. The beginning of the research (Q1 2010) coincides with the stabilisation of the housing market after the massive price increases of 2007−2008. Google Trends analysis of keyword dwelling ("mieszkanie"−in PL) gave us the so-called relative search volume index (RSV). The RSV index represents the relative level of interest in housing on a scale from 0 to 100. Figure 1 shows the results for the keyword "mieszkanie" search (2010–2021) and the beginning of COVID-19 in Poland. The monthly RSV values were converted to quarterly values due to the quarterly housing price data.

Figure 1 shows the dynamics of the monthly RSV values. As we can see, from 2010 to 2016, the level of interest oscillated between 30 and 60 RSV, with a stable increasing trend. The 2017−2019 period shows significant public interest in housing, with RSV levels rising to almost 90. The peak in popularity of searches for the term "dwelling" in the Google search engine in August 2021. However, the smoothed RSV index values oscillate around the value of 80 RSV, falling to 57 RSV in December 2021. Smoothing was accomplished using a loess procedure. An interesting result is the complete lack of negative reactions of interest in dwellings after the start of the COVID-19 pandemic in March 2020. In the following months of COVID-19, there is an increase in dwellings interest. It is even more evident that there is a change in the long-term trend, from increasing to decreasing, when considering the last two years of analysis in weekly terms (Figure 2).

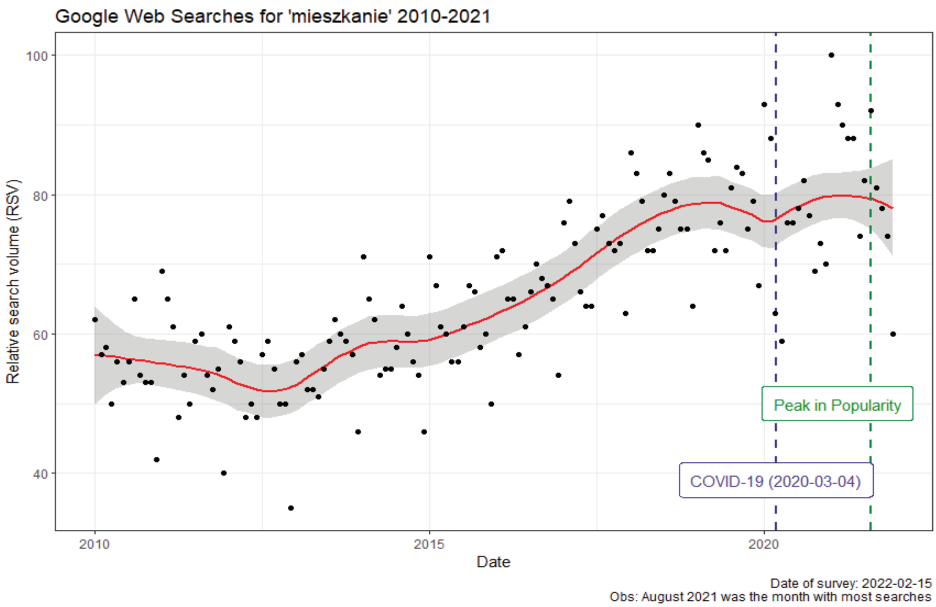



**Figure 1.** Google web searches for the keyword "*mieszkanie*" in Poland (2010–2021). The black dots indicate the monthly RSV level, the red line indicates the smoothed RSV values, the vertical purple line indicates the beginning of COVID-19 in Poland and the green vertical line indicates the highest level of interest in flats.

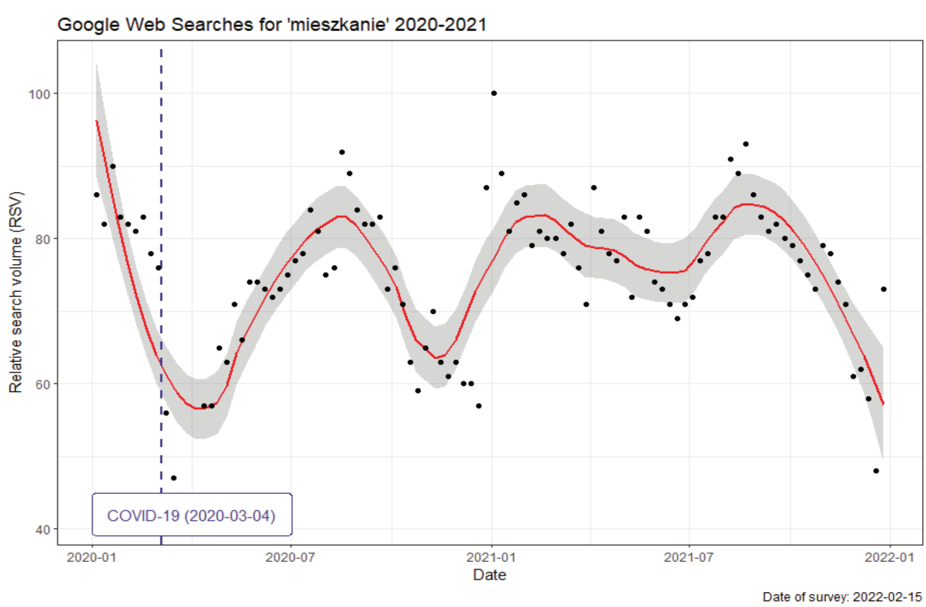
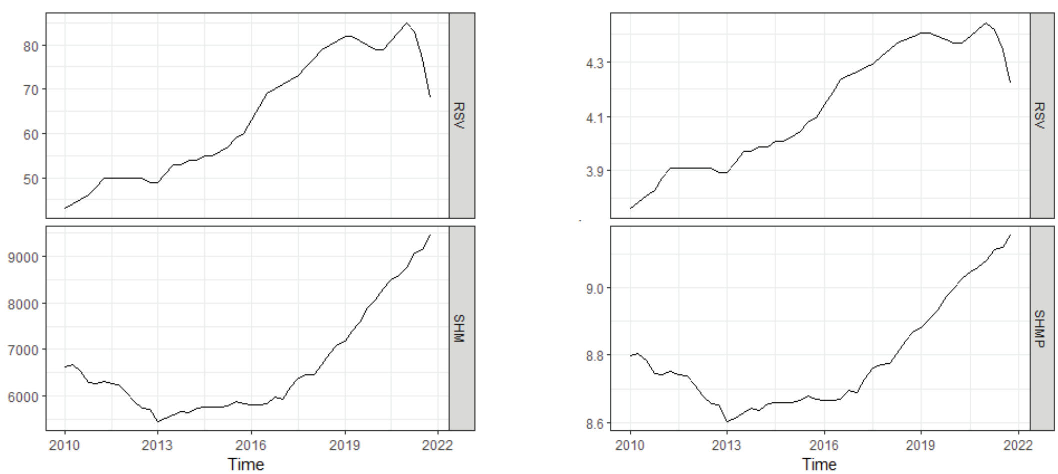



**Figure 2.** Google web searches for the keyword "*mieszkanie*" in Poland (2010–2021). Black dots indicate monthly RSV levels, the red line indicates smoothed RSV values and the vertical purple line indicates the start of COVID-19 in Poland.

In the case of the weekly RSV index results for searches for the term dwelling in 2020−2021, the traditional seasonality associated with the seasons is visible. However, by the end of 2022, there is a successively increasing decrease in interest in dwellings in Poland. It should be noted that the purpose of this investigation was not to analyse all factors that may influence the prices of dwellings. For this reason, the further part will not include other crucial factors that influence the dynamics of housing prices. One of the most significant ones is the decisions of the Monetary Policy Council of the National Bank of Poland, which influenced the increase of the main interest rates and the increase in credit costs as well as reduced credit availability for the poorer part of society.

The monthly relative search volume (RSV) index for the keyword "*mieszkanie*" has been transformed into quarterly values aligned with Poland's quarterly housing prices. Figure 3 shows the time series of the RSV index and housing prices per square meter (absolute and logarithmic values). The lack of a sufficiently long time series for the Polish real estate market is a fundamental problem that cannot be currently overcome. *A priori* it is assumed that there is no long-term relationship between the variables [51]. According to Adkins [52] and Brooks [53], a differencing (to achieve stationarity) can erase long-term information. The next part of the study used logarithms of the variables, as recommended by Canova and Drachal [51,54].




(**a**) (**b**)

**Figure 3.** Quarterly time series of relative search volume (RSV) and secondary market housing prices (SHM) in Poland (2010–2021): (**a**) absolute values of RSV and SHM; (**b**) logarithmic values of RSV and SHM.

Figure 3 shows that RSV values continuously increase from 2010 to early 2021, after which they fall dramatically. Housing prices, determined as a weighted average of prices from the seven biggest Polish cities, fall to 5.5 thousand PLN (1200 EUR) per square meter by 2013. Since then, an uninterrupted increase in prices to almost 10 thousand PLN (2200 EUR) per square meter is visible.

In the first stage of the study, the OLS linear regression model (Table 1) was used for logarithmic values of quarterly time series of secondary market prices (SHM) and relative search volume (RSV).

**Table 1.** OLS regression results for logarithmic time series of secondary market prices (SHM) and relative search volume (RSV).

| | Coefficient | Std. Err. | t-Value | *p*-Value |
|---|---|---|---|---|
| Intercept | 6.877 | 0.321 | 20.852 | <0.001 *** |
| Log(RSV) | 0.462 | 0.079 | 5.801 | <0.001 *** |
| $R^2$ | 0.42 | | | |
| Adj $R^2$ | 0.41 | | | |
| F-statistic | 33.65 on 1 and 46 df, *p*-value < 0.001 *** | | | |

Note: *** $p < 0.001$.

The results of the OLS model indicate that RSV coefficient is positive and is statistically significant. This means that the increase in web searches for "dwelling" relates to a dwelling increase trend. Due to its structure, the OLS model imposes that the RSV coefficient affects the SHM coefficient. This study employs a vector autoregressive (VAR) philosophy, which is that structures should not be imposed and it should be decided which coefficients matter. In the first step of the vector autoregression model, the optimal lag level for the time series under study should be found. For this purpose, the VARselect function from the vars package in R was used. The function returns information criteria and the final prediction error to sequentially increase the lag order up to a VAR(p)-process, based on the same sample size [42]. VAR models are multidimensional models of the ARMA class [44], where the autoregressive (AR) process of lag length prefers a time series in which its current value is dependent on its first *p-lag* values [55]. The level of lags *p* is established based on four information criteria: 'Aikaike's information criterion (AIC), Hannan-Quinn criterion (HQ), Schwarz information criterion (SC) and final prediction error (FPE). The results of the calculations in Table 2.

**Table 2.** Criteria for selecting the lag level in the VAR model.

| Criterion/Lags | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| AIC(n) | $-1.591995 \times 10^1$ | $-1.629301 \times 10^1$ | $-1.642528 \times 10^1$ | $-1.654289 \times 10^1$ | $-1.645356 \times 10^1$ |
| HQ(n) | $-1.573676 \times 10^1$ | $-1.604875 \times 10^1$ | $-1.611996 \times 10^1$ | $-1.617650 \times 10^1$ | $-1.602611 \times 10^1$ |
| SC(n) | $-1.541329 \times 10^1$ | $-1.561746 \times 10^1$ | $-1.558084 \times 10^1$ | $-1.552956 \times 10^1$ | $-1.527134 \times 10^1$ |
| FPE(n) | $1.224709 \times 10^{-7}$ | $8.487537 \times 10^{-8}$ | $7.516122 \times 10^{-8}$ | $6.792835 \times 10^{-8}$ | $7.605687 \times 10^{-8}$ |

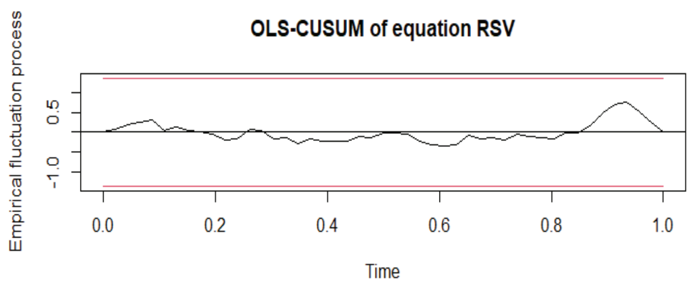
Table 2 shows that the following results were obtained: AIC(4), HQ(4), SC(2) and FPE(4). Only the Schwarz (SC) information criterion obtains a minimum lag value (2). According to the literature [55–57], caution should be taken when applying the AIC, as it tends to select a large number of lags. Instead, the SC information criterion should be preferred for VAR models because, in small samples, AICs and FPEs generally achieve higher latency values than HQs and SCs [44]. In a further step, the VAR model (2) is therefore estimated, and the results are shown in Table 3.

The VAR(2) model was then tested: Portmanteau test, heteroscedasticity test, Jarque-Bera test, Testing for Structural Breaks in the Residuals. The *p*-value in Portman Test with 12 lags is greater than 0.05 (*p*-value = 0.3331), which suggests that there is no serial correlation in the VAR model, so that passes. The test for heteroscedasticity with 12 lags gives a *p*-value greater than 0.05 (*p*-value = 0.789), which means that the model does not suffer from heteroscedasticity and the Vars model passes that test. The Jarque-Bera test The Jarque-Bera test shows that the *p*-value is greater than 0.05 (*p*-value = 0.596), so we cannot reject the null hypothesis that the residuals are normally distributed. The results of testing for structural breaks in the residuals are shown in Figure 4, which shows that there are no points which exceed the two red lines (upper and lower confidence interval), so the VAR(4) model is stable. More on the essence of this test can be found in the paper [58].

**Table 3.** VAR (2) model estimation.

| | Coefficient | Std. Err. | t-Value | *p*-Value |
|---|---|---|---|---|
| RSV.l1 | 1.888548 | 0.143355 | 13.174 | $9.61 \times 10^{-16}$ *** |
| SHM.l1 | −0.209884 | 0.219489 | −0.956 | 0.3450 |
| RSV.l2 | −0.875653 | 0.143046 | −6.121 | $3.88 \times 10^{-7}$ *** |
| SHM.l2 | 0.156733 | 0.217738 | 0.720 | 0.4760 |
| const | 0.412926 | 0.217399 | 1.899 | 0.0651 |
| sd1 | 0.021728 | 0.007761 | 2.800 | 0.0080 ** |
| sd2 | 0.008183 | 0.008306 | 0.985 | 0.3308 |
| sd3 | 0.009807 | 0.007748 | 1.266 | 0.2133 |
| $R^2$ | 0.994 | | | |
| Adj $R^2$ | 0.993 | | | |
| F-statistic | 858.1 on 7 and 38 DF, *p*-value = $2.2 \times 10^{-16}$ | | | |

Note: ** $p < 0.01$, *** $p < 0.001$.



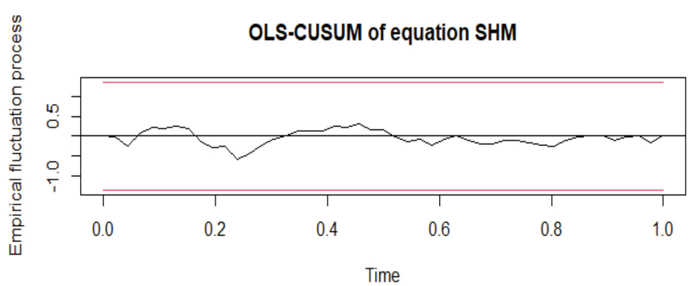




**Figure 4.** The results of the structural breakdown testing in the residuals of VAR(2).

The construction of the Var model is a basic, but also an initial stage of the analyses. Now, forecasts can be built, causality analysis can be done, impulse response functions, decompose error variance can be decomposed for structural VAR models or vector error correction models can be created [34]. A causality analysis of time series forecasting will be demonstrated in the current work.

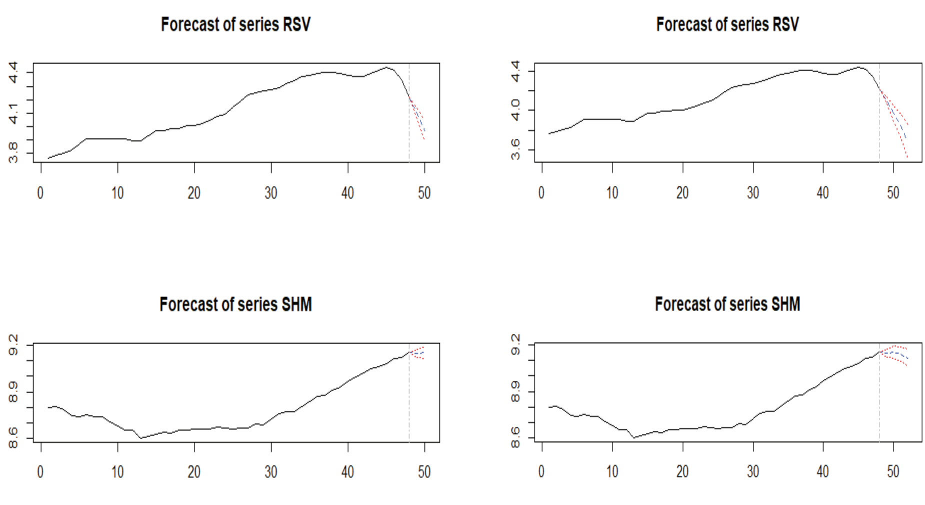
The VAR philosophy, introduced earlier in this paper, does not explicitly impose causality and, as a result, allows us to study which variable influences which one. Therefore, in this step of the VAR(2) model, a causality analysis in the Granger sense will be carried out. Causality in Granger's sense is the dependence of processes generating data. Variable X is a cause of variable Y, and including past values of variable X in the model predicting variable Y will increase prediction accuracy [59]. The Granger causality test in the VAR(2) model assumes the null hypothesis H0: RSV (relative search volume) does not have Granger-cause SHM (housing prices from secondary market) or H0: SHM does not have Granger-cause RSV. Additionally, the study used instant causality, where the null hypothesis was H0: No instantaneous causality between RSV and SHM or H0; no instantaneous causality between SHM and RSV. Table 4 shows the results.

**Table 4.** Causality testing for VAR(2).

| | Granger Causality | | Instant Causality | |
|---|---|---|---|---|
| | **F-Test** | ***p*-Value** | **Chi-Squared** | ***p*-Value** |
| RSV → SHM | 10.178 | 0.0001212 *** | 0.008469 | 0.9267 |
| SHM → RSV | 1.9589 | 0.1481 | 0.008469 | 0.9267 |

Note: *** $p < 0.001$.

The *p*-value of the Granger causality (RSV → SHM) is much smaller than 0.05, indicating that RSV Granger causes SHM. In other words, the movements in searching for the term “dwelling” in the Google search engine precede movements in housing price dynamics. As a result, we can say that the value of the RSV coefficient could be useful in predicting future changes in housing prices. In the case of immediate causality, the null hypothesis cannot be rejected, which confirms the general knowledge of the inertia property market. For an opposite relation to SHM → RSV, the null hypothesis cannot be rejected for both causalities in the Granger sense and immediate causality. In other words, the movements in dwelling prices do not precede movements in searching for “dwelling” in Google. According to the assumptions of this paper, the influence of other macroeconomic factors on the dynamics of housing prices is not analysed. In the context of the sustainable information society, it can be assumed that the society searching for the word “dwelling” on the internet is influenced by external factors in the form of a range of economic and social information. As a result, the search dynamics for the word “dwelling” depends on assessing the existing risk in the environment. We can refer to this as the RSV index (relative search volume). It allows one to evaluate the actual tendencies of the housing market, as the intensification of the search for this word on the web may indicate a real interest in the purchase of a flat in the future. On the one hand, the information society makes use of a range of available social and macroeconomic information via the web, while on the other hand, it provides information on the investment potential at a given time. Figure 5 shows the relative search volume (RSV) forecasts and the housing prices from the secondary market (SHM) in Poland for six months and one year of the forecast.




(**a**) (**b**)

**Figure 5.** Forecasting of quarterly time series of relative search volume (RSV) and housing prices from the secondary market (SHM) in Poland (2010–2021): (**a**) 1/2-year forecast; (**b**) 1-year forecast.

In the case of the shorter forecast period (1/2 year), we observe a stabilisation of residential prices, which is taking place for the first time in the last five years. The one-year forecast predicts a change from the previous upward trend in housing prices and the start of price falls in the second half of the year. At the same time, the RSV indicator is forecast to further reduce the interest in housing. In connection with this, a series of negative information reaching the society influences the decrease of interest in web searching for the term "dwelling". These phenomena include rising interest rates at the National Bank of Poland, the increasing level of inflation and the increasing requirements of banks regarding so-called creditworthiness.

## 4. Discussion

Research on the use of web searches for words such as "house", "dwelling", "rental", "apartment" and "real estate" is steadily increasing in the world literature. This is a natural consequence of the emergence of a sustainable information society, whose natural environment is collecting, processing, and generating information. The information is available at any time and any place with the current availability of the World Wide web via smartphones. Searching for a dwelling, house, or rental costs can be done on a tram or bus, while waiting for a doctor's appointment or at work. This way of obtaining information on the property market has become extremely popular in the last decade. Hence, there is a growing trend of research using data generated by Internet users, as each search engine operation (e.g., Google) is recorded, stored, aggregated and processed to produce new information. According to Matias [60], since launching Google Trends, we have seen a great deal of interest in what can be learned from search trends. Many studies have shown how to use search trends data for effective nowcasting in diverse areas, such as health, finance, economics, politics and more. This part of the discussion will focus exclusively on the real estate market, and to this extent, the subject is difficult to find in the Polish research literature. For example, the Bulczak study [61] on Google Trends for forecasting in the real estate market concerned not Poland but Great Britain from the years 2004−2014. As a result, the presented study may be one of the first and certainly one of the most up to date (the horizon of this research is 2010–2021) concerning the Polish residential market in the area of research. Due to the impossibility of comparing the obtained research results for the Polish residential market, the further scientific discussion will be based on international publications.

Limmios and You [62], in their work" Can Google Trends Improve Housing Market Forecasts", state that their research derives from the essence of empirical economics and that incorporating the Google Trend data deteriorates the forecasting ability. In this research, the keywords "real estate agency" were adopted, whereas it is the keyword "dwelling" in this study. It seems that people looking for a dwelling to buy do not type into Google the phrase "real estate agency", instead typing only what they are looking for, i.e., a dwelling, a house, a house or a plot of land, or they add the word "sell" or "rent". At the same time, the studies presented were not based on the VAR model. Askitas [63], who used the keyword "buy and sell home" in Google Trends, presented a more similar research concept, and, as a result, confirmed the high correlation with the SP/Case-Shiller Home Price Index confirmed the benefits of forecasting using this method. The concept adopted in this work is also confirmed by the experience of Berach and Wintoki [64], who considered that the intensity of the search for real estate terms for a specific city can be treated as a proxy of the sentiment of the housing market for that city. In their study, they used the keyword "real estate", which is not as unambiguous as a dwelling ("mieszkanie"−in polish). This research has another element in common with this study, as it uses data from the Housing Price Index provided by the Federal Housing Finance Agency (FHFA). This index shows quarterly price changes, as does the National Bank of Poland data adopted in this work. Interesting use of Google Trends as an indicator to analyse housing demand was presented by Huarng et al. [65]. This paper also searched Google Trends for a term referring to Real Estate Agency (as in work [62]). However, it did not refer to an unspecified type of real estate company but used the most popular non-real estate sales service in Taiwan. The keyword thus adopted may coincide with the potential demand in the housing market. This is a concept worth considering for subsequent work.

VAR models are widely used to study housing market price dynamics; however, it works simultaneously, with Google Trends and the VAR model incorporated in several studies. For example, in one study [63] based on freely accessible, real-time Google Trends data, the research analysed a statistically significant contribution to unemployment dynamics by GTU shocks in the United States with the VAR model. Davis and Heathcote [66] showed that housing investments are twice as volatile as other investments and are ahead of cyclical fluctuations, while non-residential investments constitute a lag variable. In the work of Cellmer et al. [49], a VAR was constructed, and Granger tests and impulse response analysis were performed using the impulse response function (IRF). As a result, it has been shown that the response of real estate prices to the impulse from the explanatory variables appears between the first and fourth quarters and expires after about three years. Xiao and Zhou [67] found that by building a VAR model, they can evaluate the effectiveness of regulatory policies in the Shanghai real estate market. In the following work, we analyse the dynamic spillover effects of shocks on the housing market, using a six-variate VAR model that was conducted in the subsequent work [48]. In this paper, housing market variables, housing price and housing trading volume are used, and as shock variables, housing demand shock, housing supply shock, interest rate shock, household loan shock, aggregate demand shock and aggregate supply shock are taken into account. Most of the available articles on the use of the VAR model in housing market analyses do not show a strong resemblance to the present study. This may indicate the originality and topicality of the research presented.

## 5. Conclusions

Since 2013, the housing market in Poland has shown an increasing trend, and housing prices in 2021 have exceeded the previous maxima of 2008. At the end of 2021, interest in the housing market expressed through Google searches for the term "dwelling" changed direction from increasing to decreasing. It may be argued that the decrease in the information society's interest in the analysis of dwellings available for purchase in estate sales offices precedes the decrease in the real demand in the housing market. This may result in a change in the previous trend and a decrease in residential prices. It seems that the prices of dwellings in Poland at the beginning of 2022, have been significantly overestimated and are less and less adjusted to the income level of the society. This is because for an average net salary, one can buy half a square meter of a flat. The source of such high prices in 2021 has been unusually low-interest of main rates and very low bank deposit rate returns and rising inflation at the same time as profits from deposits from other financial investments, increasing interest in investing capital in real estate. Thus, the driving force behind recent increases in housing prices has been investment demand. Google Trends has shown a decrease in public interest in real estate companies. The adopted RSV index is an interesting alternative to the variables constituting the basis for the classical forecasting of housing market prices. The next research stage should be housing prices using the VAR model, taking into account the RSV index and other available variables.

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