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Ornamental Plants and Urban Gardening

Edited by
László Orlóci and Albert Fekete

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Preface

Urban green spaces serve the physical and mental health of the population, and urban plant applications must balance the effects of climate change and urbanization. This is one of the biggest challenges facing urban ornamental plants today. The use of plants in settlements and the role and efficiency of plants in ecosystem services, as well as the physiological and social expectations for the plants used, provide opportunities for countless studies.

A dynamically changing, new profession that requires close cooperation between landscape architecture and plant sciences. The sustainability of urban green areas requires the use of appropriate plant species, a complex ecological system, and advanced maintenance technology for the design and operation of livable cities.

In order to achieve all these goals, general plant physiology and stress physiology research is necessary, primarily for the tolerance of drought and environmental pollution that is so common in urban areas; the use of traditional and molecular plant breeding methods is also essential.

László Orlóci and Albert Fekete
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Editorial

Ornamental Plants and Urban Gardening

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Abstract: Urban green areas serve both the mental and physical health of the people living in the settlements; therefore, the ornamental plants used on green areas currently have a prominent role in reducing the effects of climate change and urbanization, as well as in providing ecosystem services. This is a dynamically changing, new field that requires close cooperation with several scientific fields, such as landscape architecture and plant physiology, genetics, plant breeding, and ecology. The monitoring and research of settlement communities as ecological systems greatly serves the perception of the effects of climate change and helps to mitigate them. The sustainability and economic operation of established urban green space systems can be made effective by applying innovative technologies. The Special Issue "Ornamental Plants and Urban Gardening" was launched in 2022 and published 13 articles on the topic until 31 July 2023. The published articles also have a very wide spectrum of topics, which also shows the diversity and the interdisciplinary nature of the scientific field. In the following, we present the main topics of the published articles and the results with which their authors contributed to the enrichment of the scientific field. We present a brief summary of the articles in shorter subsections.

Keywords: ornamental plants; urban gardening; green areas; landscape architecture

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1. This Plant Application, Question of Urban Plants

Due to the development of new urban habitats, where traditional varieties cannot be adapted, the demand for the production of ornamental plant varieties with improved properties has increased [1]. At the beginning of the 20th century, plant biologists established that the frequency and efficiency of genetic modifications in treated seeds could be increased by using chemical and radiation technology [2]. Subsequently, various mutagens, such as physical or chemical mutagens, were used to induce a wide range of genetic variability, leading to and contributing to current plant breeding [3]. Thus, radiation-induced mutation breeding is a remarkable method to produce superior mutant varieties, in contrast to conventional breeding, such as selection and crossbreeding, which involves time- and labor-intensive, limited genetic trait changes [4–6]. A research article in the Special Issue was based on this topic; the article dealt with the mutational breeding of *Rudbeckia hirta*, and the results were proven by histological and stress measurements. Kisvarga et al. [7] stated that in the future, the breeding of varieties intended for urban environments that tolerate the changed climate, and with it the urban biotic and abiotic stress effects, will become an increasingly important factor. The Hungarian cultivars currently under development form a very important genetic basis, but they no longer meet the challenges of today. Mutation breeding, on the other hand, can mark a new direction and represent a new way to create varieties that can be used in urban public areas of the 21st century from old varieties. The Hungarian varieties no longer meet the requirements due to the effects of today's climate, and the old varieties are not fashionable either—which is an essential aspect in the breeding of ornamental plants. Gamma radiation had a detectable and favorable effect on the *Rudbeckia* genome. Higher doses showed more favorable phenotypic characteristics.

The difference between the generations was also noticeable, and in many cases the positive effect of the treatments remained.

Honfi et al. [8] also researched the issues of urban plant application; the use of *Limonium gmellini* subsp. *hungaricum* was investigated as a potential ornamental plant on secondary saline soils. The importance of those authors' research is also shown by climate change, one of the consequences of which may be the salinization of the soil. It is estimated that the globe loses at least 0.5–1% of its arable land to salinization every year [9], and half of the world's arable land could disappear by 2050 if current trends continue [10]. Primary symptoms of salt toxicity in plants include ion damage, osmotic stress, and oxidative stress [11]. These pressures negatively affect plant growth and development. Salinity can also cause physiological drought, which occurs when plant roots respond to environmental stimuli such as water scarcity or salt ion abundance in the soil [12]. *Limonium* sp. or recretohalophytes are characteristic halophytes that have special structures on their epidermis, such as salt vesicles and salt glands, which allow them coping with salt-rich environments [13]. During the measurements, the authors used sand and clay as the growing medium and examined the morphological and plant physiological properties of the plants at different salt concentrations. It was found that *Limonium gmelinii* subsp. *hungaricum* in clay soil was able to survive and grow better than in sandy soil despite an increasing salt concentration.

Szabó et al. [14] also examined urban vegetation, but from a different perspective. However, the basic concept here was also the ecological changes that occur during climate change. A common question in landscape architecture and horticultural practice is the adaptability and applicability of plant species with different conservation status (protected, highly protected and invasive) [15]. Invasive species, which often start their careers in botanical gardens, have the opposite effect on nature conservation. Due to their high reproductive patterns and aggressive spread, plants released from gardens can infect large areas, causing severe ecological and economic damage. Control is often a problem, even in intensively managed plantations. Observations were made in Hungary, in the Buda Arboretum. The authors established that, based on the experience observed and collected in the garden, non-native species introduced into the urban environment as integrated elements can increase the aesthetic and recreational benefits [16], as well as have a positive ecological effect on urban green spaces [17]. Invasive plants can cause a decrease in biodiversity [16], a decrease in ecosystem resilience to disturbances, and ecosystem degradation [18]. The introduction of invasive or potentially invasive taxa by botanic gardens or cultivation in nurseries can also trigger deliberate invasion [19], so plant collections have a huge responsibility for future plant use proposals.

The article of Yessoufou [20] is also related to this field. The main topic of the work is the intraspecies changes in nectar sugar mass along phylogenetics, which distinguish native plants from non-native plants in urban green areas. The author carried out his research in the south of England. The topic is relevant since the function of urban green spaces as the service of nectar production, which is related to the diversity of pollinators found in urban areas, is important but not sufficiently debated. A recent study showed that although urban green spaces do not produce quantitatively more nectar than farmland and nature reserves, the sources of nectar supply in green spaces are more diverse, mostly caused by non-native plants. Indeed, compared to other systems, urban gardens provide 85% of the urban plant nectar supply [21], but it remains unclear whether nectar supply can be demonstrated as a "hidden or non-obvious" criterion behind human selection of non-native plants. The authors investigated whether functional traits integrated into a phylogenetic framework could reveal the subtle criteria underlying the introduction of non-native plants into urban green spaces. No differences were found in functional traits between natives and non-natives. There was also no evidence that functional traits predicted nectar production, regardless of how nectar production was measured. In their measurements, the authors found that the average sugar concentration of nectar per flower is evolutionarily distributed both within closely related non-native plants and within nearby native plants. However, phylogenetically close species show similar intraspecific variation in nectar sugar mass per flower, but this is only true for non-native plants, thus revealing non-obvious selection criteria for non-native plants in urban green spaces. The results show that the phylogenetic pattern of within-species variation in nectar sugar mass per flower is the main criterion for distinguishing non-native from native plants in urban green spaces in southern England. The study suggests that differences in nectar production patterns not only affect human selection criteria for non-native species that can be selected and introduced into urban green spaces, but, pending further investigation, may also be good candidates for ecological services that may predispose non-native species to colonize.

The study of Ye [22] about turmeric was also related to the topic, which is very important in terms of both climate change and urbanization. His research will facilitate cross-species hybridization and the introduction of genetic variation from wild species into turmeric varieties in the future, which may be useful for sustainable employment in urban green spaces. Interspecific or intergeneric hybridization is one of the main methods for breeding new varieties in plants [23]. There are no reports on the fertility of interspecies hybrids of Turmeric, even though it is an excellent ornamental and edible herb with promising market potential. Until now, a large number of excellent varieties have been obtained by interspecific hybridization [24,25]. Parental fertility is one of the main factors affecting the seeding rate of interspecific hybridization [26]. The incompatibility of hybridization can be easily overcome by using species or cultivars with strong stigma susceptibility as female parents. Selecting cultivars with high pollen vigor or germination rate as male parents can significantly increase fruit set rate [27]. Meanwhile, the ploidy level and chromosome number of the parents can also affect the compatibility of the parents [28]. Whether chromosome numbers are significantly related to fertility is still unknown, and the question needs to be further investigated by studying chromosome compression and karyotype analysis. Based on hybrid identification results, all individuals from the four combinations showed male-specific bands, indicating that the true hybrid ratio of the crosses was 100%. The results will facilitate interspecies hybridization and the introduction of genetic variation from wild species into turmeric cultivars in the future, which could be useful in realizing sustainable application in urban green spaces.

2. Landscape Architecture and Green Areas (8 Articles)

The topic was introduced by guest editor and co-author Albert Fekete with his article [29], the topic of which was the 17–18th century plant application in the late Renaissance Transylvania. The topic is extremely important, as it is a great challenge for landscape architecture to take historical values into account and integrate them with new functions and uses, as well as the latest demands for improving water management, energy transition, and creating a comfortable and healthy living environment for people. During their investigation, the authors identified 81 late Renaissance residence gardens in Transylvania based on archival and literary sources as well as field studies.

It was established that in the garden history of Transylvania, the late Renaissance style spread almost a hundred years later than in other parts of Europe. Nevertheless, in terms of the number of gardens in Transylvania, the Renaissance can be called the leading garden style in this part of the country. The number of late Renaissance gardens is much higher than the number of early Renaissance or later Baroque gardens. This is the consequence of Transylvania's political and economic independence in the 17th century [30–39].

The history of the late Renaissance gardens in Transylvania is primarily about economic sustainability. For this reason, mixed gardens often appear (ornamental and vegetable gardens, and even orchards together), although in many places the various kitchen and vegetable gardens or orchards are also represented separately.

Given the condition of what remains of these historical artefacts, restoration in the strict sense is impossible. Destruction, missing archival sources, change in ownership and sustainability reasons further complicate the restoration work.

In addition to parks, urban cemeteries are also very important in urban ecosystem service and habitat protection. The topic was discussed in the Special Issue in the article of Sallay et. al. [40]. Similar to city public parks, cemeteries are an important part of the urban ecosystem; they provide a semi-natural habitat for many species of plants and animals, as well as a wide range of ecosystem services: they improve air quality, reduce the urban heat island phenomenon, and have aesthetic and recreational value. This article explores the role of cemeteries in the green infrastructure network beyond their sacred and commemorative roles and their importance as habitats for urban flora and fauna. It has been found that cemeteries can contribute to the preservation of biodiversity in cities. The role of dead trees in habitat conservation was highlighted. Dead, standing tree trunks are usually absent from cemeteries, even though they are particularly important habitats for hundreds of species. Habitat diversity should be increased, and traditional maintenance should be reduced by decreasing the mowed areas, the frequency of mowing and the use of herbicides, and the creation of more complex habitats, which may include new forests.

The issue of allergenic plants is a particularly important topic of urban plant application and landscape architecture planning, on which Magyar [41] wrote an article. The topic is extremely important, as plants are often used in allergy-related medicinal products and services, and pollen from many plant species can cause allergic disease (pollinosis) in sensitive people [42]. In the last two decades, the incidence of sensitization to pollen has increased from 13% to 30% [43]. Demonstration of allergenic plants is an important tool for patient education, contributing to the prevention of pollinosis, as patients can recognize the plants and avoid pollen exposure. The aim of this study was to evaluate the pictorial content of allergy-related web pages depicting plants. A total of 562 different photographs depicting plants were collected using an image search engine, identified and categorized according to their potential allergenicity. Out of a total of 124 plant taxa, 25% of the plants were at the genus level, and another 68% were at the species level. Plants with a low allergenic effect were included in 85.4% of the images, while plants with a high allergenic effect were only included in 4.5% of the image information. *Brassica napus* was the most frequently identified species (8.9% of all plants identified), while flowering *Prunoidae*, *Chrysanthemum* spp. and *Taraxacum officinale* was also common. Considering both the allergological and planning aspects, some plant species were recommended for more professional and responsible advertising. The Internet can provide visual support for patient education about allergenic plants, but emphasis must be placed on conveying the correct visual message. Appropriate illustrations help patients recognize and avoid allergenic plants and reduce exposure to allergenic pollen.

Also related to landscape architecture and the role of trees was the article of Nádasy et al. [44], the topic of which is spatial composition aspects in relation to the importance of trees in the urban landscape. Individual trees and tree compositions provide a wide range of cultural ecosystem services, including playing a key role in defining the character of the city. In Hungary, the tools for urban landscape protection have recently been expanded, thus putting the topic in the spotlight. However, the importance of natural elements (and especially trees) in relation to the urban landscape is still little researched. In this article, a new methodology is used to analyze and evaluate the character-shaping significance of the trees and wood compositional elements that define the urban character of the historical gardens in Hungary. In summary, the results show that the trees associated with historic gardens have a diverse and dynamically changing impact on the urban landscape, which has recently played an increasingly important role in the protection of local cultural heritage. The factors behind the visual impact on wooden elements and the different types of visibility that can help categorize and preserve the cultural services provided by these living pieces of cultural heritage have been identified. The methods and results are not country specific and can be considered broadly applicable and globally relevant. Research related to the inclusion of trees associated with historical gardens and parks in the Hungarian urban landscape protection toolkit suggests that recognition of trees as a visually significant element is lacking even within existing frameworks. While urban landscape protection regulations are implemented to varying degrees around the world, the professional recognition of objects as valuable is key to ensuring their survival and maintenance.

Teichmann et al. [45] published work on the role of schools in the Special Issue. Their more specific topic was cooperation between schools for the development and implementation of schools' self-constructed greening systems. However, greening, which improves indoor climate and people's well-being, is integrated to a very limited extent in public institutions such as schools. The reasons for this are seen in the lack of knowledge and financing opportunities. Among other things, the focus of the MehrGrüneSchulen research project is the interdisciplinary development of cost-effective greening solutions for schools. During the study, in the interdisciplinary cooperation of a technical school and a horticultural school, a total of twelve low-cost greening systems were developed for school indoor and outdoor spaces, six of which were implemented and greened in the construction yard of the technical school. In addition, the structural implementation of the adapted student plans took place in another nine schools across Austria, where the school classes were involved in the construction and on-site greening. In this way, they promote the construction of green infrastructure in Austrian schools, and at the same time promote climate-friendly construction, the development of social and moral skills, and connection and interaction with nature. This contributes to the gradual improvement of air quality and microclimatic conditions in and around schools and can increase the acceptance and awareness of building greening.

Dominici et al. also wrote about cost-effective greening methods in their article [46]. Due to the increasing lack of space in urban areas, vertical greening systems (VGS) are becoming increasingly popular as a means of increasing urban greening with building facades. VGSs are usually installed and managed by experts due to their technical complexity; however, the role of local communities is becoming increasingly important through the practice of do it yourself (DIY). The results of this study contribute to reducing the lack of do-it-yourself technical information related to the design choice and installation of VGS and indicate critical considerations that may arise when implementing VGS in small-scale urban spaces. UN SD Goal 11 encourages a growing trend and common interest in urban vertical greening, which must be supported by appropriate knowledge for beginners. Spreading knowledge about the importance and construction of VGSs as green infrastructure plays a key role in community engagement in more vertical greening and in promoting a participatory transition towards more sustainable and greener cities.

The article of Zhang et al. [47] was about coastal green roofs. Rapid urbanization and the growing demand for sustainable development have led to the emergence of green roof landscapes in oceanic cities. These roof gardens provide many environmental benefits and contribute to the overall well-being of city dwellers. However, optimizing the design and interaction experience of green roof landscapes requires the integration of intelligent technologies. The applied 3DMAX modeling and application of VR technology enriches the design process by providing immersive experiences for designers, users and stakeholders. By simulating and visualizing rooftop gardens, designers can intelligently interact with the space and make well-informed decisions to effectively improve landscape design. The compatibility between computer vision and green roof landscape design in maritime cities underscores the potential of these technologies to create aesthetic and functional green spaces.

The research topic of Yuan et al. [48] was similarly focused on coastal cities. The purpose of this paper was to study the design of maritime urban (MU) botanical landscapes based on computer vision technology (CVT) and multimodal interaction design (MID) theory, so that the design of MU botanical landscapes can meet the needs of people's psychological and visual behavior while allowing participation and experience of the landscape to better meet people's viewing, leisure and entertainment needs. Based on the theory of MID, this paper explores the application of human-to-human and human-to-landscape communication and interaction in MU installation design and attempts to explore and summarize content and methods, the interactive LD in maritime cities with theoretical foundations and research value. The aim was to raise the theoretical level of interactive LD on the one hand, and to serve as a new reference for future maritime city (MC) LD on the other. At the level of practical application, in the field of LD, the new concept of computer vision is introduced to fully understand people's visual needs and increase the practicality and pleasantness of the MU landscape, hoping to attract more people to play and relax. Due to the attractiveness of MU landscapes to tourists, the planning and execution of the landscape no longer focuses on its appearance, but on the participation and experience of people. The study shows that as a designer, one must be able to analyze and solve the problems of the landscape from the audience's perspective, and one must be able to satisfy people's physical and mental needs for decorative, interactive and botanical landscape content enrichment.

The Special Issue covered very important and current topics, the diversity of which gives an idea of the fact that we need to continue researching this new field of science, since the ever-increasing urbanization and climate change demand this. I thank the editors and the authors of the articles for their joint work.

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Histological and Physiological Effects of Treatment of *Rudbeckia hirta* with Gamma Radiation

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Abstract: The breeding of resistant, high-yield, decorative ornamental plant varieties may be impacted by climate change in the future. The use of radiation induces mutations in plants, thereby increasing the genetic variability of plant species. *Rudbeckia hirta* has long been a very popular species in urban green space management. The goal is to examine whether gamma mutation breeding can be applied to the breeding stock. Specifically, differences were measured between the M1 and M2 generations, as well as the effect of different radiation doses belonging to the same generation. Morphological measurements showed that gamma radiation has an effect on the measured parameters in several cases (larger crop size, faster development, larger number of trichomes). Physiological measurements (examination of chlorophyll and carotenoid content, POD activity, and APTI) also showed a beneficial effect of radiation, especially at higher doses (30 Gy), for both tested generations. The treatment was also effective in the case of 45 Gy, but this radiation dose resulted in lower physiological data. The measurements show that gamma radiation has an effect on the *Rudbeckia hirta* strain and may play a role in breeding in the future.

Keywords: *Rudbeckia hirta*; ornamental; urban green; gamma; breeding; annual; gardening

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1. Introduction

Due to the development of new growing areas, where traditional varieties cannot be adapted, the need to produce new varieties of ornamental plants with improved properties has increased [1]. At the beginning of the 20th century, plant biologists established that the frequency and efficiency of genetic modifications in treated seeds could be increased by using chemical and radiation technology [2]. Subsequently, various mutagens, such as physical or chemical mutagens, were used to induce a wide range of genetic variability that led to and contributed to current plant breeding [3]. Radiation-induced mutation breeding is thus a remarkable method that can produce superior mutant varieties, in contrast to traditional breeding such as selection and crossing, which is time consuming and labor intensive with limited genetic trait changes [4–6].

Mutation breeding, including natural and artificial mutations, is an excellent method in the field of ornamental plant breeding because many species can be easily propagated, which facilitates the cultivation of spontaneous and induced mutants. The breeding of mutant varieties with the help of an ion beam has already been attempted on many ornamental plants, and some species have also been used to investigate the mutagenesis process. In addition, progress is being made in clarifying the genetic mechanism of the expression of important traits, which will probably result in the development of more efficient mutation breeding methods in ornamental plant breeding [7]. There are several literature references regarding this. In the case of gamma radiation applied to chrysanthemum plants, doses of 10 Gy and 20 Gy resulted in a change in flower color. It was found that gamma radiation affected leaf length, leaf width, stem diameter, stem length, and inflorescence diameter. In addition to morphological changes, it also resulted in histological changes, as changes also occurred in the structure of the leaves [8]. Changes in the morphological characters of *Dendrobium odoardi* Kraenzl. were also observed in individuals [9]. *Tulipa* sp. (L.) gamma radiation (5 Gy) stimulated the sprouting of the bulbs, and the survival rate of the bulbs was also higher. Too-high doses (20–100 Gy) inhibited growth. As the gamma radiation increased, the anthocyanin and flavonoid content decreased. The morphological properties of leaf stomata also changed [10]. In another bulbous ornamental plant, *Narcissus tazetta* (L.) var. *chinensis*, it was observed that gamma radiation given at a low dose (10 Gy) results in a change in growth, while gamma radiation applied at a higher dose brings about other morphological changes in the plants [11]. In the ornamental version of *Capsicum*, gamma radiation caused larger flowers, male sterility, and changed fruit color in the second generation [12]. When the rhizomes of *Cyperus alternifolius* L. were treated with gamma radiation, the lowest (20 Gy) and the highest (100 Gy) dose increased the germination capacity, while the doses between the two caused distorted growth. However, the distortions disappeared in the M2 generation [13]. At the same time, it can also be used to reduce seed germination. In the case of *Pennisetum alopecuroides* (L.) Spreng, the 60 Gy dose reduced the seed yield [14]. Gamma radiation does not always bring the expected result. In the case of *Camellia sinensis* (L.) Kuntze, lower radiation doses increased the germination power, but the seedlings died en masse at the age of five months. When gamma radiation was applied at a higher dose, the germination capacity decreased, but the morphological characteristics became more favorable (larger leaf size, larger flower size, higher height) [15], as in *Adenium obesum* (Forssk.) Roem. and Schult. [16]. In the case of *Lilium*, the number of leaves and the content of chlorophyll changed as a result of gamma radiation [17]. In the case of *Echinacea purpurea* (L.) Moench, the flower color changed and the size of the inflorescence increased, and the shape of the inflorescence and the height of the plant were altered as a result of gamma rays [18]. When *Philodendron erubescens* (K. Koch and Augustin) 'Gold' plants were treated with gamma radiation, the plant size, the number of branches, and the color of the leaves changed, which could be the basis for the breeding of a new variety [19].

Tests show that low doses of gamma radiation improve the morphological and biochemical properties of some plants. Gamma ray treatments carried out in the early stages of seed germination promote the synthesis of RNA and protein, thus increasing the growth of seedlings as well as increasing the antioxidant capacity of cells, helping cells to fight against daily stress [20]. Environmental factors can be broadly divided into biotic and abiotic components [21]. Biotic stress is one of the most common causes of the death of ornamental plants, which can be changed by modifying the genetic codes [22]. Biotic factors caused by pests, bacteria, viruses, fungi, nematodes, etc., represent a serious threat to the growth and development of plants, thereby adversely affecting quality. The breeding of stress-resistant plant varieties is becoming very important in the current agricultural system. Mutagenesis is one of the most common techniques for controlling plant stress. To induce mutagenesis, plant breeders use technologies such as physical (gamma radiation, ultraviolet radiation, etc.), chemical (ethyl methanesulfonate, methyl methanesulfonate, sodium azide, etc.) and genetic (ZFN, TALEN, and CRISPR) technologies [21]. These technologies are also increasingly used in ornamental plant breeding. *Osmathus fragrans*

Lour. is very sensitive to salt stress. However, with gamma radiation, salt tolerance can be achieved in the species, which becomes more and more noticeable as the dose increases. In addition, it moderated the MDA (melonaldide) level, which was associated with a significant increase in superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) activity. The accumulation of proline can also contribute to increasing the tolerance against salt stress [23]. In the case of *Paeonia* x *suffruticosa* Andrews, it was established that 30 and 40 Gy gamma radiation affected the physiological and biochemical state of the plants. As a result of the treatment, the activity of antioxidant enzymes, including superoxide dismutase, peroxidase, and catalase, gradually increased up to the value of 40 Gy. Total soluble protein content progressively decreased, while proline and malondialdehyde content increased significantly [24]. An increase in salt stress resistance due to gamma radiation can also be observed in *Musa* L. individuals under in vitro conditions [25]. Gamma radiation improved powdery mildew resistance in *Gerbera jamesonii* 'Harley' [26]. Gamma radiation can also change the histological properties. *Catharanthus roseus* (L.) G. Don. gamma radiation had an effect on the callus biomass growth of individuals, and it also had an impact on the vincristine and vinblastine content under in vitro conditions. Callus growth was maximal at 20 Gy but decreased at 100 Gy [27]. In the case of *Dimocarpus longan* J. de Lour., gamma radiation modified the morphological features and the rate of photosynthesis [28].

Rudbeckia Hirta as a Genetic Resource

The genus *Rudbeckia* consists of approximately 30 species native to North America [29]. The genus includes annual, biennial, and perennial species [30]. The annual species *Rudbeckia hirta* includes diploid (2n = 2x = 38) and tetraploid (2n = 4x = 76) cultivars with varied flower color and flower shape, typically flowering in late summer and autumn. *Rudbeckia* is a popular ornamental taxon, suitable for urban settings due to its ornamental diversity, low maintenance, and heat and drought tolerance [31]. In Hungary, Dr. Zoltán Kováts dealt with the breeding of the species [32].

*Rudbeckia*s are highly adaptable species with valuable flowering as ornamental plants. Complementing the current varieties with new cultivars would be important in trade. Interspecific hybridization and induced polyploidy could be a significant improvement of the genus from an ornamental horticultural point of view. When comparing diploid and tetraploid individuals, induced polyploidy significantly reduced overwintering ability [33]. Due to the aesthetic value of perennial herbaceous flowering plants, such as colorful flowers, more attention is paid to these plant groups in the field of urban planting [34].

Rudbeckia hirta is a very popular species worldwide, several Hungarian varieties of which are used in public areas. 'Mackó', 'Aranyálom', 'Kokárdás', 'Sárgarigó', and 'Őszifény' are Hungarian cultivars found in many cities. These products were bred by Dr. Zoltán Kováts in the 1980s and 1990s at the Horticultural Research Institute, which today operates as part of MATE. The climate at that time was not characterized by the summer drought typical of current years, and heat waves lasting several weeks, as well as many diseases, were not present in those decades. These breeds can no longer cope with the current environmental problems. Another important factor is that the market is looking for compact, resistant varieties with many flowers and special flower colors or flower shapes. The old *Rudbeckia hirta* varieties cannot satisfy this demand. Although the classic crossbreeding and selection breeding methods are effective, producing a new variety using these methods is costly and time consuming. Mutational breeding, on the other hand, can lay a new foundation for the faster and more cost-effective production of climate-tolerant and market-demanded varieties. Treating strains of *Rudbeckia hirta* 'Őszifény' produced by selective breeding with gamma rays can be a suitable method to increase genetic variability.

After several years of selective breeding of the *Rudbeckia hirta* individuals used, they were treated with a dose of gamma radiation, and the M1 and M2 generations were also examined. We studied the effect of the applied radiation doses on the given breed. As a result of the treatments, we aimed to determine a dose or doses with which we can continue to work in the future. When determining this, it is important to compare the morphological and physiological results. Another goal of ours was to select the groups and doses of the cultivated plants with which we can pursue the breeding program and make them resistant to the current climate (abiotic and biotic stress effects). Our goal is to examine whether gamma mutation breeding can be used for the applied breed candidate, and if so, the question of how this process takes place becomes important.

During our studies, we specifically measured the differences between the M1 and M2 generations as well as the effect of different radiation doses belonging to the same generation on the morphological and physiological properties. Recognizing the difference between generations, the goal was to measure the changes in the characteristics of *Rudbeckia hirta* varieties produced through sexual intercourse between generations. This can be an important clue in subsequent gene conservation and breeding tasks.

2. Results

2.1. Morphological Evaluation

2.1.1. Leaf Cross-Section

Regarding the results of the morphological evaluation, it can be said that the radiation had an effect on both the leaf and stem cross-sections. Sampling took place in full bloom, which in Hungary happens at the beginning of September—by this time, in the case of several individuals, the foliage is already starting to age. This is clearly visible in Figure 1, where, although the cells of the epidermis are closely aligned and the basal tissue cells are intact, the spongy parenchyma breaks, and chlorophyll-deficient spots begin to form.

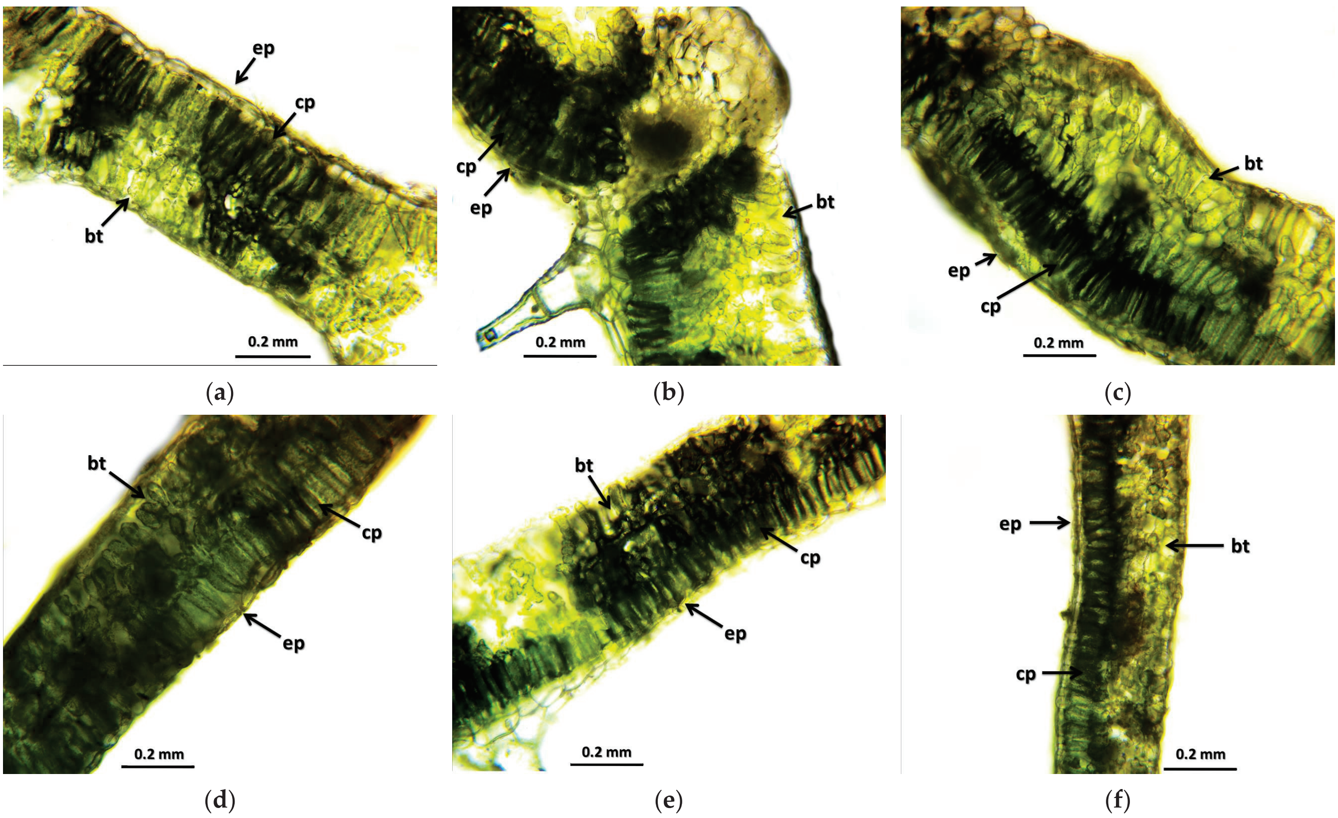


Figure 1. Leaf cross-samples of *Rudbeckia hirta* with gamma radiation treatment: (**a**) control; (**b**) 5 Gy M2; (**c**) 10 Gy M2; (**d**) 30 Gy M2; (**e**) 30 Gy M1; (**f**) 45 Gy M1. The abbreviations shown in the pictures mean the following: ep—epidermis; cp—columnar parenchyma; bt—basal tissue.

This is also evident in the leaf cross-section photos of the 5 Gy M2 stock (Figure 1b); the cells under the epidermis have disappeared, but the existing cell rows are still more closely aligned than in the case of the control group. In the case of the M1 group that received a stronger concentration, of 30 Gy M1 (Figure 1e), it can be said that this group shows the most stable tissue organization among the M1 populations. Its cells are uniform, their cell walls are closed, and no vacuoles have formed. The spongy and columnar parenchyma of the base tissue is uniform and rich in chlorophyll. In the 30 Gy M2 group (Figure 1d), the effect of fresh irradiation is visible: the leaf tissue diameter is irregular, the cells of the epidermis are thin, the basal tissue is damaged in some places but is still more complex than the leaf diameter of the control group. In the case of 45 Gy M1 (Figure 1f), it appears that this dose is probably close to the maximum usable level: the cells are smaller, the cell wall is strong, and the cell row of the epidermis is ordered. The cells of the epidermis and the columnar parenchyma are arranged and, no vulvae and cell death can be observed.

2.1.2. Stem Cross-section

Looking at the experiences of the stem cross-section, the results seen in the leaf cross-sections are also visible. The effect of gamma radiation is evident in all treated groups. In the case of the control group (Figure 2a), it can be observed that the degree of secondary thickening is not considerable.

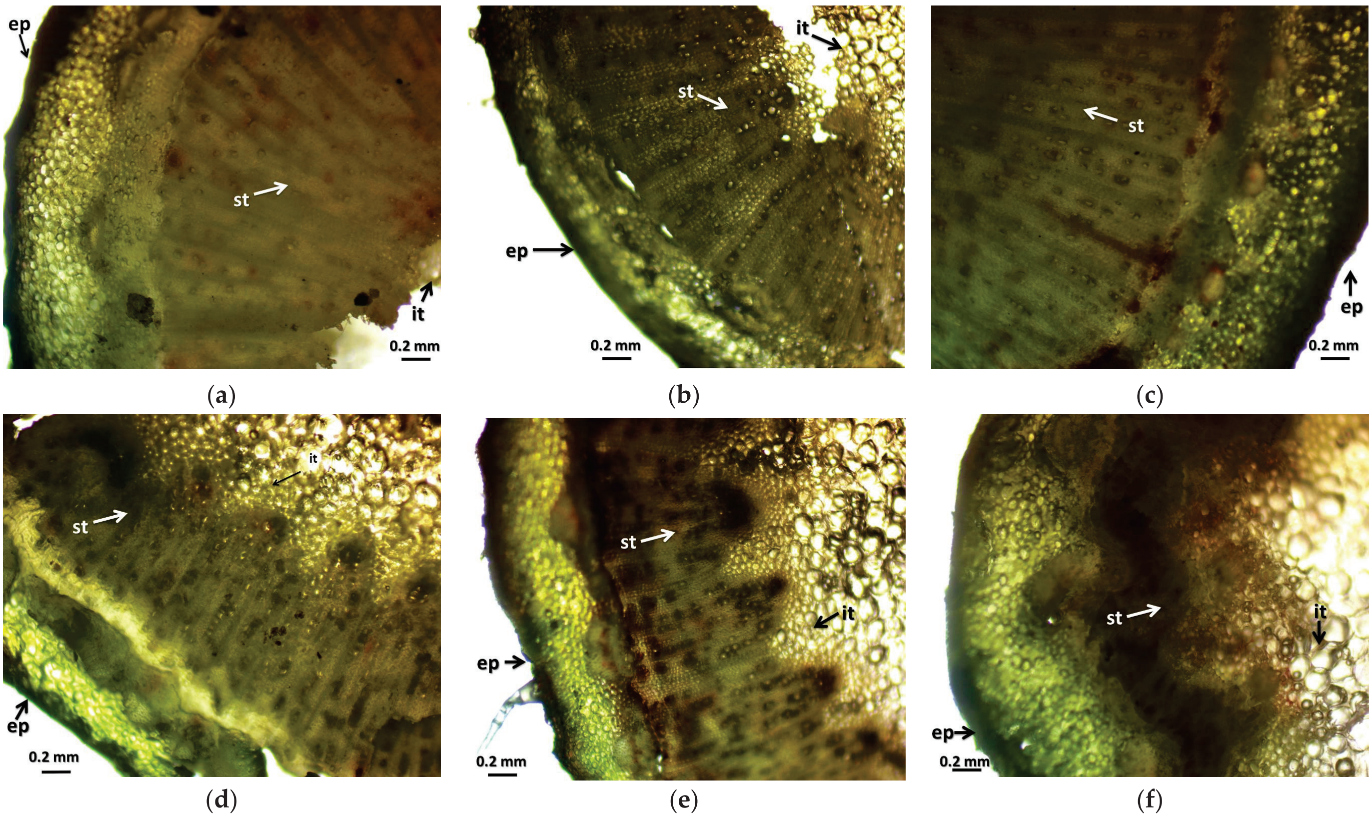


Figure 2. Stem cross-samples of *Rudbeckia hirta* with gamma radiation treatment: (**a**) control; (**b**) 5 Gy M2; (**c**) 10 Gy M2; (**d**) 30 Gy M2; (**e**) 30 Gy M1; (**f**) 45 Gy M1. The abbreviations shown in the pictures mean the following: ep—epidermis; st—secondary thickening; it—internal tissue.

Although the epidermis is strong, the cell row under the epidermis is thick, and the cells are intact, the cells of the intestinal tissue do not form well-developed, distinguishable tissue groups, and the central part of the intestinal tract is missing. In the case of M2 masses (Figure 2b–d), the central part of the intestinal tissue also fades, but the degree of secondary thickening is much stronger, and this is directly proportional to the increase in radiation dose. This effect can be observed even more intensely in the M1 stocks, also in direct proportion to the increase in radiation dose. Here, the cells of the central intestinal tissue are intact, most of the cells have a strong cell wall, the cells of the epidermis are strong, and some tissues and cell groups of the basal tissue are distinctly separated from each other. Furthermore, the dermis is thickened.

2.1.3. Trichomes

The arrangement and number of trichomes can also be an important morphological sign in terms of observing the effects of gamma radiation treatment. As can be seen in the photos, we also found differences in the size and number of trichomes. While in the control group (Figure 3a) the trichomes on the main veins of the leaf blades are uniform in size but weak, this is apparently different in the treated stands.

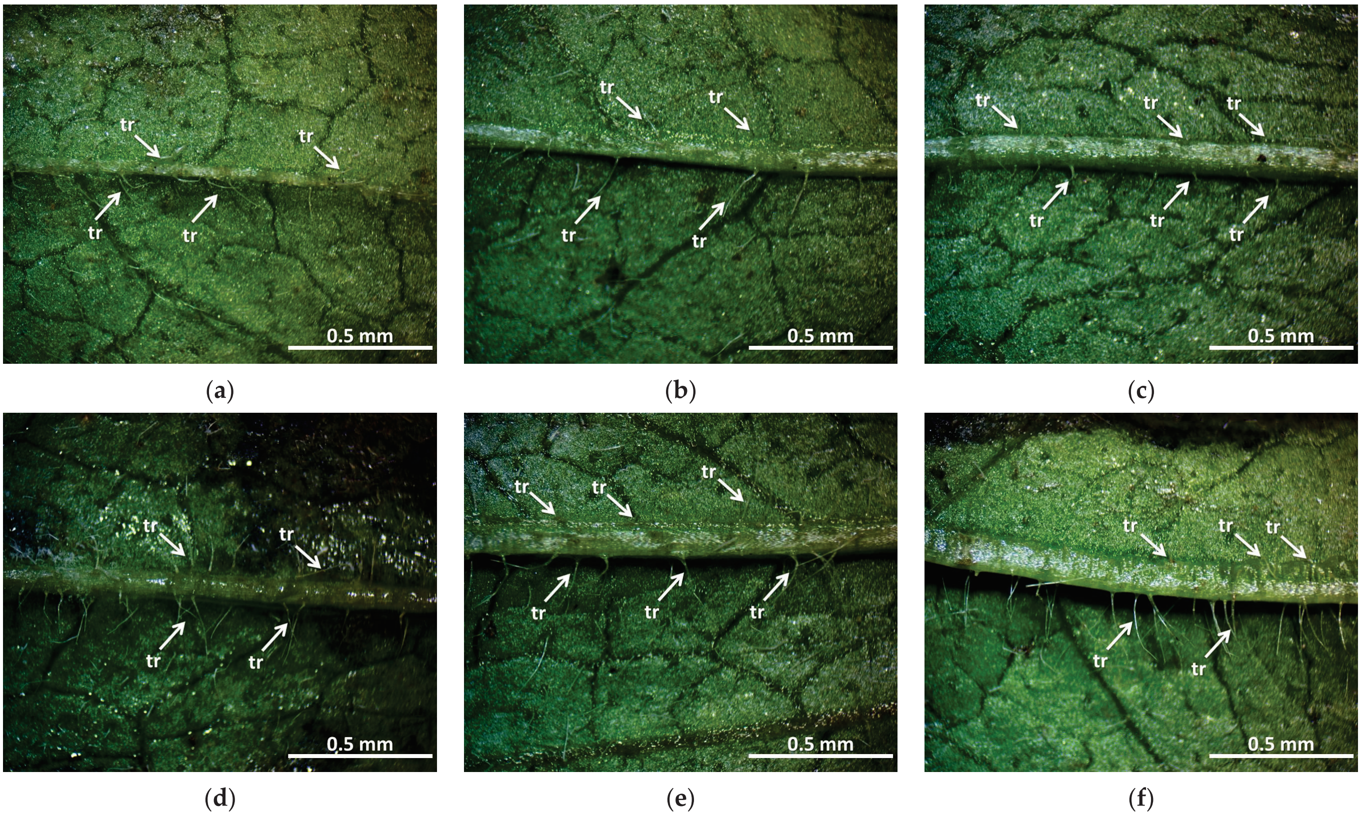


Figure 3. Trichomes of *Rudbeckia hirta* with gamma radiation treatment: (**a**) control; (**b**) 5 Gy M2; (**c**) 10 Gy M2; (**d**) 30 Gy M2; (**e**) 30 Gy M1; (**f**) 45 Gy M1. In the case of M2 stocks, the number of trichomes decreased (5 Gy M2, Figure 3b) or increased (10 Gy M2 and 30 Gy M2, Figure 3c,d). In M1 stocks, their number increased (30 Gy M1, 45 Gy M1, Figure 3e,f) and their length became longer (45 Gy M1). The marked difference between the M2 and M1 stocks is outstanding—in the 30 Gy M2 group, the trichomes are much more uniform and stronger than in the case of M1. The number of trichomes were counted using visual observation. The abbreviation shown in the pictures means the following: tr—trichomes.

2.1.4. Crop Length

The effect of gamma radiation can also be seen in the measurement results of crop length. In the case of the control group (Figure 4), the average seed length was 1.04 cm.

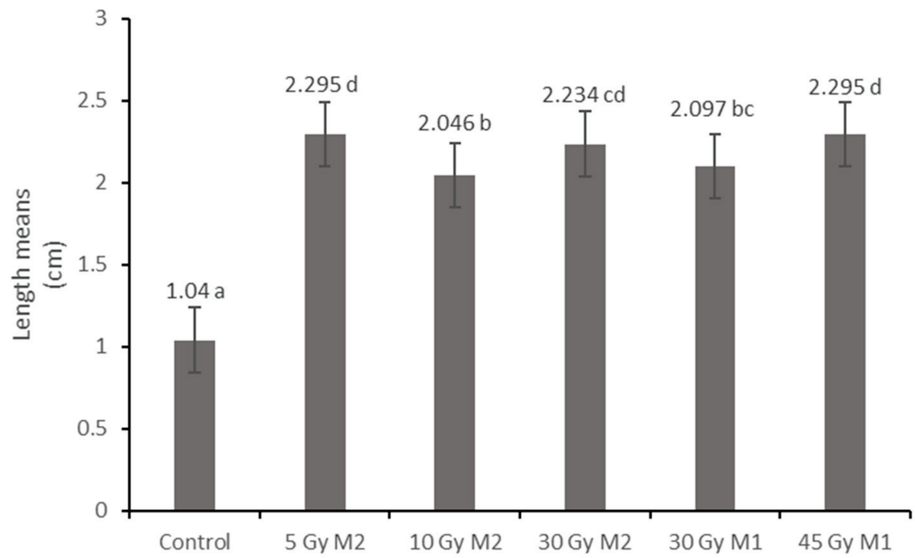
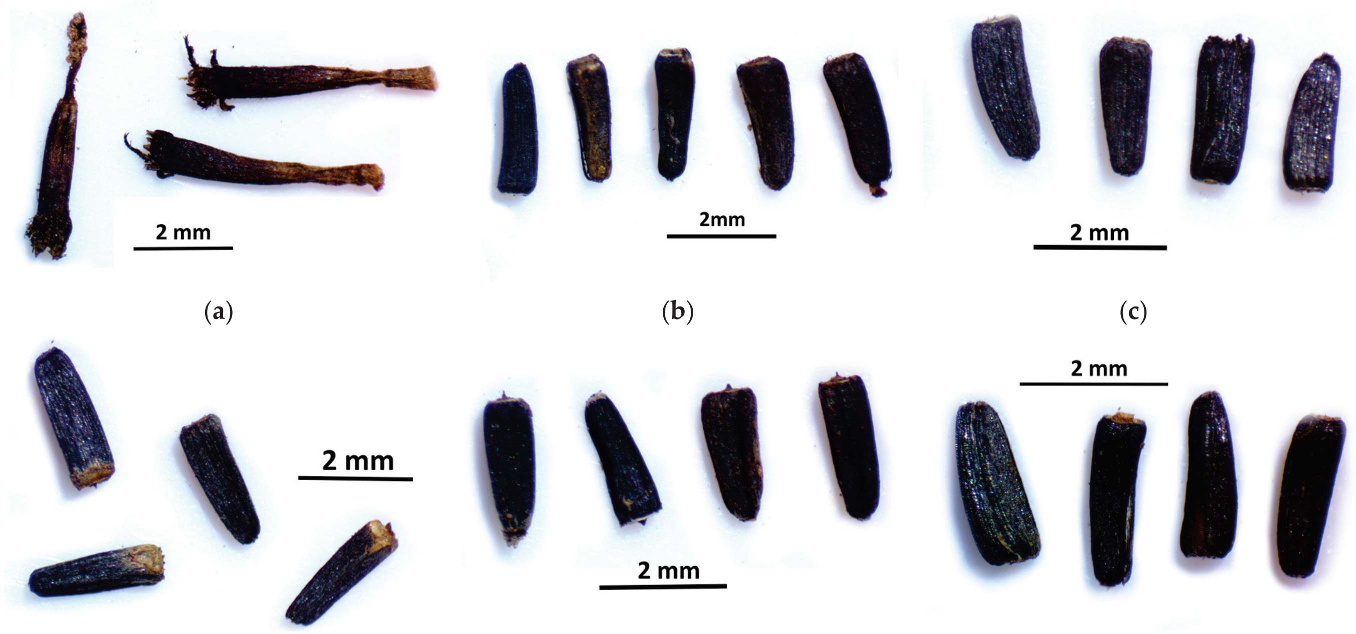


Figure 4. Crop length of *Rudbeckia hirta* with gamma radiation treatment. Different letters indicate significantly different groups (Tukey, $p > 0.05$). $p = 0.000$.

In addition, the control group contained several leeched seeds (mostly empty seed shells were typical, as in Figure 5a), though in the case of the groups that received gamma radiation, the fruits were healthy and uniform.



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

(**d**) (**e**) (**f**)

Figure 5. Crop length of *Rudbeckia hirta* with gamma radiation treatment: (**a**) control; (**b**) 5 Gy M2; (**c**) 10 Gy M2; (**d**) 30 Gy M2; (**e**) 30 Gy M1; (**f**) 45 Gy M1.

Significant differences were also observed in several cases in the treated groups. The 5Gy M2 group (Figure 5b) had the highest average crop length (2.295 mm) and the 10 Gy M2 group (Figure 5c) had the lowest (2.046 mm).

2.2. Physiological Results

Physiological measurements can also reveal a lot about the treated groups. The chlorophyll and carotenoid contents presented below, as well as the peroxidase enzyme activity results, were supplemented with a proline measurement, but this did not produce statistically verifiable results, so the results of this are not presented.

2.2.1. Chlorophyll and Carotenoid Content

The chlorophyll content results show significant differences in several cases. The average chlorophyll content of the 10 Gy M2 group was the lowest (1.031 μg), while the 30 Gy M1 group had the highest value (1.614 μg). The chlorophyll levels of the 30 Gy M2 (1.324 μg) and 45 Gy M1 (1.259 μg) groups show a statistical difference from these (Figure 6).

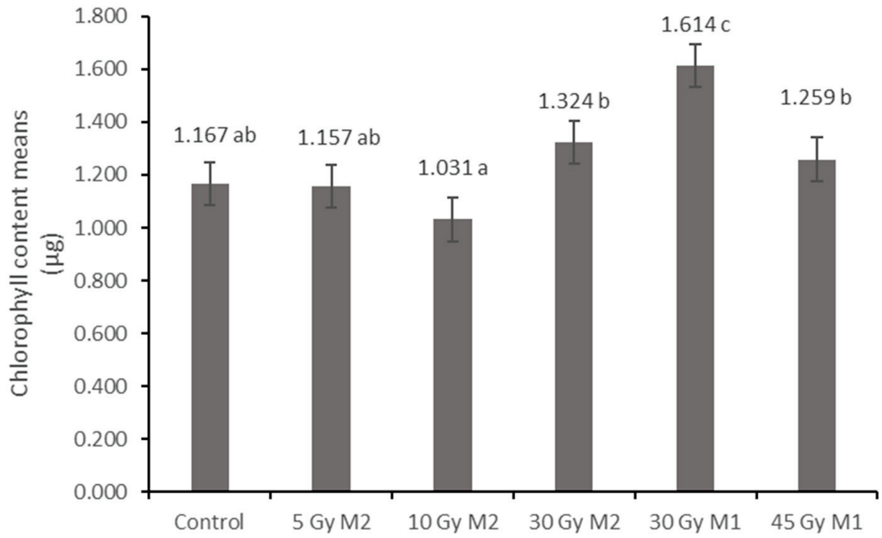


Figure 6. Average chlorophyll content of *Rudbeckia hirta* with gamma radiation treatment. Different letters indicate significantly different groups (Tukey, $p > 0.05$). $p = 0.000$.

Similar tendencies of the carotenoid contents were observed, as in the case of the chlorophyll levels. The lowest carotenoid content (0.020 μg) was measured in the 10 Gy M2 group, which is statistically different from the results of the other measurement groups. The highest carotenoid level was detected in the 30 Gy M1 group (0.029 μg). The other groups ranged between the two values (Figure 7).

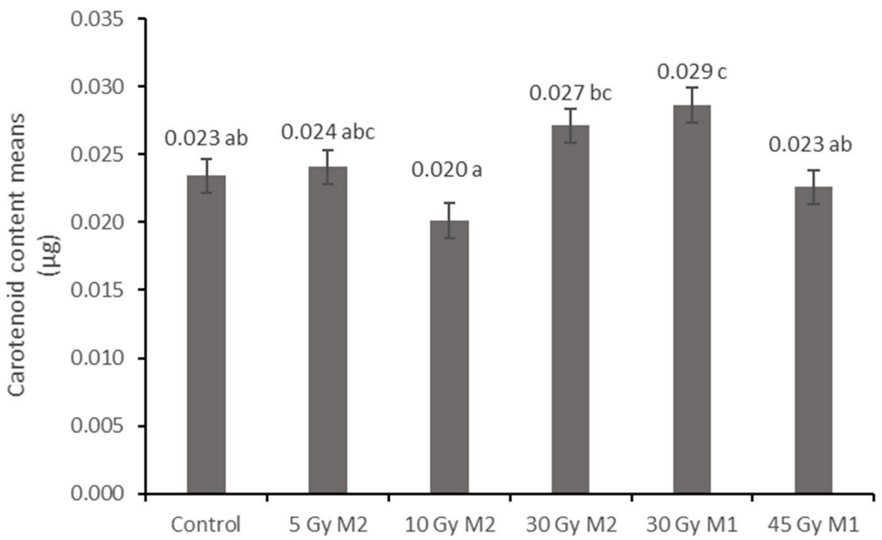


Figure 7. Average carotenoid content of *Rudbeckia hirta* with gamma radiation treatment. Different letters indicate significantly different groups (Tukey, $p > 0.05$). $p = 0.001$.

2.2.2. POD Activity

Compared with the control, the total POD activity decreased in all samples (differences are significant, $p < 0.05$). Among the treated samples, 30 Gy M1 showed the highest total POD activity, but even in this sample the POD activity suffered more than one-third drawback in the activity (to 62.2 ± 14.0% of the Ctrl). In comparison, the total POD activity in 10 Gy M2 and 45 Gy M1 was only 21.5 ± 7.7% and 27.5 ± 6.9% of the control, respectively, indicating a significant effect of the applied treatments on the overall POD spectrum (Figure 8).

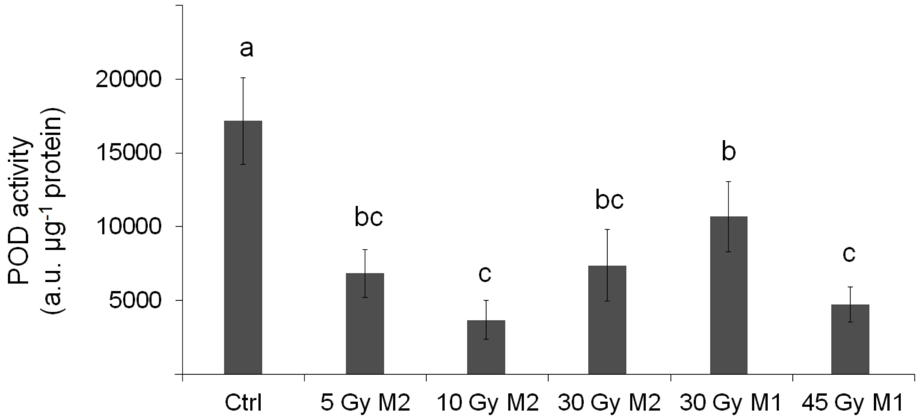


Figure 8. Total POD activity in *Rudbeckia hirta* samples. Error bars indicate SD values. To compare differences in the total POD activity, a one-way ANOVA with a Tukey–Kramer post hoc test was performed ($p < 0.05$). Letters indicate statistical groups.

2.2.3. Air Pollution Tolerance Index

Although the air pollution tolerance index (APTI) values of both Ganguly and Mukherjee [35] and Singh et al. [36] measured on the scale show no significant difference among groups using one-way ANOVA (F = 1.422, $p = 0.183$), the results can still be presented due to the APTI values (Table 1).

Table 1. Urban tolerance of groups of *Rudbeckia hirta* treated with gamma radiation.

	RWC	AAC	pH	Chlorophyll	APTI	Ganguly and Mukherjee [35]	Singh et al. [36]
Rudbeckia K	76.868	4.243	8.39	15.121	18	intermediate	intermediate
Rudbeckia 5 GY M2	93.326	3.252	8.55	18.738	18	intermediate	intermediate
Rudbeckia 10 GY M2	154.185	2.211	8.42	20.543	22	intermediate	intermediate
Rudbeckia 30 GY M1	74.374	3.586	8.49	25.769	20	intermediate	intermediate
Rudbeckia 30 GY M2	70.563	3.686	8.76	21.560	18	intermediate	intermediate
Rudbeckia 45 GY M1	83.772	3.382	8.26	17.680	17	intermediate	intermediate

It can be seen that all groups fall into the intermediate category according to all scales; however, it is striking that the M2 value of the control group and the 5 Gy M2 group is 18, while the M2 value of 10 Gy is 22, and the M2 value of 30 Gy is 20. The APTI values of the M1 generation are 17 and 18. It is clear that urban stress tolerance increased in the groups that received a higher dose of M2. Among the parameters of APTI, there were significant differences based on the relative water content (RWC) (F = 2.681, $p = 0.006$), ascorbic acid content (AAC) (F = 4.095, $p < 0.001$), and pH level (F = 18.028, $p < 0.001$); however, in the case of chlorophyll concentration, significant differences were not found among groups (F = 1.075, $p = 0.412$).

3. Discussion

In the course of our work, we dealt with the gamma irradiation treatment of *Rudbeckia hirta* and determined if the breeding stock strain we created is suitable for this type of treatment. If so, the breeding process can be facilitated by this. The effects of gamma radiation were measured and evaluated using histological and physiological methods. This revealed the effects of gamma radiation on organs, cells, and tissues, as well as the magnitude of the stress level (POD, APTI). Since POD isoforms are diverse both in their location as well as their function, alterations in the isoform composition reflects the stress defense and the cell wall composition properties of the plants [37]. The measurements were carried out with seeds irradiated with different doses, and the measurements of two consecutive generations were also compared.

It was found that the treatment of seeds can be a suitable method in the breeding process, as Oladosu et al. [2] established. A change in phenotypic properties was observed in all of the treated plants, which was also evident in the M2 generation in many cases, in connection with the findings of Beyaz and Yildiz [4].

The results of the leaf and stem cross-sections showed that by increasing the radiation dose, the leaf and the stem retain their tissue youth for a longer time. The central axis of the intestinal tissue of the stem is less or not hollow, the cells of the epidermis and dermis are stronger, and the cell walls are uniform. The degree of secondary thickening in the stem increases as the dose increases. There is also a difference between the M1 and M2 generations. The described characteristics also appeared in the M2 generation in the case of the leaf cross-section, not as strongly as in the case of M1 but perceptibly. This is similar to the findings of Susila et al. [8], Hu et al. [11], and Li et al. [10]. The columnar parenchyma cell groups full of chloroplasts visible in the cross-section of the leaf can also show a very close relationship between the amounts of chlorophyll and carotenoids. According to them, the 10 Gy M2 group had the lowest chlorophyll and carotenoid measurements, while the 30 Gy M1 represented the highest chlorophyll and carotenoid values. This assumes some analogy with the microscopic images of leaf cross-sections. The higher doses of gamma radiation initially affected the chlorophyll and carotenoid content, which are the determining factors for the vitality and good stress tolerance of plants. It should be mentioned in this context that the chlorophyll and carotenoid content measured in the 30 Gy M2 and 45 Gy M1 groups—although it does not show a statistical difference with most of the measured groups—is still high. For the *Rudbeckia* strain, doses of 30 Gy M1 and 45 Gy M1 were found to be more effective than lower doses. These results differ from those of Li et al. [10], in which a dosage strength above 20 had an inhibitory effect on several morphological and physiological processes in *Tulipa* bulbs. This is surprising, because for perennial plants with an overwintering organ the optimal dosage strength is assumed to be higher. Likewise, our results are not similar to the findings of Rêgo et al. [12]. This can also be explained by the density of the trichomes of the groups treated with a higher dose, which play a major role in preserving the plants' greater vitality.

The amount and length of the trichomes also changed in the main leaf veins of the irradiated groups. This is more visible at higher doses (30 Gy M1 and 45 Gy M1). In terms of generations, it is more even in the M2 generation. In summary, it can be said that the trichomes were stronger in all treated groups than in the control group—this may be related to better drought and climate tolerance, which is a very important breeding goal and aspect. This result is similar to the findings of Bhoi et al. [21], which state that the breeding of stress-resistant plant varieties is becoming crucial in the current agricultural system.

The effect of gamma radiation can also be seen in the size, morphological properties, and physiological state of the fruits. The seeds of the control group were not ripe at the time of sampling, and most of the seeds remained unripe. In the case of the groups that received gamma radiation, the fruits were uniform and healthy. In this regard, the radiation also helped vitality, increasing the survival chances of plants, as Ulukapi et al. [20] also stated.

The physiological results also largely reflect the experiences and conclusions presented so far. It is clear from the results of the peroxidase enzyme activity measurements that the enzyme activity of the samples taken in the climate of the end of summer in Hungary shows significantly higher values—in connection with the findings of Geng et al. [23], we achieved a similar result. The peroxidase enzyme is enriched when the plant is stressed. In the case of treated plants, the level of enzyme activity is significantly lower—this contradicts the findings of Wang et al. [24]. From this, we can conclude that the statistically verifiable lower stress level of plants treated with gamma radiation is due to the effects of gamma radiation. Bhoi et al. [21] also stated that mutagenesis is one of the most common techniques for controlling plant stress. In this case, there was no significant difference between the generations.

In this context, the APTI level did not show a statistically verifiable difference, but it is worth highlighting that the urban stress tolerance is higher at higher doses of the M2 generation.

In summary, it can be said that *Rudbeckia hirta* is a suitable species for use in urban green spaces. Hungarian-bred varieties no longer correspond to the effects of today's climate and old varieties are no longer fashionable—this is essential in ornamental plant breeding. Gamma radiation had a detectable and favorable effect on the strain of *Rudbeckia*. Stronger doses showed more favorable phenotypic characteristics. The difference between the generations was also noticeable, and in many cases the positive effects of the treatments were preserved. During our measurements, we came to the conclusion that gamma radiation is a suitable method for the breeding of *Rudbeckia hirta* as it promotes the breeding of new, stress-tolerant varieties. This was confirmed by histological and physiological methods.

In the future, it will be an increasingly important factor to breed varieties for the urban environment that tolerate the changed climate and, at the same time, the urban biotic and abiotic stress effects. The Hungarian breeds that are currently in development form a very important genetic basis, but they no longer meet the challenges of today. Mutational breeding, on the other hand, can mark a new direction and a new way to create varieties from old varieties that can be used in urban public areas of the 21st century. Our current results show that generational changes and higher applied doses are an important step for us in terms of breeding. With these results, we can contribute to the creation of an environmentally conscious, more sustainable urban plant application.

4. Materials and Methods

4.1. Characteristics of the Selected Rudbeckia

Rudbeckia is similar to the basic variety but its habit is more compact (50–60 cm), it has a larger number of inflorescences, and the burgundy and brown stains are more intense and stronger, often covering the entire petal, so the yellow color does not appear (Figure 9).

Figure 9. Selection strain no. 5 of *Rudbeckia hirta* 'Őszifény'.

4.2. Preliminary Treatment

The seeds were treated with gamma rays at the Seibersdorf Plant Breeding and Genetics Laboratory station in 2021 and 2022. Each experiment was repeated 3 times and 30 plants were examined in all groups. The plants were grown in a random block arrangement under outdoor conditions.

The seeds were irradiated at the following doses in the year in parentheses. Thus, the investigated dose effects were examined on M1 or M2 generations. For the M2 generation, plants were grown from irradiated seeds, and we collected the seeds in 2021. They were then cultivated in 2022.

- M2 (2021)—5, 10, 30 Gray
- M1 (2022)—30, 45 Gray.

4.3. Making Microscopic Images

The core examinations were performed with a Delta Optical SZ-450T type trinocular stereomicroscope, which has a stepless zoom of 10–45x.

The Euromex bScope BS.1153-PLi microscope was used for the light microscopic examinations.

Leaf cross-section eyepiece: Lens: PLi 10/0.25 Eyepiece: WF120×/20.

Stem cross-section: Lens: PLi 4/0.1.

Leaf cross-sections were cut with a manual sled microtome.

The stem cross-section was obtained by manual pruning with a scalpel.

In both cases, the Levenhuk M1400 plus camera was used to take the microscopic images.

4.4. Preparation and Microscopic Examination of Leaf and Stem Cross-Sections

The cut leaf was lifted from the knife into a watch glass filled with water using a soft, wet brush. After cutting the samples belonging to 1 leaf, we lifted the leaf samples onto the slide with a wet, soft brush. Afterwards, we dropped water on it and covered it with a coverslip and examined it under the microscope.

In the case of the treated and control plants, a cross-section was made from several points of the leaf, which was examined and photographed under a light microscope. After that, secondary thickenings and changes were examined. The Topuview program was used to take the photos and the Fiji program was used for the measurements.

The stem was cut manually with a scalpel then placed on a glass slide. Water was dropped on it, it was covered with a coverslip and placed under the microscope to be examined, and photographs were taken.

4.5. Stereomicroscopic Examination of Seeds

For each group, 1 inflorescence was collected. In order to not lose seeds, this was collected by pulling the paper bag over the inflorescence, tying it, and then cutting it off the stem. Then, the dropout took place in the bag. The samples collected in this way were sorted under a stereomicroscope so that plant debris did not get between the seeds. After that, the seeds were counted to obtain the total number of seeds, and then the leech seeds and healthy seeds were sorted out, which were also counted. The seeds were examined under the stereomicroscope with 2 types of magnification so that the size and surface differences between the individual groups became clearly visible.

4.6. Stereomicroscopic Examination of Leaf Hairiness

In the case of the examined groups, different hairiness was observed on the leaf surface. To quantify this, we used the main vein of the dorsal part of the leaf since the number of trichomes on the leaf surface could not be counted. Based on the image taken from the dorsal part, it was counted manually, marking the individual trichomes. In addition, a recording was made of the hairiness of the leaf edge.

4.7. Physiological Assessment

4.7.1. Measurement of Chlorophyll and Carotenoid Content

The measurements were made from the plates of the examined leaves based on the methodology of Helrich [38]. Until the physiological tests, the leaf samples were stored in a plastic, zippered bag in a freezer. For the chlorophyll and carotenoid analysis, 3 × 100 mg leaf samples from each group were measured. These were ground in a pestle and mortar with a small amount of quartz sand, then the crushed material was filled into a measuring cylinder and diluted to 5 mL (the diluting solution consisted of a mixture of 80% acetone and distilled water). After that, the sample was shaken (so that the rubbed substances dissolve sufficiently), then it was placed in a test tube and covered with paraffin for a day. Thus, quartz sand and larger particles that adversely affect the measurement settled to the bottom of the solution. The next day, the supernatant of each sample was placed into a cuvette using a pipette and analyzed using a Genesys 10vis spectrophotometer. The instrument measured the solution at 480, 644, and 663 nanometers. The following equations were used to calculate the total chlorophyll and carotenoid amounts from the results obtained in this way:

$$\text{chlorophyll (a + b) } \mu\text{g/g} = (20.2 \times \text{A644} + 8.02 \times \text{A663}) \times \text{V/w}$$

$$\text{carotenoid } \mu\text{g/g} = (5.01 \times \text{A480})/\text{w}$$

where: V = amount of tissue extract (10 mL); w = mass of tissue (0.1 g); A = absorbance.

4.7.2. Peroxidase Enzyme Measurement

The activity of class-III peroxidase isoforms (POD; EC 1.11.1.7) was measured according to Rao et al. [39] and Solti et al. [40]. Briefly, 500 mg frozen leaf material mixed from multiple individual leaves was homogenized with 1 mL isolating buffer: 50 mM Na-K-phosphate buffer, pH 7.0, 1.0 mM EDTA, and 0.1% (*w*/*v*) Triton X-100 and centrifuged for 20,000× *g* 20 min at 4 °C. Supernatant was solubilized in 5 mM Tris-HCl, pH 6.8, 0.01% (m/V) SDS, 10% (*v*/*v*) glycerol, and 0.001% (m/V) bromophenol blue. Proteins were separated on 10–18% gradient polyacrylamide gels as in Solti et al. [40]. POD activity was developed in 50 mM acetate buffer, pH 4.5, 2 mM benzidine, and 3 mM H_2O_2. The enzyme activity was terminated in 50% (*v*/*v*) methanol. After digitization using an Epson Perfection V750 PRO gel scanner, densities were measured using Phoretix v 4.0 (Phoretix International, Newcastle upon Tyne, UK). POD activity was normalized based on the total protein contents, determined as in Sárvári et al. [41].

4.7.3. Calculation of Air Pollution Tolerance Index

The level of air pollution can be expressed by the air pollution tolerance index (APTI) as an indirect reaction of plants. High values of APTI indicate low sensitivity, while tree species of low APTI can be considered biological pollution indicators [42–44] (Table 2).

Table 2. Categorization of species based on APTI values.

Ganguly and Mukherjee [35]		**Singh et al. [36]**	
<1	very sensitive	<14	sensitive
1–16	sensitive	15–19	intermediate
17–29	intermediate	20–24	moderately tolerant
30–100	tolerant	>24	tolerant

APTI values were calculated based on the ascorbic acid content in mg/g (A), total chlorophyll content in mg/g (T), pH of leaf extract (P), and relative water content (R) of the leaves. Using these parameters, we applied the equation proposed by Singh et al. [36]:

$$APTI = [A \times (T + P) + R]/10$$

The ascorbic acid content was measured with the redox titration method, where 2 g of leaf tissue was crushed and homogenized with 50 mL of water in 3–4 parts. After that, we collected the extract and made up 100 mL in volumetric flasks. From this extract, the leaf pH was first measured using a digital pH meter. After pH measurement, 20 mL portions of the sample were titrated in triplicate with 0.0025 mol of iodine solution in 1 mL of 0.5% starch solution. The blue color remained for 20 s. Chlorophyll was extracted from approximately 50 mg of fresh leaves using 5 mL of 96% ethanol. The absorbance of the extracts was measured at wavelengths of 653, 666, and 750 nm using spectrophotometric analysis. The total chlorophyll content (T) was calculated as follows:

$$T\ mg/g = (17.12 \times E666 - 8.68 \times E653) \times V/m \times 1000$$

where V is the volume (mL) of the leaf extract, m is the fresh weight (g) of the leaf sample, and E666 and E653 are the absorbance levels at 666 nm and 653 nm minus the absorbance level at 750 nm, respectively. For the pH measurement, 2 g of leaf tissue was crushed and homogenized in 100 mL of deionized water. To determine the relative water content, the fresh weight of individual leaves (FW) was measured. Then, the leaves were immersed in water overnight before being weighed again to determine the turgid weight (TW). Finally, the leaves were dried in an oven at 70 °C to measure the dry weight (DW). The relative water content (R) was calculated as follows:

$$R\ (\%) = (FW - DW)/(TW - DW) \times 100$$

4.8. Statistical Evaluation

Microsoft Office 365 Excel was used to document our measurement data, and Microsoft Office 365 Word was used for text editing. The processing, comparison, and examination of measurable differences in our results were carried out with the IBM SPSS Statistics 26 program using the ANOVA method. In order to achieve a normal distribution, a part of the database (fresh root mass, fresh green mass, dry root mass, dry green mass) was transformed and the Winsorization method was applied. In all cases, the measured data were analyzed at a 95% reliability (significance) level. Having evaluated the Levene test, if the Sig. > 0.05 the Tukey's test was used, and if Sig. < 0.05, the Games–Howell post hoc test was used.

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Plant Use in the Late Renaissance Gardens of the 17–18th Century Transylvania

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Abstract: The aim of this article is to find, scientifically define, and locate the most frequent occurrences of the gardens of Transylvania in the Late Renaissance period (17–18th centuries), and to collect and prepare a comprehensive plant list of these gardens. During our investigation, based on archival and literary sources, as well as field studies carried out, we identified 81 Late Renaissance residency gardens located in Transylvania. We defined the most typical garden types for the region and we delineated the most characteristic ornamental, fruit, and vegetable plants, including fodder plants, used at that time in residential gardens. Meanwhile, the article intends to give a general overview of the first decisive time period in the Carpathian Basin, represented by the Late Renaissance garden art, from a garden and landscape architectural point of view.

Keywords: renaissance garden art; plant use; landscape architecture; historic garden; garden heritage

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1. Introduction, Historical Background

The use of plants in Renaissance gardens is the subject of numerous studies and essays on botanical history in Europe [1–22]. In Hungary, there are also some historical and contemporary works on Renaissance Garden culture and the plants used [23–32], but research on the subject is far from what is desirable in relation to its importance. Research on Renaissance gardens in Transylvania has begun [23–42], but the amount of material on the plant population of gardens is small and tangential.

The study of the cultivated plants of the Transylvanian Renaissance gardens can provide interesting contributions to the history of gardens both locally and universally, since while in most countries outside Italy the Renaissance idea spread only at the beginning of the 16th century, the style appeared very early in the Carpathian Basin, and thus in Hungary, at around 1470. The launch of the style was underpinned by Hungary's strong political, dynastic, and cultural ties with Italy, the dominant factor of which was the marriage of King Matthias to Aragonian Beatrix in 1474. What followed as a direct consequence of the matrimony was the influx of notable Italian painters, sculptors, and architects of the early Renaissance to the Hungarian Royal Court [43,44].

This first, early period of the Renaissance in the Carpathian Basin was related to the royal court and its immediate surroundings, and it lasted until the death of King Matthias in 1490. Although the death of the patron King Matthias in 1490 had a negative impact on the development of Renaissance ideas and art in Hungary, the century and a half of Ottoman occupation that followed the defeat of Mohács in 1526 caused a much more serious cultural disruption. During this period, a significant part of the country's territory came under Ottoman rule, isolated from Europe.

The period between the end of the 16th century and the first decades of the 18th century is known as the second period of the Transylvanian Renaissance, which is considered the late Renaissance by art history. Due to the isolation and different cultural impacts caused by the Ottoman occupation, special forms of local characteristics developed in this period, making the historic garden features particularly rich and interesting in Transylvania. And although the Transylvanian Late Renaissance lasts for almost two centuries, its stylistic characteristics are most strongly expressed in the 17th century, which can be explained by the economic boom of the region. The independent Principality of Transylvania was in its golden age during the 17th century, when Gábor Bethlen, György Rákóczi I. and Mihály Apafi I. were the ones who financed the flourishing period of the country, also having a strong positive influence on the development of the garden culture of the region, especially in the case of residential gardens.

Although a few manor gardens are known from this period—among others the gardens of Mihály Apafi and his wife Anna Bornemisza at Ebesfalva (nowadays Erzsébetváros/ Dumbraveni, RO), Küküllővár (Cetatea de Balta, RO), Székelyhíd (Sacueni, RO), Radnót (Iernut, RO) and Fogaras (Fagaras, RO) were famous in their time—the late Renaissance Transylvanian garden culture of the 17th and 18th centuries is a less researched topic in landscape architecture, the exploration of which is also helped by the research and systematic assessment of archival data on the plant use of gardens of the period.

2. Objectives

The main objective of the research is the thorough and systematic literature review of the Late Renaissance (17–18th century) garden culture in Transylvania, the synthesis and supplementation of the contemporary garden history of the region, based on archival sources. The study and analysis of plant species used in gardens of the period is a separate research topic within the history of gardens. The comparative analysis of the cultivated plants (ornamental plants and crops) of the manor gardens, going back four hundred years, provides new data and findings to the garden art of Transylvania in the 17th and 18th centuries, while at the same time placing Transylvanian gardens in a European context.

3. Research Methodology

Our research regarding plant use in Transylvanian late renaissance gardens started in 2016, as part of a comprehensive investigation of residential gardens from Transylvania. Our approach is based on the principles of case study research. Accordingly, each site is considered as a case study and analyzed separately before a comparison is made. In the analysis, we used an explicit analytical framework in order to compare different sites with different geographical, economical, and architectural contexts by different owners. Methods of data collection: comprising first of all a quantitative investigation of the existing archival (primary and secondary) sources and materials resulting in a first overview per case. As primary sources, we have to mention here the Archives of the HungarianAcademy of Science (Magyar Tudományos Akadémia Levéltára), and the county branches of the Romanian State Archives (Arhivele Nationale Romane, Filiala Cluj Napoca; Serviciul Judetean Mures al Arhivelor Nationale). Other archives, libraries, collections, etc. were used as well during the material collection.

The research was conducted in three phases:

I. Identification of all Renaissance gardens in the study area, by examining and mapping their spatial/geographic location.

II. Definition of three fundamental types, based on the data of the study sites

- Type A: sites where the garden is not only mentioned, but described specifically with its parameters;
- Type B: sites where the garden is just mentioned, one or more gardens exist, but no description of its layout can be found.

III. Investigation and analysis of Type A sites, by the cultivated plant types and species (ornamental plants, vegetables, fruits, herbs, agricultural crops, fodder plants), based on archival materials as follows:

- the research of the distinct, clearly separable garden units defined by different types of cultivated plants of the era;

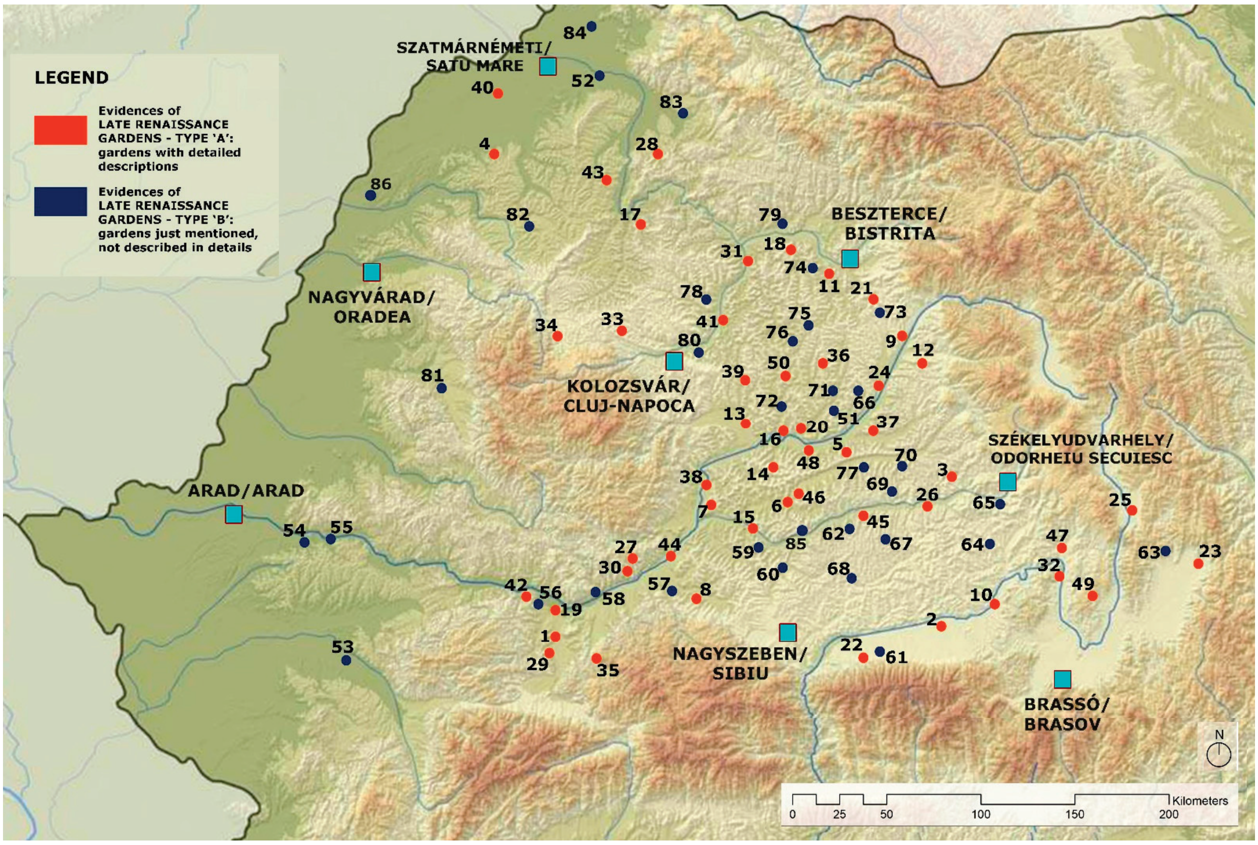
- the analysis of the frequency of the most typical plant species.

3.1. Identification of All Renaissance Gardens Sites in the Study Area

The study area is Transylvania, a region of the Carpathian Basin located in Eastern Europe, which is now part of Romania. During the archival research, 86 sites were identified where there was a Late Renaissance Garden existing. The mapping of the identified sites clearly shows their spatial location within Transylvania (Figure 1a,b). The names of the locations can be identified using the reference numbers form in Table 1.

(a)

Figure 1. *Cont.*



(**b**)

Figure 1. (**a**) The study area on the map of Europe (Source: Prepared by Authors). (**b**) Spatial distribution of the investigated sites on the map of Transylvania (Source: Prepared by Authors).

Table 1. List of during the research identified Renaissance garden's locations from Transylvania. (Source: prepared by Authors).

No	Locations with Garden Description (Type "A") Hungarian Name/Romanian Name	Data (Year)	No	Locations without Garden Description, Only Mentioning the Existence of the Garden (Type "B") Hungarian Name/Romanian Name
1	Kisbarcsa/Barcea Mica	1624	51	Porumbák/Porumbac
2	Fogaras/Fagaras	1632	52	Aranyosmeggyes/Mediesul Aurit
3	Siménfalva/Simonesti	1636	53	Lugos/Lugoj
4	Tasnád/Tasnad	1644	54	Lippa/Lipova
5	Nagyteremi/Tirimia	1647	55	Odvos/Odvos
6	Királyfalva/Craiesti	1647	56	Marosillye/Ilia
7	Meggykerék/Mescreac	1647	57	Szászsebes/Sebes
8	Drassó/Drasov	1647	58	Algyógy/Geoagiu
9	Marosvécs/Brancovenesti	1648	59	SzászcsanádCenade
10	Komána/Comana de Jos	1648	60	Sorostély/Sorostin
11	Sajókeresztúr/Cristesti	1648	61	Alsóárpás/Arpasu de Jos
12	Görgényszentimre/Gurghiu	1652	62	Sáros/Soars
13	Gerend/Luncani	1652	63	Kézdiszentlélek/Sanzieni

Table 1. *Cont.*

No	Locations with Garden Description (Type "A") Hungarian Name/Romanian Name	Data (Year)	No	Locations without Garden Description, Only Mentioning the Existence of the Garden (Type "B") Hungarian Name/Romanian Name
14	Magyarbükkös/Bichis	1655	64	Pálos/Palos
15	Búzábocsárd/Bucerdea Granoasa	1658	65	Bögöz/Mugeni
16	Mezőszengyel/Sanger	1656	66	Sárpatak/Sarpotoc
17	Szurdok/Surduc	1657	67	Keresd/Cris
18	Bethlen/Beclean	1661	68	Martonfalva/Metis
19	Déva/Deva	1667	69	Szásznádas/Nades
20	Mezőbodon/Papiu Ilarian	1679	70	Szentdemeter/Dumitreni
21	Nagysajó/Comuna Sieu	1681	71	Nagyercse/Ercea
22	Oprakercisóra/Cartisoara	1683	72	Mezőzáh/Zaul de Campie
23	Nyujtód/Lunga	1684	73	Paszmos/Posmus
24	Gernyeszeg/Gornesti	1685	74	Kentelke/Chintelnic
25	Csíkkozmás/Cozmeni	1688	75	Búza/Búza
26	Nagybún/Boiu Mare	1692	76	Gyeke/Geaca
27	Borberek/Vurpar	1694	77	Kóródszenmárton/Coroisanm
28	Kővár/Cetatea Chioarului	1694	78	Kendilóna/Luna de Jos
29	Vajdahunyad/Hunedoara	1695	79	Négerfalva/Negrilesti
30	Alvinc/Vintul de Jos	1696	80	Szamosfalva/Somesen-Cluj
31	Szentbenedek/Manastireni	1696	81	Belényes/Beius
32	Miklósvár/Miclosora	1698	82	Szilágysomlyó/Simleul Silvaniei
33	Egeres/Aghires	1699	83	Nagybánya/Baia Mare
34	Zentelke/Sancraiu	1715	84	Halmi/Halmeu
35	Malomvíz/Grid	1716	85	Küküllővár/Cetatea de Balta
36	Mezőörményes/Urmenis	1721	86	Székelyhíd/Sacueni
37	Koronka/Corunca	1724		
38	Marosszentkirály/Sancraiu de Mures	1725		
39	Aranykút/Aruncuta	1728		
40	Kaplyony/Coplean	1729		
41	Bonchida/Bontida	1736		
42	Branyicska/Branisca	1757		
43	Szilágycsehi/Cehu Silvaniei	17. c.		
44	Gyulafehérvár/Alba Iulia	17. c.		
45	Ebesfalva/Daumbraveni	17. c.		
46	Ádámos/Adamus	17. c.		
47	Olasztelek/Talisoara	17. c.		
48	Radnót/Iernut	17. c.		
49	Sepsikőröspatak/Valea Crisului	17. c.		
50	Uzdiszentpéter/Sanpetru de Campie	17. c.		

3.2. Definition of the Fundamental Garden Types, Based on the Data of the Study Sites

Out of the 86 locations identified, in 50 cases, archive documents describe in detail the existence of the garden, its units, elements, and plants ("Type A"). In the remaining 34 cases, the garden is only mentioned, i.e., the existence of one or more gardens is referred to, but no specific description of them is to be found ("Type B"). (Figure 1b and Table 1.)

3.3. Investigation and Analysis of "Type A" Sites, by the Cultivated Plant Types and Species

This section contains the source research of the plant material of the gardens. Source research on garden history is usually based on three major sources of data: written, pictorial, and material memories.

For over more than 20 years, Transylvanian castle-garden ensembles, including Renaissance gardens, have been investigated, described, and analyzed by a research group from Hungary, led by Albert Fekete. The goal of this study of Transylvanian ensembles is to obtain background information for developing a strategy of landscape preservation and development in the long run that comprises the cultural and historical values and the demands from society on what to do with them in the contemporary context. Site visits and surveys represented very important pillars of the investigation, documenting the current condition of these historic ensembles.

As far as Transylvanian Late Renaissance Garden art is concerned, the material heritage is rather scarce. None of the Transylvanian castle gardens survive in their original form, and very few elements of Renaissance garden art have survived.

What has survived is mainly associated with large-scale earthworks, such as those related to water features (canals, moats, fishponds) and terraces (e.g., orchards on hillsides). The destruction or transformation of gardens can be attributed to two main causes. One is the change in the style of gardens, with late Renaissance gardens being radically transformed in the 18th century according to Baroque and then in the 19th century to Landscape Garden ideas in all locations. Another reason for the deterioration is that the extremely fragile, mostly herbaceous vegetation, which was the typical material and essence of Late Renaissance gardens, has deteriorated considerably and disappeared completely in the absence of regular and professional maintenance.

The pictorial sources are also poor, and apart from a few illustrations in books on medical botany, there are only a few concrete details of plant use.

In the absence of material and pictographic references, the present research is based on written sources, based on the understanding of the text, among which the unpublished works, usually preserved in archives, and works of scientific nature are of particular importance.

The written sources of garden history are diverse: from documents containing seemingly insignificant mentions and poor data to detailed garden descriptions, they contain a wide range of authentic information on garden history. Garden descriptions from primary and secondary sources often provide scientific detail on contemporary garden structures, gardening techniques, and plant species used in gardens. Written sources are generally grouped into the following categories:

- Inventories, registers, and fief ownership charters
- Accounts, payrolls, and expenditure certificates
- Correspondence
- Chronicles, travelogues
- Diaries, diary fragments, reminiscences
- Writings on local history, monographs
- Scientific and professional literature, dissertations, summaries
- Journals, periodicals, newspapers, and other news items

Of these, the most relevant written sources for the study of late-Renaissance Transylvanian garden art are inventories and registers. In this work, we rely on the analysis of these sources.

Inventories and registers are primarily records of economic importance, which give detailed descriptions or more concise mentions of the gardens and estates of noble families. They provide a rich written source material for the history of Transylvanian noble gardens of the 16th and 18th centuries, and the plant material used. The value of these economically important records as sources for the history of art has been pointed out by several researchers, of whom Margit B. Nagy [33,45,46], Jolán Balogh [47–51], and Zsigmond Jakó [52–55] are of particular importance with regard to the Transylvanian aspects.

The importance of the documents on economic history for garden history is due to the fact that not only ornamental gardens, parks associated with castles and understood as artistic compositions, but also various types of kitchen gardens, such as vegetable gardens, orchards or vineyards, are an integral part of our castle garden culture. Until the 17th century, not only in Transylvania, but also in European garden culture, there was no sharp distinction between ornamental gardens and kitchen gardens. Garden inventories provide information mainly on the crops and ornamental plants grown and the gardening techniques used. However, they also contain valuable references to the structures and artistic qualities of the gardens.

By way of example, here are three brief passages illustrating the nature, content and detail of the written sources analyzed:

According to the 1681 garden inventory of the Kemény Castle in Nagysajó (Sieu, BN), the castle had several gardens, and in one of the "more beautiful" gardens, in raised beds, various crops and ornamental plants were grown:

> "Rectangular beds enclosed by beams, with very pretty vines growing on the edges of the beds; again, rose and lilac bushes. Lots of fragrant grasses and flowers and some small crops. Again there are other compartments, without fences, in which under the fruit trees there are lilies of the valley." [56]

Extract from the 1688 inventory of the vegetable garden of the Béldi Manor Garden in Csíkkozmás (Cozmeni, RO):

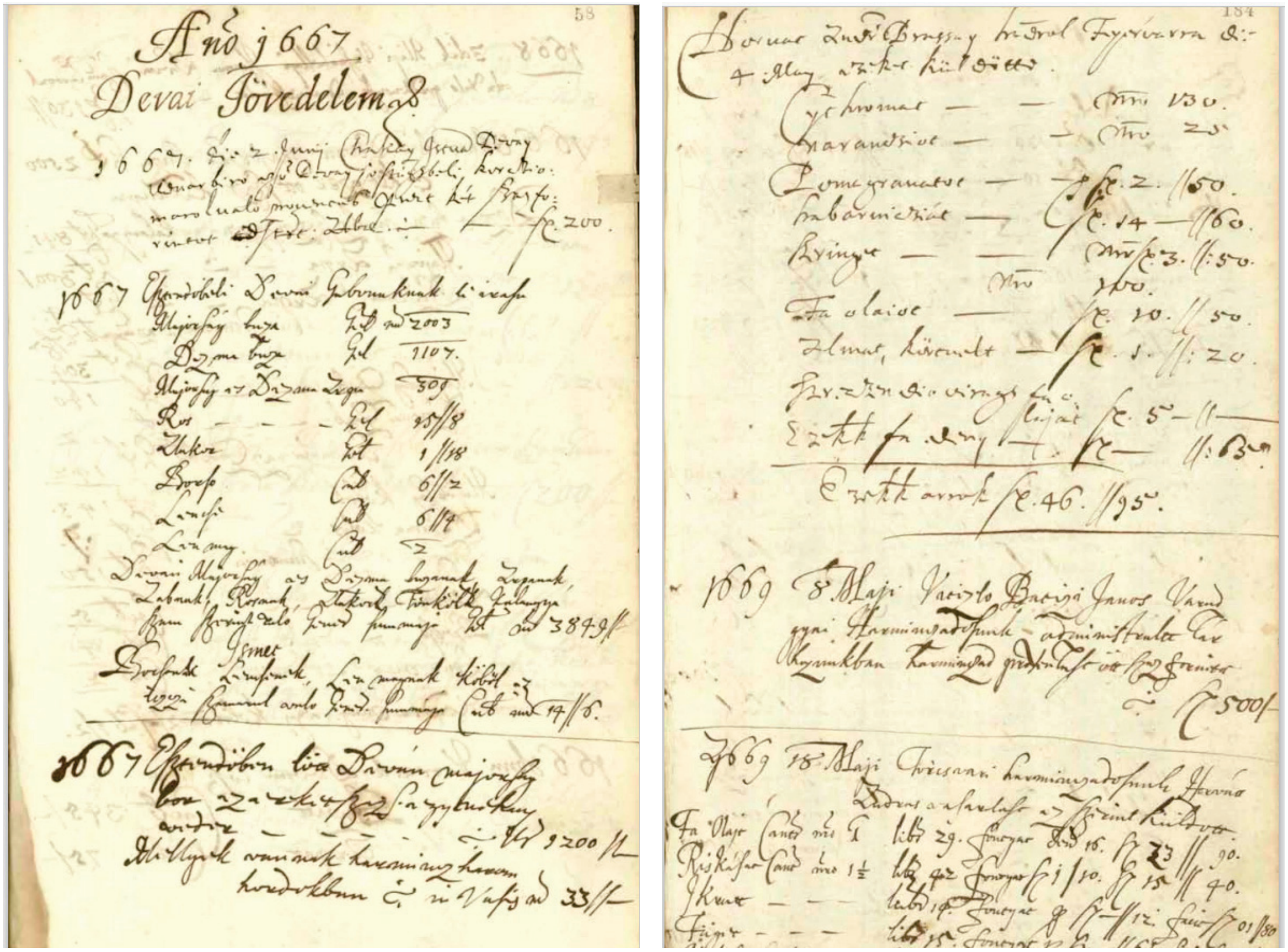
> "There are 15 tiny beds of parsley here, mixed with onions. Parsnip of nine and a half beds, all good. Onions of 13 beds. Garlic, five beds. Carrots, seven beds. Radishes, one bed. Besides these there is also plenty of tarragon, sage, sedge, etc. Gooseberry planted in a row. Some peas. A few bushes of seed cabbage and two beds of seed parsley." [57]

The 1721 description of the garden of György Bánffy's mansion in Mezőörményes (Urmenisu de Campie, MS) mentions a popular contemporary garden structure, the gezebo, in addition to the plant species used:

> "In this garden, to the right hand side, at the edge of the compartments extends southwards a row of fruit trees, pear and apple graft trees. In the middle is a shingled gazebo on four posts, standing on pedestals, surrounded by fourteen very fine vines, tied on stakes. Beside it, on the edge of the compartments, are fourteen vines on stakes. On the north side there are also some garden and wild rose trees on the edge of the compartments, and also very fine sage, sedge and white lilies . . . " [58]

As far as the registers are concerned, the economic diaries of the "grand dames" of the Principality, e.g., Anna Bornemisza, Zsuzsanna Lórántffy, or Mrs Sámuel Kálnoky [59–61], and the economic documents of the princely estates, e.g., of György Rákóczi I., are rich written sources of the Transylvanian aristocratic garden culture [62].

In the economic diary of Anna Bornemisza, the agricultural and horticultural crops of the princely estates are listed as sources of income. Figure 2a shows the income from wheat, barley, rye, oats, einkorn wheat, peas, lentils, and linseed of the Déva (Deva, HD) estate in 1667. Similar statements give an overview of the major crops grown on each estate at the time. Figure 2b is a list of expenditure on the mostly southern plants purchased by the princely court (oranges, lemons, pomegranates, olive trees, gooseberry, etc.) and the amounts spent on them, confirming the contemporary use of some exotic plants in Transylvanian gardens.



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

Figure 2. (**a**) List of cereals and fodder plants from Déva (Deva, HD), 1667. (Source: [63]), (**b**) List of southern plants purchased by the princely court in Fogaras, 1667 (Source: [64]).

The detailed 99-page register of the manor of Fogaras [65], drawn up in 1632, lists the individual components of the estate as separate items, including the gardens (vegetable garden, orchard, deer garden), meadows, and fishponds relevant to our research. In a five-item list, the 'lictariums' are mentioned, the ancestors of modern-day marmalades, whose components also refer to the Transylvanian horticultural culture of the period (Figure 3). He also enumerates the garden tools (e.g., 6 iron hoes, 1 spade, 3 iron shovels, 1 three-pronged pitchfork, 1 two-pronged iron rake) and gives detailed descriptions of the individual gardens (e.g., the crops grown).

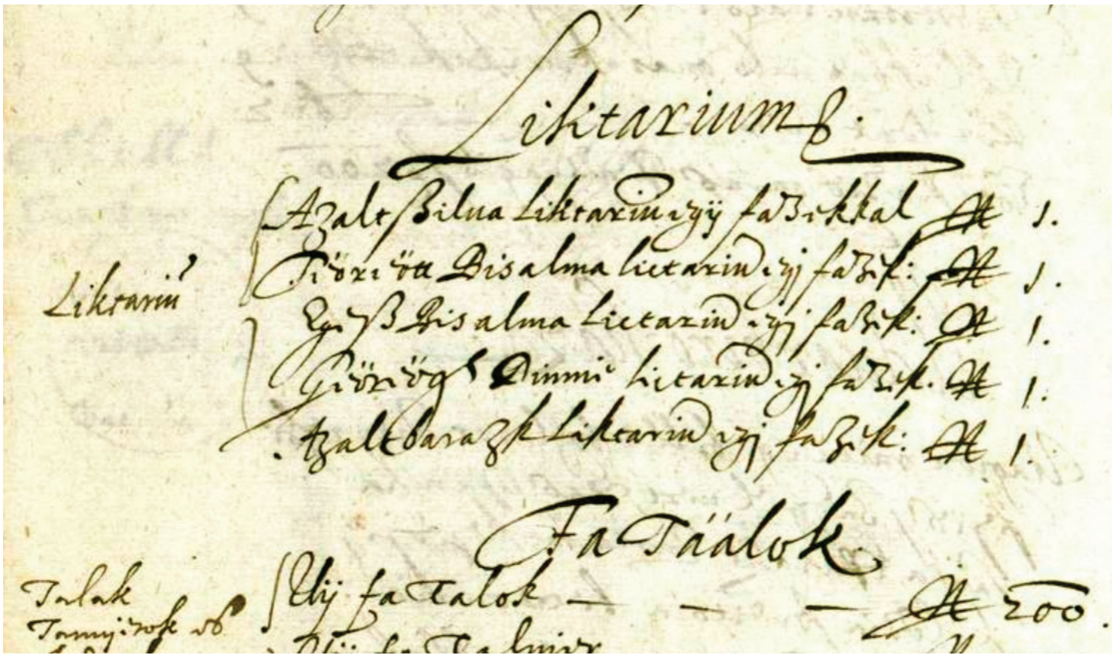


Figure 3. List of 'lictariums' in Fogaras manor estate, from 17th century (Source: [66]).

In the course of the work, a number of other archival sources were also researched. For reasons of space, we do not go into the detailed presentation and citation of these in this article, but only refer to them in the bibliography [66–71].

By their very nature, inventories show the assets primarily through the eyes of the compiler, which requires a cautious and critical approach and interpretation. Since the objects of the period (garden features) recorded in the inventory no longer exist, it is impossible to compare description with reality, and the situation is complicated by the inaccuracies and potential for misinterpretation arising from centuries of vocabulary, old-fashioned phrasing, contemporary terminology, and the difficulty of reading manuscript texts.

4. Results

The manor gardens of the period in question were of a mixed character, merging the concepts of the kitchen and ornamental gardens. If we classify the various garden types according to the plant species found in them, the gardens of the Late Renaissance period should be considered vegetable-flower gardens, geometrically compartmented gardens with some built elements. As early as the beginning of the sixteenth century, the compartment, in which the flowers were planted in regular order and with geometrical precision, became the central part of ornamental gardens throughout Europe. This garden motif, like many others, also appeared in Eastern Europe with a delay of a century. The distribution of the compartments was at once science and art, and horticultural handbooks taught in this era the design of the compartmented garden (Figure 4).

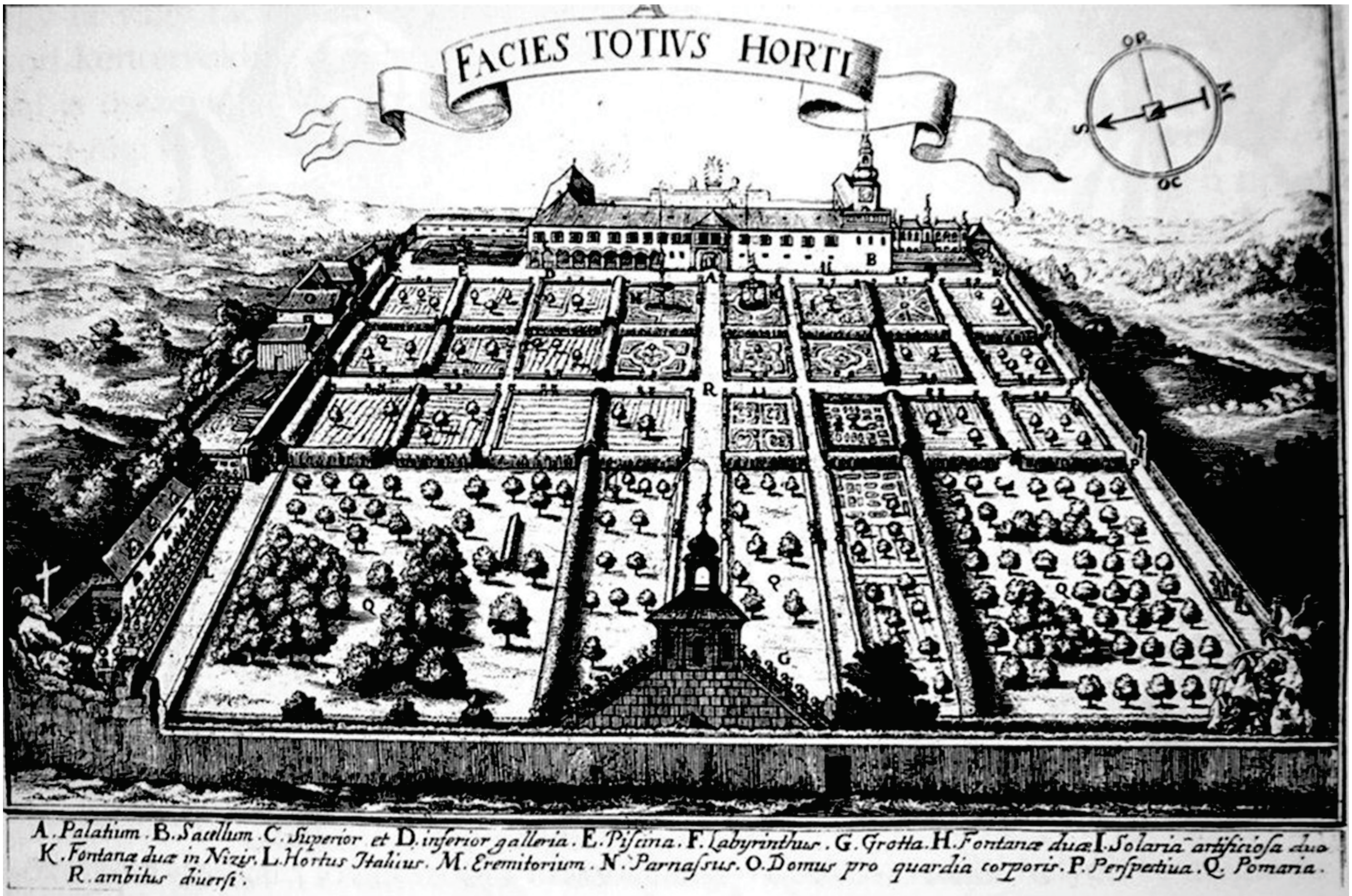


Figure 4. Drawing of the Bishop's Garden from of Bratislava in 1664, showing the compartmented division of planted beds (Source: [26]).

4.1. Definition of Late Renaissance Garden Units

We have defined a garden unit as a garden or garden section with distinct denomination and function (plant use). We have investigated and analyzed the frequency of occurrence and location of each garden unit. In the case of "Type A" sites, we have identified a total of three characteristic garden units on the basis of the archives, which occurred regularly in the examined Late Renaissance gardens: flower garden, vegetable garden, and orchard.

4.1.1. The Flower Garden

Mostly formal gardens planted with herbaceous flowers, often decorated with herbs, in regular order. Of the explored sites, 20 places are mentioned having flower gardens. Despite the fact that the flower garden was primarily decorative, it appears in many places together with kitchen gardens/allotments.

> "The design of the flower garden depends also closely on the composition of the landscape, and is the reflection of a lifestyle, a perspective, a philosophy and a changing socio-economic environment. With their flowers, the late Renaissance gardens of the Carpathian Basin were also the gardens of reality and freedom, because of the pomp of the West and the Ottoman dependency of the East. The symbol of national freedom at this time is the garden, where in addition to the flowers, the splendor and comfort of the gazebos showed this real world and the arising thoughts aof future independence as reconcilable," [29]

As Csoma and Tüdős pointed out (see above), the garden must be approached as a microcosm of the landscape, and gardening must be regarded as the forerunner of landscape transformation.

We analyzed the inventories of the flower gardens in numerous cases thanks to the whole plant lists made of the species found there, but occasionally the species composition was not determined on the basis of live plants but from the prepared vegetable distillates. We collected 42 mentions of different flowers (with ornamental, medicinal, or condimental effects). The taxonomic identification of three of these flowers (marked with an asterisk in the Figure 5) has not been possible based on the folk nomenclature used in archival materials, so it is not known exactly what kind of flowers they are. The flower species used in Transylvanian Late Renaissance gardens are shown in Figure 5. These show that the most common flowers are rose (mentioned in 10 locations), sage, lily (nine locations), and carnation (seven locations), while some flowers, such as lilac, bellflower spur flower, etc., are found only in a single garden.

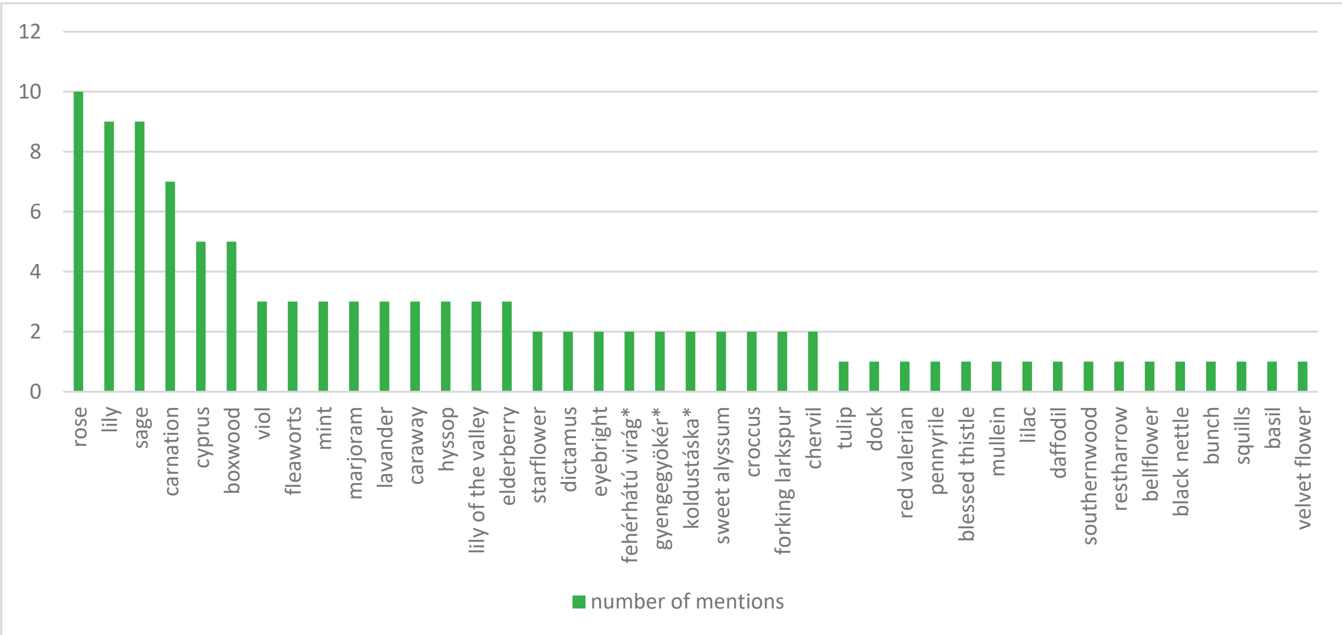


Figure 5. Flower species used during 17–18th centuries in the Transylvanian residential gardens, mentioned in the inventories and other archival materials. The taxonomic identification of the species marked with an asterisk has not been possible based on the folk nomenclature used in archival materials, so it is not known exactly what kind of flowers they are. (Source: prepared by the Authors, based on [45–71]).

With regard to the varieties of the gardens, we found that the highest number of flower species was mentioned in the case of Komána (Comana de Jos, 25 different flower species) and Uzdiszentpéter (Sanpetru de Campie, 24 flower species). The number of described flower species largely depended on the season in which the census was taken and the depth of plant knowledge of the census taker.

4.1.2. The Vegetable Garden

In general, a section of a geometrical garden was considered, mainly with ordered plantings of vegetables. Whenever one of the planted vegetables was in a larger proportion in the garden, the garden was named after the respective vegetable variety: cabbage garden in Görgényszentimre (Gurghiu, RO, 1652) or maize garden in Branyicska (Branisca, RO, 1757). Our research identified vegetable gardens on 30 sites based on the descriptions. In these 30 locations, we collected 30 mentions of different vegetables (and fodderplants). This highlights that the most common vegetable was the cabbage (mentioned in 20 locations), followed by some cereals and fodderplant species, e.g., wheat (20 locations), hemp (14 locations), and oats (13 locations), while some vegetables (such as pumpkin, chervil, asparagus etc.) were found only in a single garden (Figure 6).

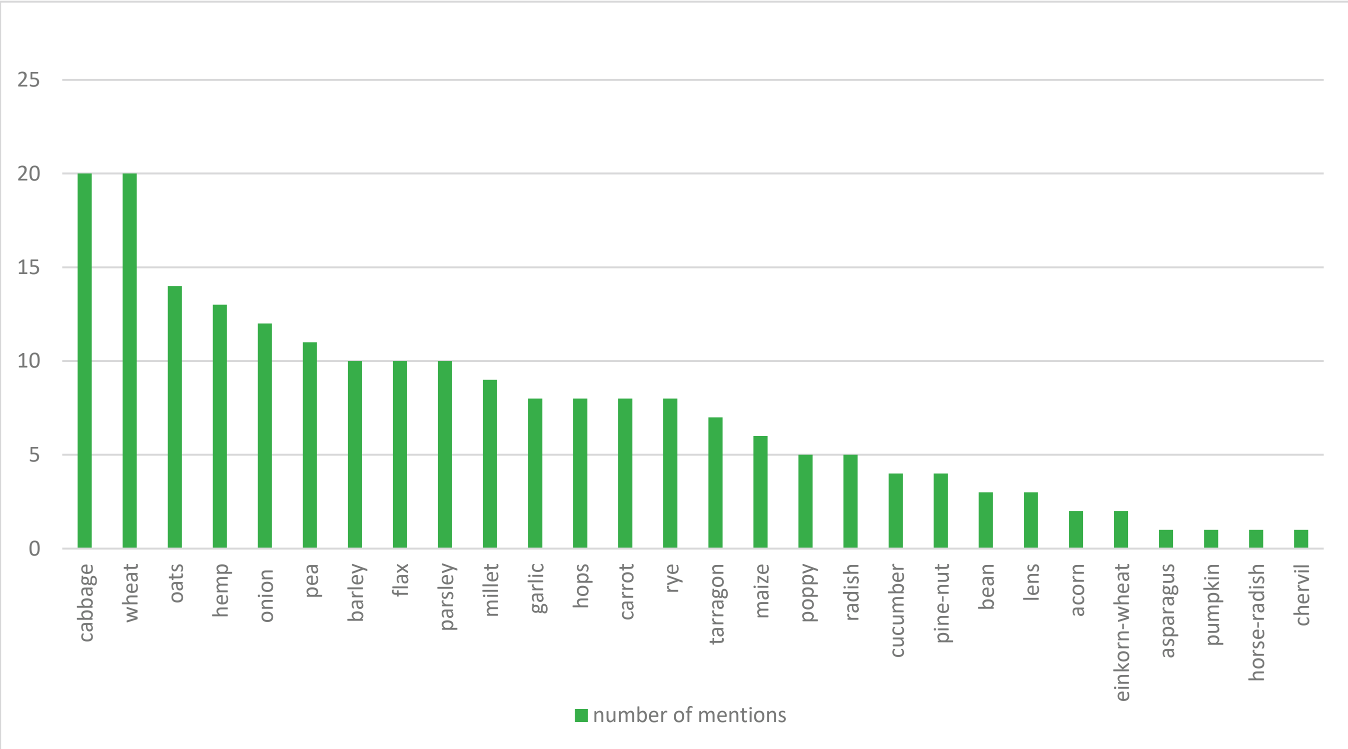


Figure 6. Frequency of the most common vegetables, cereals and fodder plants used during the 17–18th centuries in the Transylvanian residential gardens, mentioned in the inventories and other archival materials (Source: prepared by the Authors, based on [45–71]).

4.1.3. The Orchard

A garden area where mostly fruit trees were planted was considered. Similar to the vegetable garden, the name of the garden area could also be the name of the dominant fruit variety here: sour cherry garden in Uzdiszentpéter (Sânpetru de Câmpie, RO, 1679), apple garden in Csíkkozmás (Cozmeni, RO, 1688), plum tree garden in Görgényszentimre (Gurghiu, RO, 1652). Orchards are mentioned in 39 locations in the descriptions. Orchards (or fruit trees) were very often found in flower garden compartiments, too. This category includes the following sites: Négerfalva (Negrilesti, RO, 1697), Borberek (Vurpar, RO 1701), Szásznádas (Nadasul Sasesc, RO 1712), Szászcsanád (Cenade, RO 1736) Marosszentkirály (Sancraiu de Mures, RO, 1753)(B. Nagy, 1970), Sárpatak (Sapartoc, RO, 1736), Nagyercse (Ercea, RO, 1750), Vajdahunyad (Hunedoara, RO, 1681), Branyicska (Branisca, RO, 1726), Szentbenedek (Manastirea, RO, 1784), and Mezőörményes (Urmenis, RO, 1721).

Figure 7 shows a terraced orchard garden on the castle hill from Segesvár (Sighisoara, RO), and some compartmented gardens organized in the manor courtyards (bottom, right), on the river shore, at the end of 17th century.

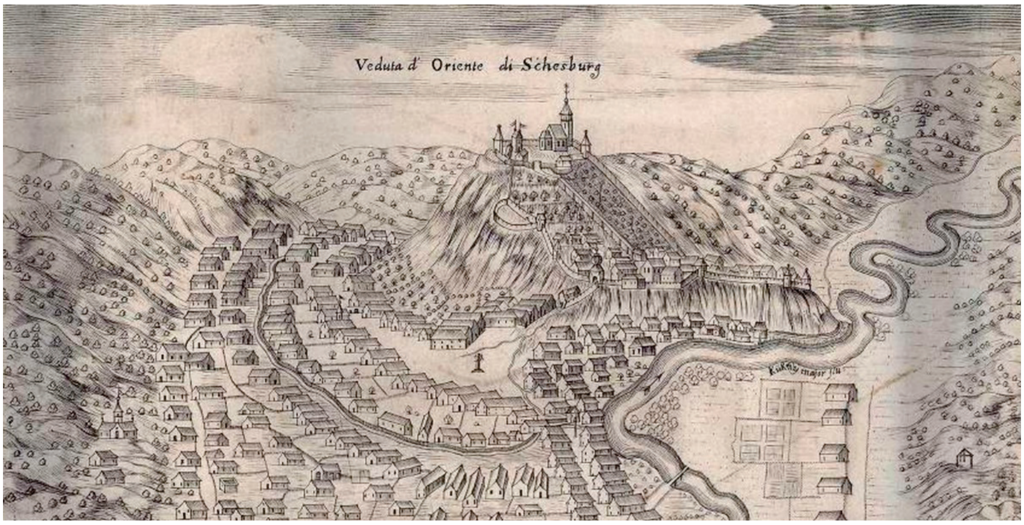


Figure 7. View of Schassburg the turn of 17/18 centuries, with representation of orchards and compartmented gardens (Source: [72]).

During the research, we found references to a total of 21 different fruit varieties in 39 residence gardens. The fruit varieties mentioned in contemporary inventariums and their frequency are shown in Figure 8 and Table 2 for each location. These show that the most popular fruits are plums (mentioned in 23 locations), grapes (19 locations), and sour cherries (17 locations). According to records, the rarest fruits are rowan, quince, cherry, almond, and raspberry. At the same time, Mediterranean plants are also included in the inventarium at two locations: lemon in Uzdiszentpéter and olive tree in Fogaras.

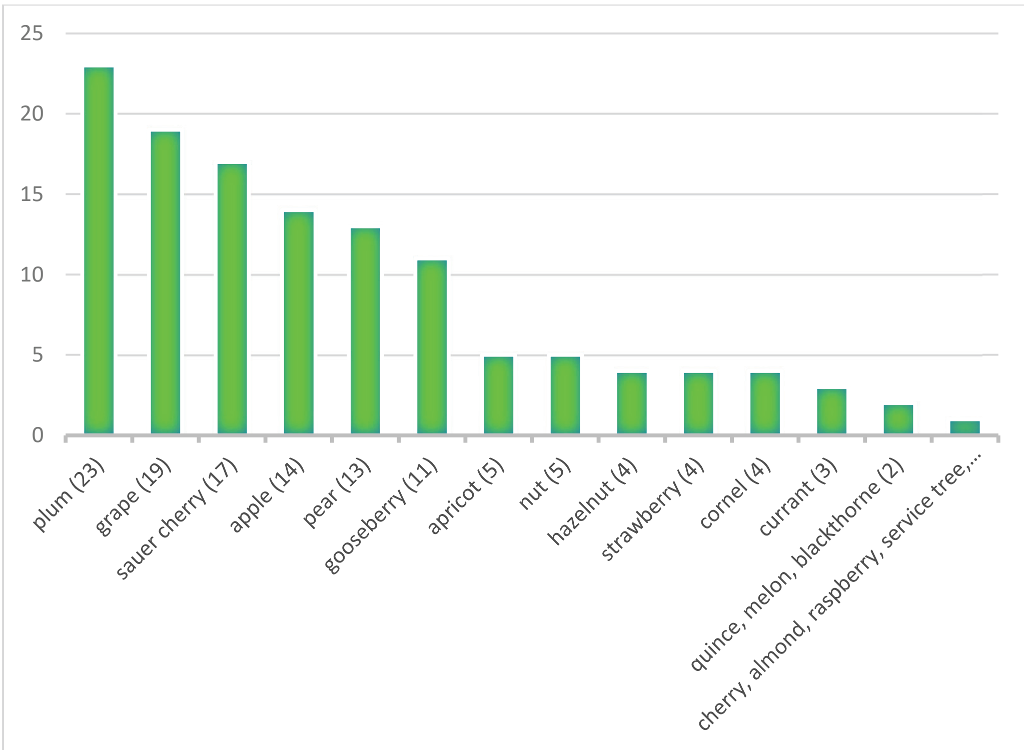


Figure 8. Fruit species mentioned in archival materials and its frequency in the gardens (Source: prepared by the Authors, based on [45–71]).

Table 2. List of residential gardens with fruit gardens with a specification of the used fruit varieties (Source: prepared by the Authors, based on [45–71]).

No	Location	Data (Year)	Apple	Apricot	Sorb	Quince	Lemon	Melon	Nut	Strawberry	Gooseberry	Cherry	Blackthorne	Pear	Almond	Raspberry	Sauercherry	Hazelnut	Oil Tree	Cornel	Plum	Grape	Currant
1	Kisbarcsa	1624																				x	
2	Fogaras	1632			x	x					x								x		x	x	
3	Siménfalva	1636															x				x	x	
4	Tasnád	1644	x											x						x	x	x	
5	Nagyteremi	1647																				x	
6	Királyfalva	1647																					
7	Meggykerék	1647																					
8	Drassó	1647															x						
9	Marosvécs	1648	x											x			x			x	x	x	
10	Komána	1648		x					x	x		x	x				x			x	x		
11	Görgény	1652												x							x		
12	Gerend	1652															x				x	x	x
13	Búzábocsárd	1658																				x	
14	Mezőszengyel	1656																					
15	Szurdok	1657															x						
16	Bethlen	1661																			x	x	
17	Mezőbodon	1679	x								x										x		
18	Uzdiszentpéter	1679		x			x	x	x	x	x		x							x	x		
19	Nagysajó	1681	x						x	x	x			x			x	x			x	x	x
20	Oprakercisóra	1683																			x		
21	Csíkkozmás	1688	x								x			x									
22	Nagybún	1692	x											x			x				x		
23	Borberek	1694	x	x					x	x				x			x	x				x	
24	Kővár	1694																				x	
25	Vajdahunyad	1695																				x	
26	Szentbenedek	1696	x								x			x			x				x	x	
27	Egeres	1699	x								x			x			x	x			x		
28	Zentelke	1715															x						
29	Grid	1716	x																		x		
30	Mezőörményes	1721	x	x					x		x				x		x	x			x	x	
31	Koronka	1724		x										x							x		
32	Marosszentkirály	1725															x					x	
33	Aranykút	1728	x			x		x			x			x		x	x				x	x	
34	Bonchida	1736									x						x				x	x	
35	Gernyeszeg	1751	x											x							x		
36	Branyicska	1757	x														x				x	x	
37	Szilágycsehi	17. c.																			x		
38	Gyulafehérvár	17. c.	x											x									
39	Ebesfalva	17. c.									x												x
	TOTAL Number		**14**	**5**	**1**	**2**	**1**	**2**	**5**	**4**	**11**	**1**	**2**	**13**	**1**	**1**	**17**	**4**	**1**	**4**	**23**	**19**	**3**

5. Discussion

In the garden history of Transylvania, the Late Renaissance style was almost one hundred years late in spreading compared with other parts of Europe. In spite of that, in terms of the number of gardens in Transylvania, the Renaissance can be called the leading garden style in this part of the country. The number of Late Renaissance gardens is much higher than the number of Early Renaissance or later Baroque Gardens. This is a consequence of the political and economic independence of Transylvania in the 17th century.

The history of the Transylvanian Late Renaissance garden is mainly about economical sustainability. This is why mixed gardens (ornamental and vegetable gardens and even orchards together) frequently appear, although in many places various kinds of kitchen and vegetable gardens or orchards were also independently represented.

In terms of their compositional characteristics, Transylvanian Late Renaissance gardens are largely integrated into the general European system. They followed the models, sometimes as simplified small-scale paraphrases of them, but there are also examples that have specific local characteristics (in ethnographic and topographic terms or in plant use).

Given the state of what is left over from these historical artefacts, restoration in the strict sense is impossible. Devastation, missing archival sources, changing ownership, and sustainability reasons make the restoration work even harder. During the investigation, analysis, and fieldwork regarding the Transylvanian ensembles, we had ample contact with local stakeholders, politicians, owners, NGOs, users, and other people related to the Transylvanian ensembles. The core of the problem is concentrated around two poles: one of heritage and cultural meaning, the other centered on the search for new functions and uses. These two are often contradictory and conflicting; they can be categorized in the polarity between development and conservation. In all landscape architectural projects, this contradiction plays a role, but in the case of historical phenomena they are even more pronounced and demand special attention.

It will be a major challenge for landscape architecture to take into account the historical values and to integrate them with new functions and uses as well as the recent demands of improving water management, energy transition, and the creation of comfortable and healthy living environments for people.

6. Conclusions

This research offers an overview of the four-hundred-year history of the Late Renaissance gardens of Transylvania, focusing on the plant use of the Late Renaissance manor gardens. The research has collected and ordered the most important gardens of that era, highlighting the most representative flower, vegetable, and fruit species cultivated and described in archival documents.

Moreover, the study defines the most typical garden types of the study area in the period concerned, naming the compartmented flower gardens, vegetables gardens, and orchards as main garden types. However, the study also shows that the different types of gardens were very often mixed, with flower gardens often containing vegetable or fruit trees, and vice versa.

The plant lists and registers that have been discovered help us to gain an insight into the plant use habits of the Transylvanian manor gardens of the 17th and 18th centuries and demonstrate the sophistication of the garden culture of the period and the richness of the plant selection used. The research is of horticultural and landscape architectural importance as it highlights the plant use traditions and demonstrates the continuity and applicability of many cultivated plants in Transylvanian gardens.

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plants

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Article

The Patterns of Intraspecific Variations in Mass of Nectar Sugar along a Phylogeny Distinguish Native from Non-Native Plants in Urban Greenspaces in Southern England

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Abstract: To serve human needs, non-native species are selected based on an array of functional traits, which generally confer competitive advantages to these species in their recipient environments. Identifying non-obvious functional traits that indirectly inform human selection of non-natives to introduce into urban greenspaces is not yet part of common discussions in invasion biology. We tested whether functional traits integrated within a phylogenetic framework, may reveal those subtle criteria underlying the introduction of non-native plants into urban greenspaces. We found no differences in terms of functional traits between natives and non-natives. We also found no evidence that functional traits predict nectar production, irrespective of how nectar production was measured. Finally, we found that the mean sugar concentration of nectar per flower is evolutionarily shared both within closely related non-native plants as well as within close native plants. However, phylogenetically close species share similar intraspecific variation in mass of nectar sugar per flower, but this is true only for non-native plants, thus revealing a non-obvious selection criteria of non-native plants for urban greenspaces. Our results indicate that the phylogenetic patterns of intraspecific variation in mass of nectar sugar per flower is the major criterion distinguishing non-natives from native plants in urban greenspaces in Southern England.

Keywords: functional traits; invasion biology; nectar production; native plants; non-native plants; urban greenspaces

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1. Introduction

Species are moved across the globe accidentally or intentionally by humans [1] for specific ecosystem services these species provide, e.g., horticultural, medicinal, or ecological services [2,3]. However, although introducing non-native species into new environments provides some benefits (e.g., erosion control, medicinal uses, etc.), their introductions also raise environmental concerns [1]. One of those concerns is the naturalization and then invasion of these species [4]. Then two important questions to ask are (i) what are the functional traits that predispose non-native species to naturalization? and (ii) in the scenario of intentional selection and introduction, what are the contributions of human, as the selection agent of those species, to this naturalization? The first question is widely explored [5]. Indeed, almost 60 years ago, Baker [6] deployed great efforts to document functional traits that predispose non-native plants to weediness and invasion (see also [5,7]). However, the second question still deserves attention. A recent study demonstrated that non-native plants of economic values (e.g., animal food and ornamental) are almost 20 times more likely to naturalize than not, and the naturalization likelihood increases for non-native plants that provide higher number of uses ([3]; see also [2]), thus showing the importance of human selection criteria of non-native plants in contributing to their naturalization. I define human selection criteria as the reasons (e.g., erosion control, medicinal uses, food, horticultural values, etc.) underlying the decision by humans to intentionally move a species beyond its native range. In the present study, I referred to these intentional reasons as 'obvious selection criteria' which are determined by some plant functional traits. I argued that there are other selection criteria, apart from the obvious ones, that I termed 'hidden or non-obvious criteria'. I defined hidden criteria as those that are not part of the criteria that inform the intentional selection by humans of a given non-native plant for introduction into a new range, but which play critical roles in the success of non-native plants in their introduced ranges. As such, hidden criteria may include phylogeny, nectar production, etc. Ref. [3] showed a phylogenetic pattern in the naturalized flora, thus implying that human selection criteria of non-native plants have a phylogenetic component. These studies [2,3] provide evidence that the understanding of obvious (e.g., horticultural and medicinal) or hidden criteria (e.g., phylogeny) subtending human selection of non-native species is key for predicting their outcomes (e.g., naturalization) or the mechanisms that provide an upper hand to non-native species in the competition for ecological dominance.

Various strategies through which non-native species are conferred competitive advantages over natives are widely reported [8,9]. For example, the ability to adjust their flowering phenology and thus their interactions with pollinators confer such advantages to non-native species. Non-native species tend to flower over longer periods compared to natives [5] or shift their flowering period to track a changing climate [10]. Non-native species are also reported to co-opt pollinators of native species [11], a strategy which will eventually lead, in the long run, to the decline of the population of native plant species [12]. This co-option is facilitated by the development of a suite of traits, e.g., large and durable floral displays, copious nectar, and pollen rewards [11], which represent key innovations promoting the fitness and invasion of non-native species. The fitness of alien plants into a new environment requires the development of key strategies to co-exist with native species [13], and a pre-requisite for such co-existence for some non-native plants is a successful competition over native species for pollinators [11,14].

Indeed, the introduction of non-native species into a new environment is disruptive to the established ecological networks, including alterations in the flow of nutrients and energy [15] and biotic interactions [9,16,17], resulting in the establishment of new selection pressures [18–20]. Flowers are one of plant's organs actively used in the realization of biotic interactions, energy flow, and selection pressures (see [14]). One of the functional attributes of flowers is the production of nectar, suggesting that any adjustment to the flowering phenology would affect the nectar production. Consequently, we expect that non-native plants, flowering for an unusually longer period [5] or shifting their flowering phenology [10] to co-opt the pollinators of native plants [11], may eventually produce more nectar than native plants. The rationale for this expectation is that, given the ongoing unprecedented decline in insect pollinators worldwide and particularly in England [21], producing higher volume of nectar (than natives) may be a strategy to recruit and satisfy the needs of more pollinators (that are now becoming rare [10]), which then might eventually prefer high-nectar-producing non-native plants to natives. In support of this hypothesis, evidence exists showing that pollinators, e.g., hummingbirds which are obligate nectar feeders, have developed an ability to distinguish between high and low nectar-producing plants across the landscape [22,23]. This means that, in the scenario where non-native plants produce more nectar than native plants, hummingbird-pollinated non-native plants would be favored for pollination.

Unfortunately, most of the available data on nectar production are from natural systems [24–26], making it impossible to investigate whether nectar production is a part of non-obvious or hidden criteria that inform human selection of non-native species that are to be introduced into a new environment. Interestingly, data on nectar production in man-made systems such as urban greenspaces are now emerging [27,28]. Indeed, in the context of an ever-declining population of pollinators [21], urban greenspaces are increasingly appreciated as hotspots of pollinators diversity [29,30].

Urban greenspaces are public or private open spaces comprising all sorts of greenery, including parks, green roofs, woodlands, community gardens, lawns, sporting fields, ornamental plant arrangements, etc., which form an urban ecological system for a sustainable city [31–33]. Urban greenspaces are acknowledged as extremely beneficial to human health conditions [34,35] and therefore represent a study model of interest. Their salutogenic benefits to humans are diverse, ranging from low mortality and morbidity in the context of pandemics [35–37], increased mental wellbeing [37–39], and clean air [40]. The mechanisms underlying these health benefits may be linked to human direct usages of greenspaces [34]. For example, the exposure to greenspaces boosts the protective activities of natural killer cells [41], and they protect humans against infections [42]. Also, species composition of the urban greenspaces may also be critical in their effects on human health. For example, positive effects of urban greenspaces to humans have been linked to the presence of essential oil-producing plants [43,44]. Since urban greenspaces are man-made ecosystems—humans determine their species composition—understanding the selection criteria of species, e.g., functional traits, as well as the origins (native vs. non-native plants) of species to compose the urban greenspaces becomes a pre-requisite for a well-informed design of urban greenspaces that would be fully beneficial not only to the environments but also to human health conditions.

Another important function of urban greenspaces that is not well debated is their nectar production services, which is linked to the diversity of pollinators in urban areas. In a recent study, ref. [27] showed that, although urban greenspaces do not produce quantitatively more nectar than farmland and nature reserves, the origin of nectar supply in greenspaces is more diverse, driven mostly by non-native plants. Specifically, compared with other systems, urban gardens account for 85% of urban plant nectar supply [27], but it remains unclear whether nectar supply can be detected as 'hidden or non-obvious' criteria underlying human selection of non-native plants.

In the present study, the aim was to determine non-obvious criteria informing the selection of non-native plants by humans. To this end, we compared native and non-native plants from different angles, expecting to determine those non-obvious criteria. Specifically, we first investigated if there are significant differences between natives and non-natives in terms of functional traits. Then, we asked the following question: do plant functional traits (life-forms, origins, and floral traits) predict nectar production? Finally, we tested if phylogeny predicts nectar production in both native and non-native plants. These three questions provide opportunities for comparative analysis between native and non-natives, allowing to identify the suite of criteria that inform human selection of non-native plants to be included in urban greenspaces. Identifying such criteria may shed light on human contribution to the selection of the functional traits that predispose non-native species to naturalization and eventually to invasion.

2. Results

First, we investigated if there are significant differences between natives and non-natives in terms of functional traits. We found no such differences (life-forms: $\chi^2 = 1.88$, df = 2, $p = 0.39$; floral structures: $\chi^2 = 3.29$, df = 11, $p = 0.98$).

Second, we asked the following question: do plant functional traits (life-forms, origins, and floral traits) predict nectar production? Fitting a phylogenetic ANOVA, we found no such evidence, irrespective of how nectar production was measured. For example, plant origins do not correlate with nectar production measured either as Nectar_mass_SD (Holm–Bonferroni corrected $p = 0.797$), Sugar_per_FU_ug (Holm–Bonferroni corrected $p = 0.60$), or Nectar_mass_mean (Holm–Bonferroni corrected $p = 0.89$). Also, plant life-forms do not predict nectar production, Nectar_mass_SD ($p = 0.826$), Sugar_per_FU_ug ($p = 0.569$), and Nectar_mass_mean ($p = 0.856$), and neither do floral structures, Nectar_mass_SD ($p = 0.658$), Sugar_per_FU_ug ($p = 0.078$), and Nectar_mass_mean ($p = 0.771$).

Finally, we tested if phylogeny predicts nectar production. We found evidence supporting this, but only for Nectar_mass_SD and Nectar_conc_mean (Figure 1) whether all species (natives + non-natives) are combined (Nectar_mass_SD: K = 0.22, $p = 0.003$; Nectar_conc_mean: K = 0.18, $p = 0.03$; Table 1) or considered separately: non-native only

(Nectar_mass_SD: K = 0.22 $p = 0.004$; Nectar_conc_mean: K = 0.18, $p = 0.03$; Table S1) or native only (Nectar_conc_mean: K = 1.06, $p = 0.04$, Table S2).

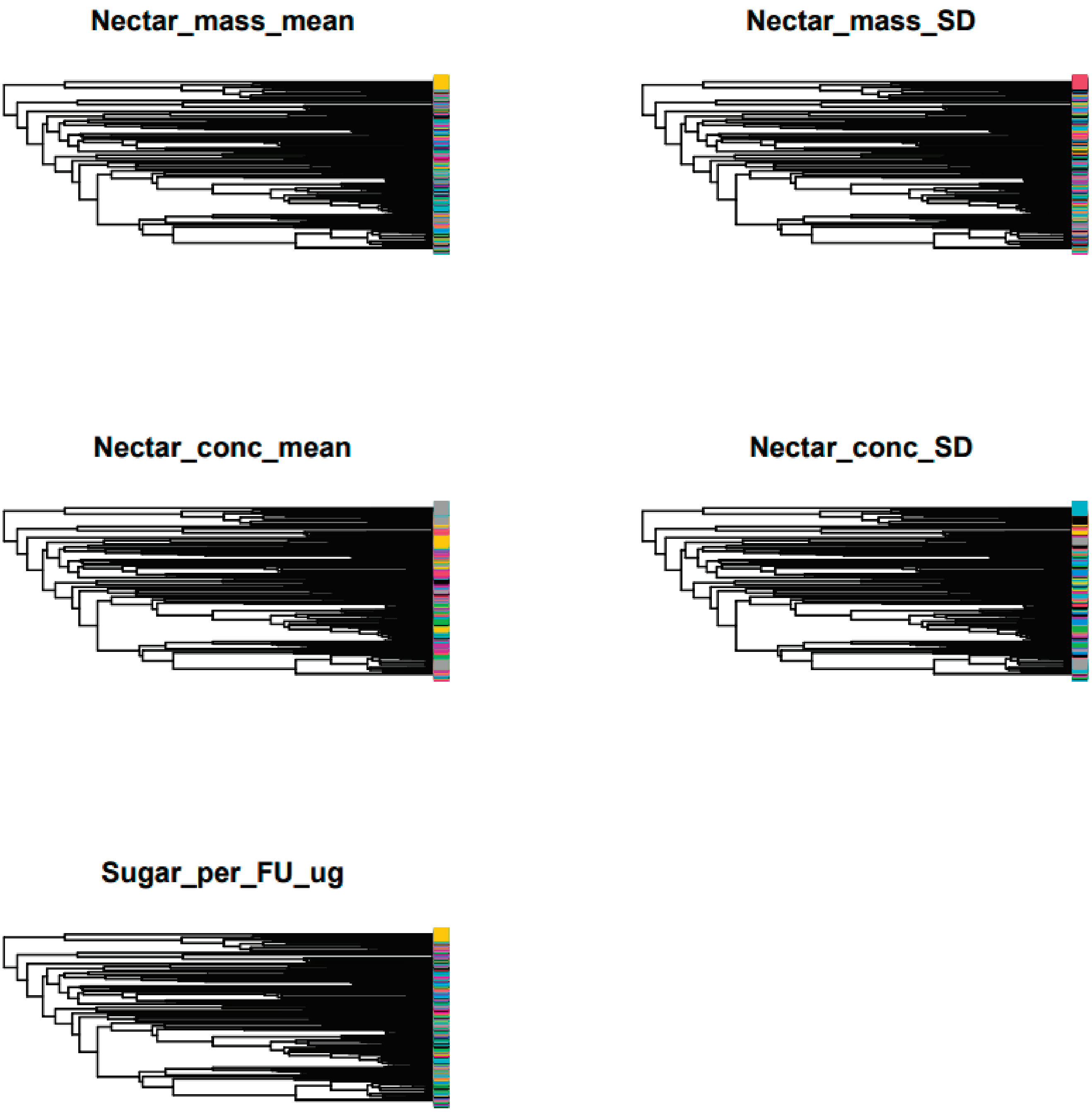

Figure 1. Illustrations of phylogenetic signal in nectar production. A repeat of the same color along a phylogeny for several clades means a repetition of same value of nectar production, implying phylogenetic signal. Nectar_mass_mean = daily mean mass of nectar sugar per flower; Nectar_conc_mean = the mean sugar concentration of nectar per flower; Nectar_conc_SD = standard deviation of the mean sugar concentration (intraspecific variation); Sugar_per_FU_ug = mass of nectar sugar per floral unit; and Nectar_mass_SD = standard deviation of the mean mass (intraspecific variation).

Table 1. Coefficients of the Blomberg K test of phylogenetic signal in nectar production based on all species (natives + non-natives). * = marginal significance, ** significance.

Nectar Production	K	PIC.var.obs.	PIC var.rnd.mean	*p*-Value	PIC.var.Z
Nectar_mass_mean	0.178063154	143,425.8953	443,998.8927	0.062	−0.384427948
Nectar_mass_SD	0.223061818	41,689.07254	193,459.6056	0.003 **	−0.55471627
Nectar_conc_mean	0.179022884	9.094378937	14.9308214	0.039 *	−1.421055868
Nectar_conc_SD	0.130033662	1.489374074	1.749948461	0.417	−0.352449477
Sugar_per_FU_ug	0.110024302	640,764.1636	1,389,605.143	0.276	−0.39843441

3. Discussion

The attraction of pollinating insects by plants depends on certain functional traits including floral traits, suggesting that if non-native species lure or co-opt the pollinators of native species [11,13], the flowers of non-native plants may be structurally or functionally different from those of native plants. We would therefore expect floral traits to help distinguish between native and non-native. We found no significant differences between native and non-natives in terms of functional traits such that life-forms, and floral structures do not predict species origin, that is, cannot be used to differentiate between native and non-native plants in urban greenspaces (floral trait similarity). This finding has several implications. The floral trait similarity between non-native and native plant species implies that both species may be sharing similar pollinators (flower visitor overlap; [45]). One consequence of such visitor overlap is an interspecific pollen transfer between native and non-native plants and vice versa [46]. This pollen transfer may lead to reproductive failure due to incompatibility of pollens with ovaries ([47]; but see [48]), and native plants are reported to be the most negatively affected by such reproductive failures, ultimately leading to the decline in the long term of the native plant populations (see [49]).

Another consequence of floral trait similarity between non-native and natives is strong competition of both species for pollinators (competitive exclusion principle), which may eventually lead to native plant species losing pollinators to non-natives (see [11–14]). However, such dramatic expectation, i.e., loss of pollinators, was not observed in the study of Ref. [45], but they did report a stronger competition. In the context of the ongoing decline of pollinators populations [21], which is putting the survival of native plants at risk, increasing opportunities for pollinators of native plants to be shared with non-natives may further heighten this risk. Instead, introducing into urban greenspaces non-native plants that do not share similar floral traits with natives, that is, who would not be competing strongly with native plants for pollinators [45], is most preferrable as this would be an opportunity for an increased diversity of pollinators in the urban areas.

Furthermore, the absence of significant differences in floral structures between native and non-native plants is likely driven by humans, that is, humans may select and introduce non-native species that preferentially exhibit a suite of traits that are similar to those of the native species. If that is the case, then this would be evidence of non-random selection of non-native plants (see nonrandom hypothesis; [2]). Such non-random selection of plants by humans for the services they provide is widely proven for native species (e.g., [50]), but not so for non-natives (except in a handful studies; [2,51,52]). However, most of those studies demonstrated a nonrandom introduction of non-native species for medicinal purposes. The present study provides additional evidence that the nonrandom selection of non-native species could actually be based on floral traits (indirectly on nectar production services), which is indicative of an indirect human mediation of plant–insect interactions as well as an indirect human mediation of native–non-native plant interactions.

Why does the identification of services for which humans select and introduce non-natives plants into a new environment matter? One of the reasons is that services are linked to the invasion ability of non-native plants, and this is based on the following rationale. Functional traits are linked to the services that plants provide and at the same time correlate with the invasion status of species [5]. Therefore, we should expect services to also correlate with the invasion outcome of non-native plants [52]. Such relationships between services and invasion have been tested and supported, but indirectly [5,11]. Furthermore, we should also expect non-native plants providing multiple services to be strong candidates for multiple independent introductions in various quantities into new environments [53–55]. Such non-native species are more predisposed to invasion as predicted in the propagule pressure theory [53]. The question then is the following: is nectar production a good candidate for services informing human selection of non-native plants? Although we have evidence of pollinators distinguishing plants that produce more nectar from those producing low quantity of nectar [22–24], the contribution of nectar production to species invasion is not yet debated in the invasion biology discourse. The first step taken to initiate such a debate is to determine if selection of non-native plants to introduce is also driven by humans' direct or indirect preference of nectar production services that these plants provide. In a recent study, Yessoufou and Ambani [52] demonstrated that non-native woody plants providing either medicinal, food or fuel services to humans are more likely to be naturalized in South Africa. How about nectar production?

Evidence of interspecific variations in the quantity of nectar production is well established [27,28,56,57], ranging from 0.1–10 μL (for standing crops) to >650 μL (for columnar cacti and agaves; e.g., [56]). This interspecific variation is interpreted as adaptive strategy of flowering plants to pollinators [24]. For example, adaptive evolution or co-evolution has been invoked between flowers and pollination by hummingbirds, leading to the production of nectar of specific sugar concentrations [58]. Such adaptive measures imply that closely related plant species share specific pollinators, similar competitive ability for pollinators, food preferences, etc. [59]. As such, we would expect a phylogenetic signal in interspecific nectar production in flowering plants. In an early study, Ornelas et al. [60] tested whether phylogeny and flowers' traits (e.g., flower size) correlate with interspecific variations in nectar production of hummingbird-visited plants. They demonstrated a significant phylogenetic signal in nectar volume and its sugar concentration. They further demonstrated evidence of adaptive measures between nectar and sugar productions with corolla length [60]. In the present study, we found no evidence of functional traits predicting nectar production, irrespective of how nectar production was measured. Specifically, we found that neither plant origins, plant life-forms, nor floral structures predict any of the metrics of nectar production. If any of the plant functional traits does not correlate with nectar production, this means that the criteria used by humans to select horticultural plants for urban greenspaces are similar across all plants, and this similarity drives similar nectar production. If that is the case, we should then expect a significant phylogenetic signal in interspecific nectar production.

Unlike Ornelas et al.'s [60] study, our analysis failed to detect a significant phylogenetic signal in interspecific variation in nectar production. However, we found evidence of phylogenetic signal in the intraspecific variation in mass of nectar sugar per flower (Nectar_mass_SD) and in the mean sugar concentration of nectar per flower (Nectar_conc_mean) whether all species (natives + non-natives) are combined, or only non-native plants are considered separately. For native plants, the signal was found only in Nectar_conc_mean. Nectar_mass_SD is indicative of the intraspecific variation in mass of nectar sugar per flower, and as such, the phylogenetic signal that we found in Nectar_mass_SD suggests that closely related species share similar intraspecific variation in mass of nectar sugar per flower but this evolutionarily shared intraspecific variation in mass of nectar sugar per flower is found only for non-native plants. This signal may mean two things. First, it means strong adaptations of flowering plants to pollinators in terms of nectar mass sugar production. Second, this is also a strong evidence of nonrandom selection of the non-natives by humans that they introduce into their urban greenspaces. However, the mean sugar concentration of nectar per flower is too evolutionarily shared, both within closely related non-native plants as well as within close native plants. Nectar characteristics (production and concentration) were reported to show high inheritability [61,62], and this is supported by our finding of significant phylogenetic signal (see also [25,26]). These nectar characteristics are known to correlate with floral traits [60,63,64] and are under strong pollinator-mediated selection [65].

In invasion biology, the question of what predisposes non-native plants to naturalization and invasion is a widely investigated question. Some of these investigations report that some functional traits (e.g., phenology, height, seed production, etc.) provide an upper hand to non-native species in terms of competitive ability, thus predisposing them to naturalization and invasion [5]. These traits are the same traits that are linked to the services and goods that humans are after, resulting in selection of non-native species that they introduced into a new environment [2,3]. This means that if traits of interests linked to the services non-native plants provide to human can be identified, one can predict what may predispose non-natives to naturalization and invasion [2,3]. However, while some of these traits are obvious because they are intentionally selected by humans, others are hidden, that is, are not part of the initial set of traits humans are after (e.g., phylogenetic relatedness, nectar production, etc.). Those hidden traits, e.g., phylogeny, play an important role in driving naturalization and invasion (see Darwin Naturalization Hypothesis; [5]). Our aim was to determine non-obvious criteria informing at least indirectly the selection of non-native plants by humans. The findings indicate that none of the functional traits considered are unique to non-natives, and none of them predicts nectar production of native and non-native plants. However, phylogenetically close species share similar intraspecific variation in mass of nectar sugar per flower, but this is true only for non-native plants, thus revealing human hidden selection criteria of non-native plant selection for urban greenspaces. Altogether, our results indicate that the phylogenetic patterns of intraspecific variation in mass of nectar sugar per flower is the major criterion distinguishing non-natives from native plants in urban greenspaces in Southern England. We therefore suggest that such intraspecific variation is potentially one of the functional traits predisposing non-native species to naturalization and invasion in England.

Overall, by showing that some aspects of nectar production distinguish native plants from non-native plants introduced into urban gardens, this study first pointed to potential roles that nectar production played in human selection of non-native plants but also suggest that nectar production services may be a potential criterion for multiple introductions in different numbers of non-natives. As predicted in the propagule theory, such non-natives may eventually become naturalized and invasive in their recipient environment. This hypothesis warrants to be tested to eventually clarify the potential role of nectar production in invasion biology. What we already know is that at country [52] or at global scale [3], non-natives providing multiple or unique economic services are more likely to naturalized in their introduced environments. The present study suggests that differences in patterns of nectar production not only influence human selection criteria of non-native species that can be selected and introduced into urban greenspaces but also could be, pending further investigations, good candidates for ecological services predisposing non-natives to naturalization and invasion in recipient environments.

4. Materials and Methods

4.1. Study Area

Ref. [28] collected and published the data analyzed in the present study in Southern England in 2018–2019 in Ashley Down allotment, Brackenwood Plant and Garden Centre, Didcot town, Royal Horticultural Society Garden Wisley, Speldhurst village, University of Bristol Botanic Garden, University of Bristol Halls of Residence, and University of Bristol Royal Fort Gardens, UK. Specifically, the data were collected in public and private gardens, allotments, garden centers, hedges, and road verges as well as flower meadows in urban greenspaces such as ornamental borders and shrubberies, lawns, paths, and hard standings (see further details in [28]).

4.2. Data Collection

Data analyzed in the present study were retrieved from ref. [28] and comprised 225 flowering plants sampled between 2018 and 2019 in Southern England's urban greenspaces.

First, we retrieved the taxonomic details of the plants, including species and families but also their origins (native or non-native to British Isles), as well as their functional traits, e.g., life-forms (shrub, herb or climber), and floral traits (single flower, single capitulum, secondary umbel, single raceme, single thyrse, single compound cyme, single cyme, single corymb, single branch of capitula, and part of panicle). Second, we retrieved data on nectar production by 225 flowering plants from ref. [28] that sampled plants at two to three locations. Prior to nectar measurement, ref. [28] prevented insects' interactions with the flowers by mesh bags for 24 h and then measured nectar either directly from flowers (102 taxa) or indirectly (123 taxa) by rinsing nectaries with distilled water. Nectar measurements include the daily mean mass of nectar sugar per flower (Nectar_mass_mean), the mean sugar concentration of nectar per flower (Nectar_conc_mean), the mass of nectar sugar per floral unit (Sugar_per_FU_ug), and the standard deviation of the mean mass (Nectar_mass_SD). Nectar_mass_SD captures the intraspecific variations in mass of nectar sugar. However, sugar concentrations were measured only in the scenario of direct measurement because of the dilution involved in the scenario of indirect measurements. All the measurements were conducted, on an average, on 18 flowers per taxon (range: 10–52). For the purpose of representativeness, flowers of different ages and sexes and across different positions on the plants and in different positions in the inflorescence were selected [25]. Collected data are presented in Table S3.

Overall, the data analyzed include 225 plant taxa in 158 genera and 55 families. Within this dataset, 157 plants are herbaceous, 63 are shrubs, and 5 are woody climbers, whereas 14 are native to UK and 211 are non-natives (see further details in [28]), showing the higher preference of humans towards non-natives than natives in their urban greenspaces.

4.3. Phylogenetic Tree of All the Species

I reconstructed the phylogenetic tree of all the 225 species (File S1) as implemented in the R package 'V.PhyloMaker' [66]. First, a species list was constructed arranged by species, genus, and family names as recommended in [66]. Then, the phylogenetic tree was reconstructed using the R function 'phylo.maker' using the mega-tree 'GBOTB.extended.tre', which is the combination of updated phylogenetic trees of previous studies [67,68].

4.4. Data Analysis

All analyses were run in R version 4.3.1 [69] (see File S2). First, I tested if native plants were functionally (life-forms, floral traits) different from non-natives introduced into the urban greenspaces. This test was conducted using chi-square test. Second, I investigated whether plant functional traits (life-forms, origins, and floral traits) predict nectar production. This was performed by fitting a phylogenetic ANOVA (R function phylANOVA) in library Phytools [70] to correct for the non-independence of trait values due to species shared ancestry. This approach used a combination of phylogenetic independent contrasts (PICs; [71]), and a simulation-based phylogenetic ANOVA [72] leading to Holm–Bonferroni corrected p values. Finally, to test if phylogeny predicts nectar production, we used the Blomberg K test [73] implemented in the R package Picante 1.2 [74]. Data analyzed for phylogenetic signal test are presented in Table S4.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/plants12183270/s1, Table S1. Coefficients of the Blomberg K test of phylogenetic signal in nectar production based on only of the subset of non-native plants; Table S2. Coefficients of the Blomberg K test of phylogenetic signal in nectar production based on only of the subset of native species; Table S3. All data collected and analyzed in the present study; Table S4. Data analyzed for phylogenetic signal test; File S1. Phylogenetic tree generated for all plants included in the present study; File S2. R script used for all conducted analyses.

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Data Availability Statement: Data analyzed are available as Supplementary Materials in this manuscript and can also be found in Ref. [22].

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plants

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Article

Potential Allergenicity of Plants Used in Allergological Communication: An Untapped Tool for Prevention

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Abstract: Plants are often used to illustrate allergy-related medical products, services, patient information materials and news. The illustration of allergenic plants is an important tool in patient education, contributing to the prevention of pollinosis, as patients can recognize plants and avoid pollen exposure. In this study, it is aimed to evaluate the pictorial content of allergy-related websites depicting plants. A total of 562 different photographs depicting plants were collected using image search, identified and categorized according to their potential allergenicity. Of the total 124 plant taxa, 25% of plants were identified to the genus level and a further 68% were identified to the species level. Plants with low allergenicity were found in 85.4% of the pictures, while plants of high allergenicity were shown in only 4.5% of the pictorial information. *Brassica napus* was the most frequent species identified (8.9% of the overall identified plants), while blooming Prunoidae, *Chrysanthemum* spp. and *Taraxacum officinale* were also common. Considering both allergological and design aspects, some plant species have been proposed for more professional and responsible advertising. The internet has the potential to provide visual support for patient education in allergenic plants, but emphasis must be put on the transmission of the correct visual message.

Keywords: allergy; plant; pollen; patient education; visual advertising

1. Introduction

The pollen of many plant species can cause allergic disease (pollinosis) in susceptible people [1]. In the last two decades, the prevalence of sensitization to pollen increased from 13% to 30% [2]. The most common symptoms of pollen allergy are sneezing, red eyes, runny nose, concentration problems and fatigue. Symptoms can be controlled by pharmaceutical treatments such as local and systemic antihistamines and steroids and by a non-pharmacologic approach in which allergens must be avoided. Patient education often aims at the recognition of allergenic plants to avoid pollen exposure or take protective measures to minimize the health risk. Therefore, allergen avoidance can be considered an essential part of the management of allergic diseases [3].

The allergenicity of plants depends on several factors (such as the plant's abundance, the pollination strategy and the antigen content of the pollen grains), as a result of which the allergenicity of different plant species can vary widely from non-allergenic to highly allergenic [4]. The information on plant allergenicity should be disseminated and presented in an easily understandable way, preferably with illustrations, as visual information can be more powerful than verbal information [5,6]. In particular, to recognize plants, illustrations are needed [7].

Plants are often depicted in information materials of allergy-related products (e.g., medicines and air purifiers), services (clinics, salt rooms), patient information and news (pollen forecasts). Nowadays, the Web is the most effective medium of advertisement for these contents [8]. According to a study performed in Poland, approximately 76.9% of adult Internet users (N = 1000) go to online platforms to obtain medical information [9]. A questionnaire survey found that most of the people affected by ragweed allergy follow pollen information (93%), mostly by websites and television, but a considerable amount of them (18%) are not interested in the source of information [10]. A study on the YouTube

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videos on allergic rhinitis showed that a total of 36% of the videos can be classified as misleading, while 43% can be classified as useful [11]. The lack of content regulation (e.g., peer-review) on a vast number of websites make it difficult for the patients to critically distinguish the information. It is well known that picture-based webpages have a better advantage in advertising attention versus text-only content [12]; thus, plant pictures are intensively used on websites dedicated to pollen allergy treatment and prevention. Pictorial information of plant allergenicity has not been studied before in detail, although other types of visual information with an impact on the patients have been frequently analyzed (e.g., medication instruction labels, pictograms and infographics, e.g., [13,14]). Due to the extensive use of pictures, it is timely to evaluate the pictorial information of plant allergenicity provided by websites. The aim of this study is to evaluate whether the images provided by allergy-related websites are suitable for conveying appropriate information about the allergenicity of plants.

2. Materials and Methods

Pictorial information on plant allergenicity was collected from the Internet from May 2021 to July 2022 using the image search engine of Google (for research with a similar strategy, see, for instance, [15]). The Boolean operator 'AND' was used to combine the following keywords: 'pollen' AND 'allergy'. Pictures were manually examined to ensure that multiple photos of the same series of illustrations were removed.

Plants found on the pictures were identified using botanical and horticultural literature. The identified plant taxa were categorized by their potential allergenicity using the CARE-S index [16]. In this index, categories are calculated as a function of genetically determined factors of plants: immunogenicity (Im), morphology (Mo) and pollen production (Po). The allergological literature was reviewed for IM. The morphology of male flowers and pollen is considered to categorize plants according to their pollination strategy. Light, small (usually >40μm) and dry pollen grains with a low specific gravity, or with air sacs with a (nearly) smooth surface, were considered to be anemophilous. The pollen production of cultivars with a high or reduced pollen yield was also considered in the categorization. For a detailed description of the Im, Mo and Po parameters, see [16]. The combination of these parameters yields the following formula:

$$AC_p = Im \times Mo \times Po$$

where AC_p is a raw value of the potential allergenicity which is converted to an index with five categories, referred to as the CARE-S index (CAtegorization System for REgulation of Allergenic Plants by Strong Evidence) (Table 1).

Table 1. Values of the CARE-S index and the corresponding levels of potential allergenicity. AC_p = raw calculated value of allergenicity categories [16].

AC_p	Potential Allergenicity	CARE-S Index
0	non-allergenic	0
$0 < AC_p \leq 2$	low	1
$2 < AC_p \leq 4$	medium	2
$4 < AC_p \leq 6$	high	3
$6 < AC_p \leq 8$	very high	4
n.d.	no data; further studies needed	unknown

In order to evaluate the role of the plants in the ads, their co-occurrence with other visual components of the pictures (such as depicted patients, allergic symptoms and medicines) were also analyzed. Additionally, the qualitative relationships of plants with other visual elements were assessed with formal analysis, a technique used to evaluate visual elements and principles of design [17,18]. The most common pictures were reverse-image-searched for counting occurrences using the 'Google Search by Image' function on

Google ([19], https://images.google.com/ (accessed on 8 August 2022)), as this technology offers an opportunity to rapidly collect picture-based information [20]. To see how frequently plant illustrations are used on allergy-related websites, another Google search was performed using the words 'pollen' AND 'allergy'. The websites are grouped according to their main function (daily news, healthcare magazines, clinics, products, professional associations). Only one illustration per website was considered: the first one of the results of the image search.

3. Results

A total of 562 different photos depicting identifiable plants were found on allergy information websites. In the pictures, 124 plant taxa, belonging to 41 plant families, were identified; among them, 25% of the plants could be identified to the genus level, and a further 68% could be identified to the species level, representing taxa from various biogeograpical regions. Most plants (32.7% of the cases, 29 species) belonged to the Asteraceae family, followed by Rosaceae (19.2%, 9 spp.) and Brassicaceae (3.7%, 3 spp.). Fabaceae was a less common but diverse family containing 11 species (Table 2).

Table 2. Plant taxa used in the illustrations of allergy-related marketing materials. Frequency: the % of the taxa; potential allergenicity according to the CARE-S index [16]: 0: non allergenic, 1: low, 2: medium, 3: high, 4: very high, n.d. = no data; W: woody, H: herbaceous, E: entomophilous flower; A: anemophilous flowers—catkin, B: other type of anemophilous flowers; Y: yellow, G: green, C: other bright-colored. * mostly *Crysanthemum* × *morifolium*, *C. maximum* and *C. coronarium*.

Taxa	Family	Frequency	Potential Allergenicity	Woody/Herbaceous	Pollination Type	Flower Color
Acacia dealbata	Fabaceae	0.4	2	W	0	Y
Achillea filipendulina	Asteraceae	0.2	1	H	0	Y
Achillea millefolium	Asteraceae	0.4	1	H	0	C
Achillea ptarmica	Asteraceae	0.2	1	H	0	C
Alcea rosea	Malvaceae	0.2	0	H	0	C
Allium sp.	Amaryllidaceae	0.5	0	H	0	C
Alnus spp.	Betulaceae	0.4	4	W	A	C
Alstroemeria ligtu	Alstroemeriaceae	1.2	1	H	0	C
Ambrosia artemisiifolia	Asteraceae	2.1	4	H	B	G
Anthemideae (cf. *Anthemis*)	Asteraceae	0.5	1	H	0	Y
Apiaceae	Apiaceae	2.0	0	H	0	C
Aster spp.	Asteraceae	0.4	2	H	0	C
Asteraceae	Asteraceae	3.4	1	H	0	C
Begonia hybrid	Begoniaceae	0.4	1	H	0	C
Bellis perennis	Asteraceae	1.1	1	H	0	C
Betula spp.	Betulaceae	0.9	4	W	A	Y
Bougainvillea spp.	Nyctaginaceae	1.1	0	H	0	C
Brassica napus	Brassicaceae	8.9	1	H	0	Y
Brassicaceae	Brassicaceae	0.4	1	H	0	Y
Calendula officinalis	Asteraceae	0.2	1	H	0	C
Camellia japonica	Theaceae	0.2	0	W	0	C
Capsella bursa-pastoris	Brassicaceae	0.2	0	H	0	C
Carpinus sp.	Betulaceae	0.2	2	W	0	C
Ceiba speciosa	Malvaceae	0.2	n.d.	W	0	C
Centaurea sp.	Asteraceae	0.5	1	H	0	C
Cercis siliquastrum	Fabaceae	0.2	0	W	0	C
Chrysanthemum spp.*	Asteraceae	6.4	1	H	0	C
Cichorieae	Asteraceae	0.4	1	H	0	C
Cichorium intybus	Asteraceae	0.4	1	H	0	C
Cladanthus mixtus	Asteraceae	0.7	n.d.	H	0	C
Consolida regalis	Ranunculaceae	0.2	0	H	0	C
Coronilla varia	Fabaceae	0.2	0	H	0	C

Table 2. *Cont.*

Taxa	Family	Frequency	Potential Allergenicity	Woody/Herbaceous	Pollination Type	Flower Color
Corylus avellana	Betulaceae	0.7	4	W	A	Y
Crocus sp.	Iridaceae	0.2	n.d.	H	0	mostly Y
Cytisus × praecox	Fabaceae	0.5	1	W	0	Y
Dactylis glomerata	Poaceae	0.7	2	H	B	G
Dahlia sp.	Asteraceae	0.2	1	H	0	C
Delphinium sp.	Ranunculaceae	0.2	1	H	0	C
Dianthus barbatus	Caryophyllaceae	0.2	n.d.	H	0	C
Dianthus caryophyllus	Caryophyllaceae	0.2	1	H	0	C
Dipsacus fullonum	Caprifoliaceae	0.2	0	H	0	C
Doronicum orientale	Asteraceae	0.4	1	H	0	Y
Epilobium angustifolium	Onagraceae	0.2	0	H	0	C
Erigeron annuus	Asteraceae	0.2	n.d.	H	0	C
Euphorbia pulcherrima	Euphorbieae	0.2	0	W	0	C
Eustoma exaltatum ssp. *Russellianum*	Chironieae	0.2	1	H	0	C
Eustoma grandiflorum	Chironieae	0.7	1	H	0	C
Forsythia × intermedia	Oleaceae	2.3	n.d.	W	0	Y
Genista sp.	Fabaceae	0.2	0	H	0	C
Gerbera hybrida	Asteraceae	2.5	1	H	0	C
Gladiolus communis subsp. *Byzantinus*	Iridaceae	0.2	n.d.	H	0	C
Gladiolus hybrid (e.g., 'Nova Lux')	Iridaceae	0.2	1	H	0	C
Gladiolus × gandavensis 'Bangladesh'	Iridaceae	0.4	1	H	0	C
Grevillea alpina 'Olympic Flame'	Proteaceae	0.2	0	W	0	C
Gypsophila paniculata	Caryophyllaceae	0.2	n.d.	H	0	C
Helianthus annuus	Asteraceae	0.7	1	H	0	Y
Helianthus 'Lemon Queen'	Asteraceae	0.5	1	H	0	Y
Hibiscus syriacus	Malvaceae	0.2	0	W	0	C
Hydrangea arborescens	Hydrangeaceae	0.2	0	H	0	C
Iris × germanica	Iridaceae	0.4	0	H	0	C
Kalanchoë blossfeldiana	Crassulaceae	0.7	0	H	0	Y
Kerria japonica	Rosaceae	0.5	0	W	0	Y
Knautia cf. *tatarica*	Caprifoliaceae	0.2	0	H	0	C
Kolkwitzia amabilis	Caprifoliaceae	0.2	0	W	0	C
Laburnum anagyroides/ L. × watereri	Fabaceae	0.2	0	W	0	Y
Lamium purpureum	Lamiaceae	0.5	0	H	0	C
Lavandula angustifolia	Lamiaceae	0.7	0	H	0	C
Leucanthemum maximum	Asteraceae	0.2	1	H	0	Y
Leucanthemum vulgare	Asteraceae	2.7	1	H	0	C
Lilium sp. (hybrid)	Liliaceae	1.8	1	H	0	C
Limonium sp.	Plumbaginaceae	0.2	1	H	0	C
Lupinus polyphillus	Fabaceae	0.2	1	H	0	C
Maloideae	Rosaceae	1.2	0	W	0	C
Mandevilla sanderi	Apocynaceae	0.2	0	H	0	C
Narcissus pseudonarcissus	Amaryllidaceae	0.9	0	H	0	Y
Nerium oleander	Apocynaceae	0.5	0	W	0	C
Papaver rhoeas	Papaveraceae	0.4	0	H	0	C
Pennisetum orientale	Poaceae	0.2	2	H	B	G
Pericallis × hybrida	Asteraceae	0.2	1	H	0	C
Petunia × hybrida	Solanaceae	0.7	0	H	0	C
Phalaenopsis hybrid	Orchideaceae	0.4	0	H	0	C
Philadelphus coronarius	Hydrangeaceae	0.2	0	W	0	C
Phlox diverticata	Polemoniaceae	0.2	0	H	0	C

Table 2. *Cont.*

Taxa	Family	Frequency	Potential Allergenicity	Woody/Herbaceous	Pollination Type	Flower Color
Phlox paniculata	Polemoniaceae	0.2	0	H	0	C
Physostegia virginiana	Lamiaceae	0.5	0	H	0	C
Poaceae	Poaceae	1.4	2	H	B	G
Primula vulgaris	Primulaceae	0.2	0	H	0	Y
Prunoideae	Rosaceae	13.0	0	W	0	C
Prunus padus	Rosaceae	0.2	0	W	0	C
Prunus serrulata ‘Kanzan’	Rosaceae	0.2	0	W	0	C
Prunus triloba	Rosaceae	0.2	0	W	0	C
Ranunculus sp.	Ranunculaceae	0.7	1	H	0	Y
Rhododendron sp.	Ericaceae	0.2	0	W	0	C
Rosa sp.	Rosaceae	3.6	1	W	0	C
Rumex sp.	Polygonaceae	0.2	2	H	B	G
Salix spp.	Salicaceae	0.9	n.d.	W	A	Y
Salvia cf. *pratensis*	Lamiaceae	0.4	0	H	0	C
Salvia splendens	Lamiaceae	0.2	0	H	0	C
Scabiosa/Succisa/ Knautia sp.	Caprifoliaceae	0.2	0	H	0	C
Senecio spp.	Asteraceae	0.2	1	H	0	Y
Silene flos-cuculi	Caryophyllaceae	0.2	0	H	0	C
Silene vulgaris	Caryophyllaceae	0.2	0	H	0	C
Solidago canadensis	Asteraceae	0.9	2	H	0	Y
Solidago virgaurea	Asteraceae	0.5	2	H	0	Y
Sorbus cf. *aria*	Rosaceae	0.2	0	W	0	C
Spartium junceum	Fabaceae	0.2	0	W	0	C
Spiraea sp.	Rosaceae	0.2	0	W	0	C
Syringa vulgaris	Oleaceae	3.0	1	W	0	C
Tamarix sp.	Tamaricaceae	0.5	2	W	0	C
Tanacetum vulgare	Asteraceae	0.5	1	H	0	Y
Taraxacum officinale	Asteraceae	6.2	1	H	0	Y
Trifolium pratense	Fabaceae	0.7	1	H	0	C
Trifolium repens	Fabaceae	0.4	1	H	0	C
Tulipa spp.	Liliaceae	2.0	0	H	0	mostly Y
Verbascum sp.	Scrophulariaceae	0.2	0	H	0	Y
Veronica longifolia	Plantaginaceae	0.4	0	H	0	C
Viburnum × *burkwoodii*	Adoxaceae	0.4	1	W	0	C
Viburnum opulus ‘Roseum’	Adoxaceae	0.2	0	W	0	C
Viburnum rhytidophyllum	Adoxaceae	0.2	n.d.	W	0	C
Vicia villosa	Fabaceae	0.2	0	H	0	C
Viola wittrockiana	Violaceae	0.2	0	H	0	C
Wisteria sinensis	Fabaceae	0.4	0	W	0	C
Xeranthemum annuum	Asteraceae	0.2	0	H	0	C

The most frequently referred taxa were Prunoidae, *Brassica napus*, *Chrysanthemum* spp. and *Taraxacum officinale*, which, together, made up 34.5% of the identified plants. *Brassica napus* was the most frequent species identified, forming 8.9% of the overall identified plants. Mostly, herbaceous (71.0%) taxa were illustrated as allergenic plants, while woody taxa were less frequently depicted (29.0%). Catkin-bearing plants (*Alnus*, *Betula*, *Corylus* and *Salix* spp.) have been used rarely (3.6%). Colorful flowers (96.0%) were preferred, while inconspicuous, green flowers, e.g., of grasses, were relatively uncommon (4.0%). The dominant color on the pictures was yellow (38.9% of the pictures, 21.8% of the taxa), mostly depicting *Brassica napus*, *Taraxcum officinale* and *Forsythia* × *intermedia*, followed by a white color, being dominant in 30.9% of the pictures (represented mostly by Prunoideae). Pink was third on the color preference list, being in 14.5% of the total pictures, often depicting ornamental taxa belonging to Prunoideae. Other flower colors appeared less frequently in allergy-related marketing (purple 7.5%, red 6.3%, green 3.9%, orange 2.2%, blue 1.0%).

Potential allergenicity (CARE-S index) was applied to categorize the identified plants. For herbaceous taxa, the CARE-S index was not available in the literature, because former publications focused on urban trees. Thus, the CARE-S index was calculated for 106 taxa for the first time (see Supplement Table S1). In 85.4% of the allergy-related pictures, plants with low allergenicity (CARE-S 0 and 1) were found. As some picture contained more than one plant species, the frequency of the allergenic plants was also calculated. Only 3.2% of the plants belonged to highly allergenic species (CARE-S 4), vs. 79.8% of the plants belonging to low-allergenicity taxa. Among non-allergenic (CARE-S 0) taxa, the most common plants (13.0% of the total taxa) belonged to the subfamily Prunoideae, containing ornamental trees and shrubs, such as *Prunus serratula* 'Kanzan'. In the CARE-S 1 group (low potential allergenicity), *Brassica napus*, *Chrysanthemum* spp. and *Taraxacum officinale* were the most frequently presented plants (having 8.9, 6.4 and 6.2% of the total taxa, respectively). Among allergenic plants, Poaceae (mostly *Dactylis glomerata*, CARE-S 2), *Ambrosia artemisiifolia* (CARE-S 4) and *Solidago* spp. (CARE-S 2) were the most frequently illustrated (in 2.3, 2.1 and 1.4% of the total taxa, respectively), while other common allergens (*Alnus*, *Betula*, *Corylus* spp.) were rarely shown (<0.9%). *Forsythia* × *intermedia* was the most frequent species in the illustration materials (2.3% of the total taxa) with unknown allergenicity (i.e., no sufficient information to calculate the CARE-S index). Figure 1 shows the potential allergenicity of plants belonging to different plant families.

Based on the Google search, 63.0% of the allergy-related information on the Internet (N = 108 websites containing the words 'pollen' AND 'allergy') was illustrated with plants. The images have been found as a prominent visual element in advertisements for various allergy-related products, services of the clinical and pharmaceutical sectors, alternative medicine and products such as air purifiers. Plant images were also used in the news, i.e., as illustrations of pollen information in daily news or in articles on news websites. In detail, 37.8% of the plant illustrations were found on websites of clinics. Daily news and healthcare magazines were the source of 22.5% and 19.8% of plant illustrations, respectively, while products (11.7%) and professional associations (8.1%) contributed to a lesser extent. A total of 82.0% of the webpages presented misleading pictorial information by showing non-allergenic plants with allergic persons. The improper presentation of plants was found in 31 of 42 clinics, in 22 of 25 daily news sources, on 12 of 13 webpages offering products, in 20 of 22 healthcare magazines and in 6 of 9 professional associations.

Stock photography websites served as major suppliers of most plant photographs licensed for the above-mentioned specific uses. The plants and patients with allergy symptoms are often illustrated together (N = 403), and almost all of them (99.0%) demonstrated an allergenic effect of the illustrated plant by blowing nose (43.3%), sneezing (35.8%), running nose or having irritation of the nose (5.5%), red eyes (3.0%) or wheezing (0.3%); they alleviated allergy by wearing a surgical mask (7.3%) or gas mask (3.0%), applying a nasal spray/drop (0.8%), using an inhaler (0.3%) or taking pills (0.5%). Among the depicted patients (N = 353), mostly young women (70.5%) were illustrated, while young men (11.0%), girls (10.5%), boys (4.2%), elderly women (3.1%) and elderly men (0.6%) were shown in a lesser number. In the most popular picture, having 886 search results, a young woman sneezing on a dandelion (*T. officinale*) field was shown. This picture appeared in different languages in allergy-related advertisements (36.0% products and 18.0% clinics) and news (36.0% daily news and 10.0% healthcare magazines, among 50 websites analyzed for content) and was awarded with a high usage score [21].

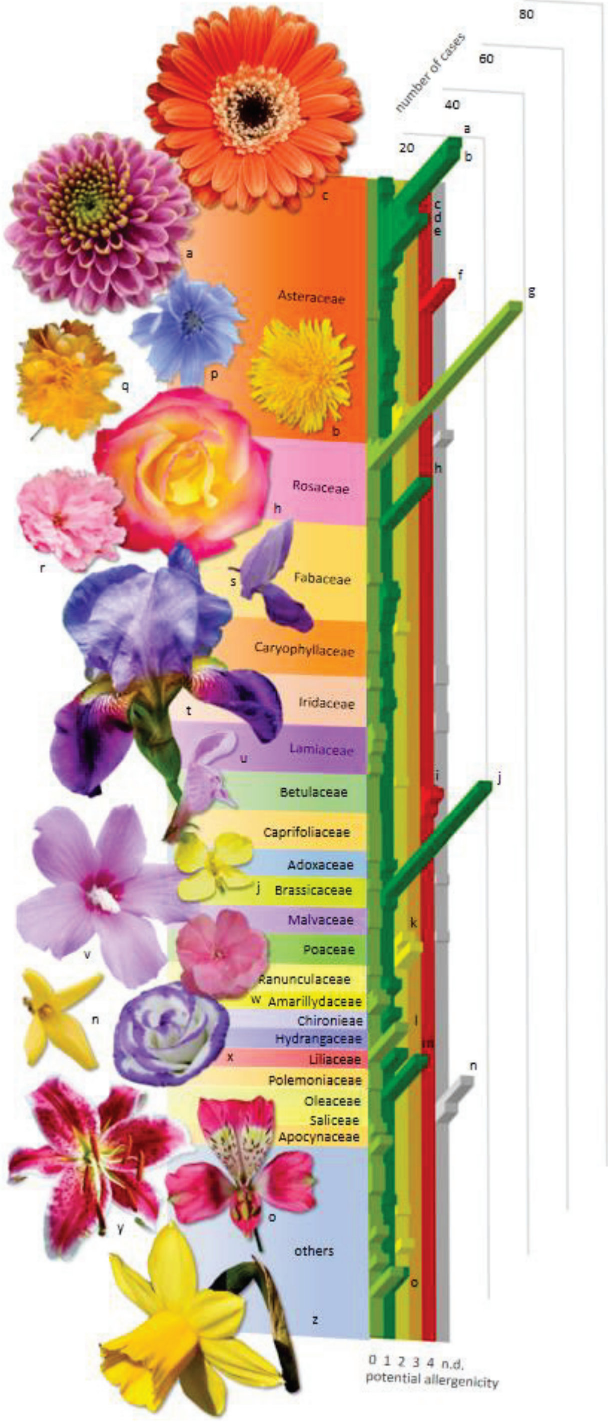

Figure 1. Plant taxa identified in allergy-related marketing materials. On the right side, a graph shows the number of cases (occurrence of plant species in allergy-related marketing materials) in allergenicity groups 0–4 plus n.d. (light green–gray graph bands). The potential allergenicity of plants is expressed by the CARE-S index [16], where 0: non allergenic (light green), 1: low (dark green), 2: medium (yellow), 3: high (orange), 4: very high (red) potential allergenicity, n.d.: no data (gray). The names of individual plant species are not shown (for this, see Table 2), but they are grouped according to plant families. Some remarkable species, however, are highlighted on the graph (a–o). a: *Chrysanthemum* spp., b: *Taraxacum officinale*, c: *Gerbera hybrida*, d: *Leucanthemum vulgare*, e: Asteraceae, f: *Ambrosia artemisiifolia*, g: Prunoideae, h: *Rosa* sp., i: *Betula* spp., j: *Brassica napus*, k: *Dactylis glomerata*, l: *Tulipa* spp., m: *Syringa vulgaris*, n: *Forsythia* × *intermedia*, o: *Alstroemeria ligtu*, p: *Cichorium intybus*, q: *Kerria japonica*, r: *Prunus serrulata* 'Kanzan', s: *Wisteria sinensis*, t: *Iris* × *germanica*, u: *Lamium purpureum*,

v: *Hibiscus syriacus*, w: *Nerium oleander*, x: *Eustoma grandiflorum*, y: *Lilium* sp. (hybrid), z: *Narcissus pseudonarcissus*. Some examples of plant species are shown in the photographs on the left side (a–z; for species names, see above). Source of the images: copyright-free photos from pixabay.com (a, j, n, o, t, u, x–z), unsplash.com (c) and freepik.com (r). Some photos were taken by the author (b, h, p, q, s, v, w). The photos have been edited to clearly illustrate the flower morphology of the plants with nil or low potential allergenicity (individual flowers separated from the plant, background removed, brightness and contrast adjusted).

With the formal analysis of pictures (N = 80), the artistic role of the plants in the ads and their relationship with other visual components of the pictures (such as depicted patients, allergic symptoms and medicines) were assessed. The visual elements and design principles often used in this type of illustration are recognizable (Supplement Table S2). The role of the visual elements was to draw the viewer's attention to the central issue of the advertisement, i.e., the allergic reaction of the patient. The most pronounced visual elements were shapes and lines, color, value, space and composition. A combination of visual elements can be used to build up the principles of design, which aim to create effects, i.e., feelings in the viewer. According to this, two major design concepts can be identified in the allergy-related ads. The first type of visual advertising concept gives the impression that the patient is surrounded by and is 'sinking into' a large field of 'allergenic' plants (Figure 2). The second type of visual advertising concept conveys the feeling that the 'allergenic' pollen is 'falling onto' the patient, usually from trees (Figure 3). The first and the second types of concepts were presented in 58% and 42% of the pictures, respectively.

Figure 2. Formal analysis of the most frequently used picture in advertisements of allergy-related products and services depicting plants. The picture represents a popular design concept in visual marketing in allergies. Red arrows, lines and shapes are tools of formal analysis, showing how the viewer's eyes are led by major elements and design principles (underlined in the text below) of the picture to the central figure (patient) and affected organs (mouth and nose). Note that the predominant color of the flowers in both images is yellow. The picture depicts a woman standing on a dandelion (*Taraxacum officinale*) field. The negative space (represented by herbaceous weed population) is large, homogenous, colorful and contrasting to the patient. The plants' airborne cypselae fruits and sneezing suggests a causal relationship between the plant and the allergic reaction. The viewer's eye is led by the lines of hills (a,b) as well as by colors, values and contrasts

of the vegetation (c,d) to the central figure, whose movements (e,f) express a strong allergic reaction. The viewer's impression (i.e., the effect of the artwork) is that the patient is 'sinking into' a field of allergenic weeds while sneezing and wheezing. The current picture (aquarelle painting) is made by the author (Donát Magyar) to represent the design of the original photograph [21].

Figure 3. Formal analysis of a frequently used picture in advertisements of allergy-related products and services depicting plants. The picture represents a popular design concept in visual marketing in allergies. Red arrows, lines and shapes are tools of formal analysis, showing how the viewer's eyes are led by major elements and design principles (underlined in the text below) of the picture to the central figure (patient) and affected organs (mouth and nose). The picture depicts a woman walking on a street, while the pollen of the trees (*Forsythia* × *intermedia* and Prunoidae) are 'falling onto' her, provoking an allergic reaction. The composition is unbalanced (weighted against the patient by the higher proportion of the dark area). Action is shown by lines of branches of 'allergenic' trees pointing to the patient (g,h), whose allergic reaction is emphasized by movements (j) and shapes (l, delineated by hands raised to the nose or mouth). A negative effect of plants is suggested by colors and values, as well as by lines, according to the direction of the patient's gaze (k). The current picture (aquarelle painting) is made by the author (Donát Magyar) to represent the design of the original photograph [22].

4. Discussion

4.1. Plants in Ads: The Botanists' Perspective

In this study, predominantly (85.4%) non-allergenic plants were found on the Web, mainly as visual advertising materials of allergological products and services. This result indicates that the plants have not been used properly by the designers or those who are responsible for the content, as their allergenic effect has not been taken into account.

Brassica napus (rapeseed or canola) was the most frequently depicted species as an allergenic plant in marketing materials, but it has a low potential allergenicity. The illustration of this plant in allergy-related information materials is not only misleading but can have negative effects on other sectors, such as agriculture. Rapeseed represents a large segment of the edible oil and biodiesel market; its production was estimated at 58.4 million tons/year [23]. Undoubtedly, rapeseed is preferred by designers, probably because of its attractive yellow flowers. Rapeseed, like many other non-allergenic plants with colorful flowers, provides a habitat and food for honeybees and other endangered pollinators. *Helianthus annuus* (sunflower), another important crop plant, was also illustrated as an allergenic species, despite its low relevance in pollen allergies. Its pollen has a low concentration in the air, except during harvesting, as demonstrated by a study reporting symptoms caused by sunflower [24]. However, under natural conditions of pollen release, the high potential allergenicity cannot be attributed to the sunflower. Prunoidae were the most common non-allergenic taxa depicted as an allergen. Some species belonging to this plant family (*Pyrus calleryana*, *Malus trilobata*, *Prunus padus*) are optimal candidates for creating a low-allergen garden or urban green spaces, especially *Prunus serrulata* 'Kanzan', the protagonist of Japan's cherry blossom festival hanami. Dandelion (*Taraxacum officinale*, Asteraceae) is an insect-pollinated weed. This plant was often depicted in marketing materials, triggering allergy by its cypselae fruits ('blowballs') and wind-blown *pappus* (which aids in seed dispersal). However, these organs do not contain any pollen. The *pappus* is too large (diameter ~7 mm) to be aspirated [25]. Blowballs may attract customers' attention toward allergy-related presentations, creating inadequate associations. This plant appears in 39 and 38 allergy-related advertisements and news sources, respectively, and in the most popular picture, with 886 search results. *Chrysanthemum* spp. has often been mispresented as an allergenic plant, but it is a popular flower crop with high commercial importance. The potential allergenicity of this plant as well as other decorative herbaceous taxa (such as *Dianthus*, *Gladiolus*, *Gypsophila*, *Lilium*, etc.) is usually low, as their allergic effect is rarely reported in outdoor environments or homes. It is worth mentioning that these taxa can cause occupational allergies, mostly in florist workers [26–32]. These studies show that florists not only experience respiratory allergies but also dermatitis due to skin contact with handled plants [33]. Besides pollen allergens, triggers of florists' symptoms include sesquiterpene lactones [34] and parasites of the decorative plants [35]. Neither skin allergy nor parasites are considered in the current study, which focuses on pollen immunogenicity of the respiratory system [16]. It is therefore necessary to maintain the position that the portrayal of the decorative flowers as allergens is misleading. Although information materials on allergenic plants that transfer knowledge to patients are available [36–39], they were largely omitted from the studied illustrations, possibly because of the different perspective of advertising professionals and designers.

4.2. Plants in Ads: The Designers' Perspective

The primary question for the designer is what makes an image successful in allergy-related advertisements. Apparently, perceived flower beauty is influenced by flower shape and color [40]. A simple Google image search for the keyword 'flower' results in colorful, large flowers in 98.8% of images (N = 500, daisies, roses and lotuses, in most cases). This demonstrates our primary association or archetype regarding the word 'flower'. As a consequence, when one talks about flowers, most people think of colorful, large flowers rather than catkins or other inconspicuous inflorescences of wind-pollinated, allergenic plants. Professional designers may not be an exception. In guidelines for designing symbols, the essential characteristic of the icon 'flower' is represented by a daisy [41]. This symbolism may also contribute to the frequent (and possibly often unconscious or ignorant) misuse of large, salient, non-allergenic flowers in the illustration of allergy-related content on the internet.

As this study focuses on plants, their main visual feature, color, is discussed in detail. Color, as a functional component of human vision, can capture attention and contribute to the success of an advertising campaign of a product or a service [42,43]. Increasing the salience of a given concept leads to increased activation of the parts of the brain devoted to processing it [44] due to the role of salience in the process of expectation-shaping [45]. Visual salience is important in medical advertisements, too [46]. The success of the application of yellow-colored plants in allergy-related marketing materials can be explained by the visual priority of yellow relative to luminance matched colors at opposing ends of the wavelength spectrum (i.e., red and blue) [47]. Against these colors, yellow was consistently seen as occurring first in the laboratory tests performed by Hu et al. [47]. According to this study, there is a temporal priority in processing yellow among competing colors, indicating its special salience rooted in the attentional and motivational regulatory functions. In the allergy-related marketing pictures, blue is often pitted against yellow e.g., when the background of a rapeseed field (yellow flowers) is contrasted to the sky (blue). A strong contrast also appears against dark green when yellow flowers (e.g., dandelion) are depicted on a meadow. Studies have shown how yellow, blue, green and red carry various meanings for different but related pharmaceutical products [48,49]. It was found that sore throat medicine is preferred in yellow and green [50]. Apparently, the color of marketing materials for allergy medicines has not been investigated in detail. However, according to the present results, it seems that salient colors of the flowers, especially yellow, are thought to be attractive to the customers of medical products and services in allergology. Possibly, costumers associate yellow with pollen and honey [51], while blue represents air, freshness, cleanliness and, consequently, breathing clean air [52].

Some components with a high frequency in the pictures were identified by the Web-based search. The most frequent components found in these pictures besides plants are: allergic person (99.0%), represented by a young woman (70.9%), blowing nose (43.3%) or sneezing (38.9%) and standing on a field surrounded by yellow flowers (38.9%). Interestingly, all of the above-mentioned properties can be found in the most popular picture, 'Woman sneezing with tissue in meadow', having 886 search results [21]. Using the technique of formal analysis, major elements (color, lines and space) and principles of design (contrast, movement and emphasis) could be identified in the pictures that are popular in the marketing of allergy-related products. The best compositions put emphasis on the patient (by positive space and contrast) and plants (by color and contrast) and contain a dynamic expression of patients' allergic reactions to plants (Figures 2 and 3). By an artistic use of contrast and lines (displayed by the branches of the plants, the patient's arms, the shape of a handkerchief, etc.), the viewer's eye is directed to move from the trigger (flowers) to areas of emphasis (respiratory organs, mouth and nose). Allergic symptoms and their strength are exhibited by dynamic movements, among which the most expressive is sneezing. Among symptoms, blowing nose was more frequently illustrated than sneezing, probably because photo models can more easily imitate it than sneezing. In the pictures with high search results, the artistic tools—whether used consciously or intuitively—were able to enkindle impressions, feelings or 'somatic understandings' (according to [53]), as was shown by the visual ads applying concepts of 'falling on' (tree pollen falling onto the patients) or 'sinking into' (patients sinking into a field of allergenic weeds). Apart from the obvious associations of some design elements with particular actions, emotive sensations were produced by certain linear patterns, e.g., lines directing the eye downward evoke moods of sadness or defeat [54].

The application of medicines, pills, nasal drops and inhalers was rarely shown, as this may limit the usability of the picture in advertising a wider variety of medical products and services. On the other hand, plants seem to make an important contribution to the success of pollen allergy-related ads, as they are major visual elements of the advertisements.

4.3. Misinforming by Illustrations: An Unnoticed Trap

The misuse of plant pictures is possibly rooted in Plant Awareness Disparity [55], often called 'plant blindness' [56], a term used for 'the inability to see or notice the plants in one's own environment'. Plant Awareness Disparity leads to, *inter alia*, (i) the inability to recognize the importance of plants in human affairs; or (ii) the misguided, anthropocentric ranking of plants as inferior to animals, leading to the erroneous conclusion that they are unworthy of human consideration [56,57]. Research results indicate that people are more and more ignorant to pants and can no longer identify them [58]. Recognizing that plants have an impact on our health can help to increase awareness of plants, as was demonstrated in a study testing the recognition ability regarding toxic plants [59]. According to the tests, toxic plants were more rapidly detected both by children and adolescents than non-toxic plants. Unlike toxicity, which is mostly related to fruits, allergenicity is related to flowers. The recognition of toxic plants was crucial for the survival of our ancestors for thousands of years, while pollen allergy is a relatively new issue. Thus, the risk perception of flowers is probably not developed in humans, unlike the risk perception of toxic fruits, which is—according to the habitat selection theory [40]—controlled by color preference, a heritage of the past that is hardwired in our brains. Flowers have aesthetic rather than survival-relevant value in human culture [40].

Pictures have an important role in health education, where they can facilitate conceptual processing [60,61]. The present study has shown that the current imagery in allergy-related advertisements has little or no potential for health education for allergy sufferers. Similar to the current study, Remvig et al. [11] concluded that Internet-based information of allergic rhinitis is often misleading. The quality of YouTube videos on allergic rhinitis does not correlate with the popularity of the video. Nonprofessional YouTube channels publish the most popular content; meanwhile, they are responsible for the most misleading videos, whereas associations tend to be the most reliable source of information. Although information about allergenic plants is crucial in primary prevention (i.e., to avoid allergen exposure) [62], more than 50% of allergy sufferers have no or only vague recognition of the plant species causing their symptoms (Szigeti et al., unpublished). Plant allergenicity information is available mostly on websites but also on printed materials. Journals, posters and leaflets placed in healthcare institutions such as pharmacies and allergologists' consulting rooms are mostly provided by governmental and non-profit organizations (NPOs, NGOs and CSOs) aiming to improve public health. Profit-oriented firms (e.g., pharmaceutical companies) also have an important role in the prevention of allergic diseases. Their multimedia advertising campaigns have enormous potential to raise public awareness and communicate health information. Direct-to-consumer advertising is a particularly powerful tool, having benefits for providing quick and accessible health information to the public [63]. However, it is important that health communicators and policy officials carefully consider advertising's role in health contexts, monitor the dynamic regulatory environment and develop a deeper understanding of consumers' perceptions and uses of pharmaceutical advertising [64]. The information distortion and extraneous decoration of pharmaceutical advertisements were often criticized [65,66]. According to Knoesen et al. [67], pharmaceutical advertisements often contain irrelevant and false information that presents potential risks if misunderstood and/or misinterpreted. Othman et al. [68] concluded that the low quality of pharmaceutical advertisements is a global issue. Since these observations were published in 2009, there is still a conflict between promotion and information in the pharmaceutical industry [69]. Although most of these critical studies focus on written information in advertisements, visual information seems inaccurate and misleading as well.

Most consumers cannot perceive the incongruity between pictorial and textual information as mismatching [70]. When verbal and pictorial information are at a mismatch, people tend to rely on the pictorial information [71]. This phenomenon is explained by the well-known picture superiority effect on memory (i.e., the advantage of information presented as a picture over words; see [72]). Moreover, information that is cognitively easier to process is more likely to be accepted as true [73]. Compared to texts, images attract attention more easily and are processed more quickly [6,74], as understanding images requires less cognitive effort than words, i.e., images are processed in a more unintentional and unconscious way [75,76]. The depicted properties of advertised products are more accessible in consumers' mind [74] and more easily stored by memory [77]. On the other hand, pictorial information is found to be highly influential in the false memory creation process [78]. It seems that misinformation in visual communication is particularly insidious (i.e., it is less observable but all the more damaging) and therefore deserves more attention.

4.4. Integrating Art and Botany—A Proposal for a Successful Strategy

As was demonstrated, the depiction of non-allergenic plants in allergy-related information or marketing materials is misleading, but in a correct form, it can be beneficial, providing useful knowledge to the patients. As designers are not necessarily health experts and health professionals are not necessarily trained to produce visual marketing materials, multidisciplinary collaboration is required [79]. By combining design and botanical knowledge, a correct and more targeted marketing strategy can be developed. Colors are obviously effective marketing tools; thus, colorful and allergenic plants should be selected for illustrating allergy-related marketing materials. The list of plants suggested for this integrated marketing strategy is shown in Table 3 and Figure 4.

Table 3. Plant species recommended for illustrating visual marketing materials of allergy-related products.

Latin Name	English Name	Flower Color	Time of Interest (Pollination Period)	Area of Interest (Bioclimatic Region)	Potential Allergenicity (CARE-S Index)	Invasive
Acacia dealbata	silver wattle, blue wattle or mimosa	yellow	January-March	mostly warm regions; Australia (native), California, New Zealand, Portugal, South Africa, Spain	2	yes
Acer negundo	box elder, Manitoba maple	green, pink and red	April-May	mostly temperate regions; North America (native), South America, Australia, much of Europe, New Zealand, South Africa, parts of Asia	4	yes
Betula spp. (*B. ermanii*, *B. papyrifera*, *B. pendula*, *B. pubescens*)	birch	yellow	March-May	mostly temperate and cold regions	4	
Callistemon/*Melaleuca* spp.	bottlebrush	red	October-May	Western Australia (native), temperate regions	2	
Corylus spp. (*C. avellana*, *C. corulna*)	hazel	yellow	January-April	mostly temperate and cold regions	4	
Cryptomeria japonica	sugi, Japanese cedar, Japanese redwood	orange	February-March	mostly in Japan, China, Azores	4	
Solidago canadensis	Canadian goldenrod	yellow	July-October	mostly temperate and cold regions; North America (native), Europe, Japan and China	2	yes

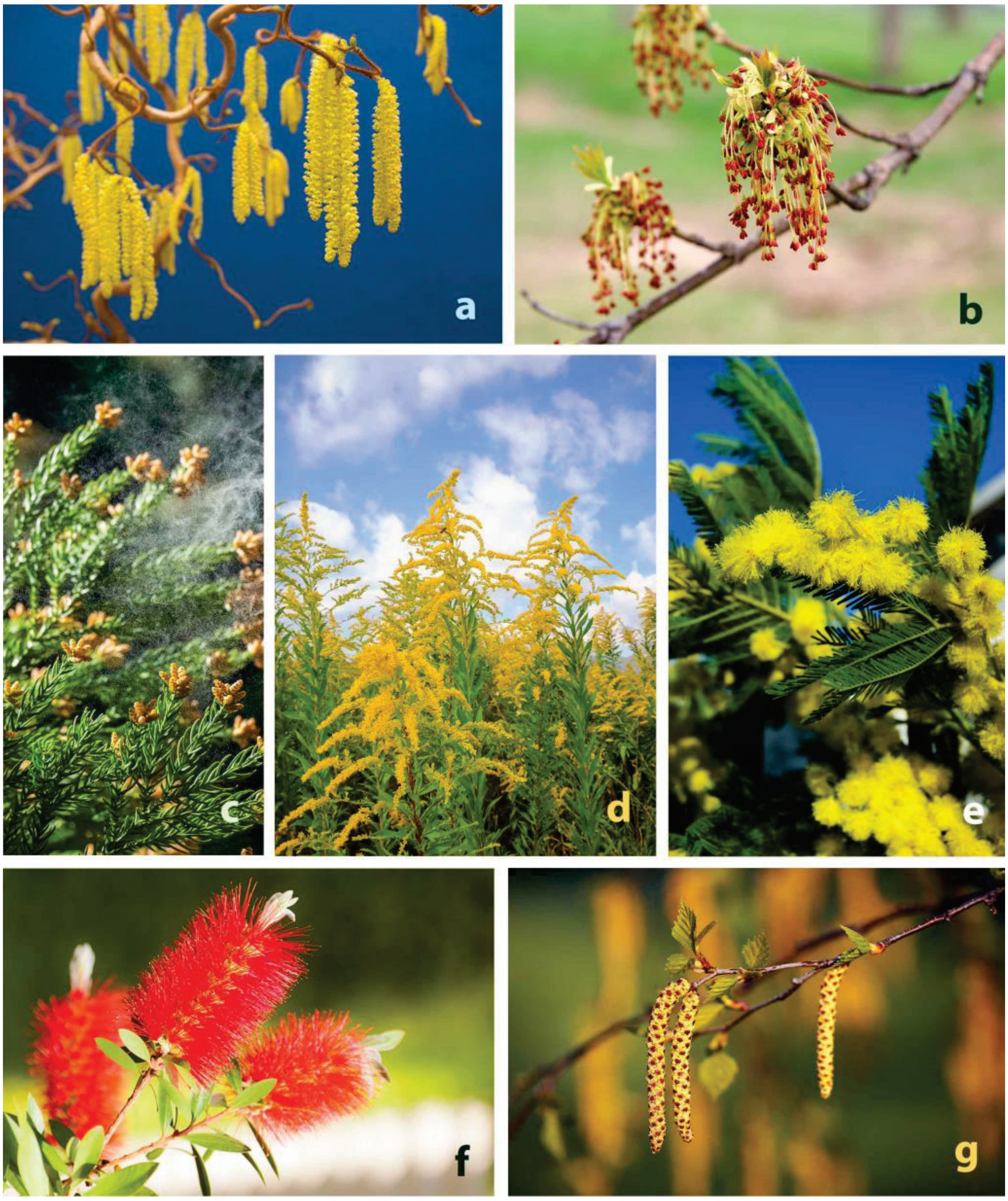

Figure 4. Recommended plant species for illustrating visual marketing materials of allergy-related products. (**a**): *Corylus avellana*, (**b**): *Acer negundo*, (**c**): *Cryptomeria japonica*, (**d**): *Solidago canadensis*, (**e**): *Acacia dealbata*, (**f**): *Callistemon* sp., (**g**): *Betula pendula*. Source: stock.adobe.com (accessed on 10 December 2022) (account NPHC).

Despite their attractive, yellow catkins, some allergenic plants, such as *Betula* and *Corylus*, appeared surprisingly infrequently (0.9 and 0.7%) in marketing materials. Illustrations on catkins can preferably be published in spring, considering the pollination period in the temperate region. *Solidago*, another plant with attention-grabbing yellow flowers, can cause symptoms in summer and autumn. In warm, temperate regions, *Acacia dealbata* is a major allergen plant [80]. It is also a noxious invasive plant. Illustrations of its beautiful, yellow flowers can be effectively used for both preventive patient education and marketing purposes in geographical regions where this plant threatens the natural flora through invasion.

Common ragweed (*Ambrosia artemisiifolia*) deserves distinct attention, as it is considered to be the most important allergen in many countries where its eradication is a high-priority task (e.g., Austria, Canada, France, Hungary, Italy, Serbia and the USA). Eradication campaigns and the recognition of this plant are often promoted by advertisements financed by the local governments (e.g., [81,82]. Some information materials also aim to educate the public regarding distinguishing ragweed from ornamental plants with similar leaves, e.g., *Tagetes* spp. and *Chrysanthemum vulgare* [83]. As a success of proper visual information materials, ragweed was recognized vs. the similar plants by 55.6, 68.0 and 75.6% of children, belonging to 6–10, 11–14 and 15–18 age groups [84]. Unfortunately, ragweed is less suitable for visual marketing (having small, inconspicuous inflorescence), but its display on commercial products would transmit a message that the company is supporting public interest objectives. As ragweed is an invasive weed species, raising awareness of this plant has a positive impact on agriculture, too.

5. Conclusions

In the marketing of allergological products, there is a dilemma: attract visitors' attention (i.e., using bright colors of non-allergenic flowers) or convey correct information (i.e., show relevant, i.e., allergenic, but less attractive flowers)? This research has shown that plant imagery in advertisements has little or no potential for health education for allergy sufferers; in fact, it is rather misleading. More professional and responsible advertising can contribute to more informed patients. To take advantage of the opportunity of using plant pictures in allergy-related advertisements, designers need a better understanding of allergenic plants, and health professionals should collaborate with them. To produce visual communication materials that are of the most benefit to patients and take into account marketing aspects as well, it is suggested that advertisers use colorful and allergenic plants for illustrating allergy-related marketing materials. These practical implications are of interest for both allergologists and designers, as they contribute to the development of a more focused health education and marketing strategy. Correct illustrations will help patients recognize and avoid allergenic plants and reduce exposure to allergenic pollen.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/plants12061334/s1, Table S1: Potential allergenicity of plant species. Previously published potential allergenicity of some species is available at Magyar et al., 2022 [16] or https://www.diszkerteszek.hu/files/md46-care-s-calculator.xlsx (accessed on 15 March 2023); Table S2: The process of the formal analysis of artworks.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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plants

Article

Computer Vision Interaction Design in Sustainable Urban Development: A Case Study of Roof Garden Landscape Plants in Marine Cities

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Abstract: The rapid urbanization and the increasing need for sustainable development have led to the emergence of green roof landscapes in ocean cities. These rooftop gardens provide numerous environmental benefits and contribute to the overall well-being of urban dwellers. However, optimizing the design and interaction experience of green roof landscapes requires the integration of intelligent technologies. This paper explores the application of computer visual design techniques, specifically 3DMAX modeling and virtual reality, in the intelligent interaction design of green roof landscape plants in ocean cities. Designers can use computer visual design (3DMAX) and other technologies to interact intelligently with the roof landscape in order to improve landscape design. Through case studies, this indicated that computer vision is excellent for image processing of rooftop landscapes and also demonstrates a high degree of compatibility between computer vision and green rooftop landscape plant design in marine cities. This paper highlights the significance of intelligent interaction design and computer visual design techniques in optimizing the integration of green roof landscape plants in ocean cities. It emphasizes the potential of 3DMAX modeling and VR technology in creating immersive and engaging experiences for designers, users, and stakeholders alike. The findings contribute to the growing body of knowledge in the field of sustainable urban development and provide insights for designers, policymakers, and researchers seeking to enhance green roof landscapes in ocean cities. The dissertation highlights the potential of using computer vision design techniques to enhance the roof garden landscaping process and advocates for more efficient and effective ways to design, visualize, and improve rooftop gardens by utilizing software equipped with computer vision technology such as 3DMAX, ultimately contributing to the advancement of sustainable urban landscapes.

Keywords: plants; green roof landscape; intelligent interaction design; computer visual design; marine cities

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1. Introduction

Marine city roof landscape plants not only have excellent cooling and insulation effects but also can beautify the environment, purify the air, improve the local microclimate, and greatly increase the green coverage rate of the city [1]. They are a roof form worth vigorously promoting. With the progress of the times, the planting and design of rooftop landscape plants have become increasingly diverse, so studying rooftop landscape plants in marine cities is of great significance. To optimize the design and functionality of these green havens, the application of intelligent interaction design becomes crucial. This paper section aims to explore the concept of interaction design and its relevance in improving the user experience of rooftop gardens [2].

Interaction design is a multidisciplinary field that focuses on creating meaningful and engaging interactions between users and products, systems, or environments. In the context of green roof landscapes, interaction design involves the deliberate shaping of the user's experience and interactions within the garden space. It encompasses various elements including spatial arrangement, plant selection, sensory stimuli, and user-centered considerations [3].

More and more people are studying green roof landscape plants in ocean cities. "Virtual Reality Applications in Landscape Architecture: A Review" by Elsayed et al. (2020) explored the use of virtual reality (VR) in landscape architecture, including green roof design and interaction [4]. It discussed the benefits and limitations of VR in creating immersive and interactive experiences and its potential in enhancing user engagement and understanding of green roof landscapes [5].

"Computer Vision-Based Techniques for Plant Phenotyping in Green Roofs" by Alsadik et al. (2020) focused on the application of computer vision techniques for plant phenotyping in green roofs [6]. It explored the use of image-processing algorithms and machine learning for plant growth analysis, including the measurement of leaf area, plant height, and biomass estimation. The findings provide insights into the potential applications of computer vision in optimizing plant growth in rooftop gardens. "Visualization and Virtual Reality Tools for Green Roof Design and Simulation" by Musa et al. (2018) explored the use of visualization and virtual reality tools in green roof design and simulation [7]. It discussed the integration of 3D modeling and VR technology to enhance the visualization and interaction of rooftop garden designs. The study emphasized the importance of user experience and engagement in the design process. Calheiros, C.S.C. believed that planting plants on green roofs has attracted considerable attention nowadays [8]. Subsequently, there is a hypothesis that native plants would be more adaptable to the environment, provide greater environmental benefits, and be more aesthetically pleasing than non-native plants. Although green rooftop landscape plants in ocean cities are widely planted today, there are still some aspects that need to be improved.

The research methodology of this paper involves a combination of literature review, case studies, and empirical analysis. The literature review provides a comprehensive understanding of the existing knowledge and research in the field of intelligent interaction design and computer visual design techniques [9]. Case studies and examples are used to illustrate the practical application of these techniques in the context of green roof landscape plants in ocean cities. Additionally, empirical analysis considers the gathered data and evaluates the effectiveness of the implemented computer visual design techniques through user evaluations, feedback, and quantitative measures. The research methodology ensures a comprehensive exploration of the research objective and provides valuable insights into the integration of computer visual design techniques in green roof landscape plants [10].

By employing intelligent interaction design principles, rooftop gardens can offer more than just a visual spectacle. They can become immersive and interactive spaces that stimulate curiosity, learning, and a deeper connection with nature. Intelligent interaction design takes into account the diverse needs and preferences of users, fostering engagement, and promoting a sense of well-being [11]. For instance, the arrangement of plants within the garden can be strategically designed to create a sensory journey, engaging users through a variety of colors, textures, and fragrances. The pathways and seating areas can be optimized to provide opportunities for exploration, relaxation, and social interaction. By leveraging intelligent interaction design, rooftop gardens can cater to the diverse needs of users whether they seek a peaceful retreat, a space for social gatherings, or an educational experience [12].

Furthermore, interaction design can be enhanced through the integration of computer visual design techniques such as 3D modeling and virtual reality. These technologies enable designers and users to visualize and interact with green roof landscapes in a dynamic and immersive manner. Three-dimensional modeling allows for realistic representations of the garden space, facilitating the evaluation of plant placements, spatial arrangements, and overall design concepts. VR technology, on the other hand, offers users the opportunity to virtually explore and interact with the rooftop garden, offering a deeper understanding of the plant ecosystem and experience of the space from different perspectives [13].

Computer vision is also a commonly used technology nowadays, and its use regarding green rooftop landscape plants in ocean cities is also a trend. Computer vision has excellent image-processing functions, which can identify the distribution of various samples in the landscape. This is very helpful for the design of rooftop landscape plants in ocean cities. In this experiment, computer vision technology was also used to identify the greening rate of green rooftop landscape plants in ocean cities. From the results, it can be found that computer vision is still very effective in analyzing the greening of green landscape plants in marine cities [14].

The use of new tools and design methods utilizing computer methods in green roof planting landscape design helps designers to create more precise and knowledge-based greening designs. This article describes the application of computer vision design techniques, especially in the field of roof garden landscaping, using software such as 3DMax2020. This involves using the capabilities of such software to digitally model and visualize roof garden layouts, plant arrangements, and other landscape elements. These tools, often rooted in computer vision principles, empower designers and architects to meticulously simulate, model, and visualize every intricate facet of landscapes, structures, and objects. By incorporating these techniques into green roof landscaping, we aim to facilitate a more precise, informed, and knowledge-driven approach to greening design.

2. Intelligent Interaction of Green Roof Landscape Plants in Ocean Cities Based on Computer Vision

2.1. Overview of Green Roof Landscape Plants in Ocean Cities

Just like other architectural landscapes and forests, the green roof landscape of ocean cities is a combination of water, mountains, and rocks based on terrain and natural features to form a garden. In urban greening, roof greening accounts for a large proportion and is also known as a plant that leaves the soil environment. With the increase of buildings and population, people's desire for natural greening has become more urgent [15]. Instituting greenery on roofs is thriving in a unique form. Not only is it more closely integrated with architectural plants, but it also enriches the aesthetic of the building, providing people with a wider view and more green space with landscapes. Roof greening is carried out within a limited space and is subject to many limitations. Therefore, detailed planning and design are required for the elements, structure, volume, and style of roof greening [16].

In addition to designing according to the technical principles of architectural design, roof greening in ocean cities also needs to consider the structure of the roof, the waterproof and drainage structure of the roof, the growth characteristics of plants, and the growth techniques of plants. These are all technical requirements for creating roof landscapes. The key to the success of roof greening construction lies in the bearing capacity of the roof, the ability of the roof for drainage and waterproofing, and the combination of greening plant species [17]. In order to solve the problem of bearing capacity in roof greening, landscape plants with too large a volume should not be installed in the roof landscape. In the treatment of the site, it should be mainly flat, and the roof landscape can be designed according to the natural conditions of the roof to meet the greening needs of the building landscape and increase the level of landscape space.

2.2. Design Principles for Rooftop Landscape Plants in Marine Cities

Natural layout: Most of the plants in the roof landscape are arranged in a natural way so that the roof landscape can form a natural garden effect. The natural layout of the roof landscape is meant to match the roof landscape with the surrounding buildings and water bodies and then combine trees and flowers to form a dense natural landscape [18].

Rule-based layout: In rule-based layout, the designer needs to pay attention to the decoration of plants so that the plants in the garden form a regular and hierarchical plant configuration. This plant configuration has a fresh and solemn landscape atmosphere, which can give people a good feeling.

Mixed layout: The mixed roof landscape not only possesses the landscape characteristics of natural and regular layout but also has its own unique style. In the changes of spatial composition points and surfaces, it forms a variety of spatial levels. This type of rooftop landscape is designed to enhance the continuity of the plant landscape and emphasize the diversity of landscape plants, thereby closely combining different types, styles, and landscapes to form an extremely beautiful rooftop landscape [19].

The composition of the green roof landscape in marine cities is shown in Figure 1.

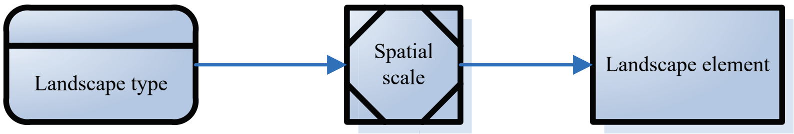


Figure 1. The composition of green roof landscape in an ocean city.

2.3. Role of Rooftop Landscape Plants

Enhancing urban climates in ocean cities: Rooftop landscape plants have demonstrated their capacity to contribute significantly to urban climate improvements. These plants play a pivotal role in absorbing particulate dust and mitigating the presence of toxic gases in the atmosphere, simultaneously regulating the humidity levels within urban environments. Moreover, they serve as effective buffers for reducing noise pollution in residential zones, showcasing a notable noise-reduction efficacy. Through the process of photosynthesis, green plants exhibit an impressive ability to sequester substantial quantities of carbon dioxide from the surrounding atmosphere, thereby acting as a countermeasure against the formation of urban "heat islands". Additionally, these rooftop plants offer a protective function, preserving the integrity of the waterproofing layer on rooftops, consequently extending the operational lifespan of the roofs [20].

Beautifying the urban air landscape: The development of ocean urbanization is very rapid. If different forms of rooftop landscape plants can be arranged at the top of these buildings, then above the city, there would not be just a lifeless concrete roof. Relevant data show that if there is green comprises 25% of the sight line, it can make people feel happy. The existence of rooftop landscape plants can precisely meet this demand, which can regulate people's psychological state and effectively improve the mental outlook of urban populations [21]. The multifaceted roles of rooftop landscape plants extend beyond mere visual enhancement. These botanical elements, carefully selected and positioned, act as urban ecotones, seamlessly blending nature into the urban fabric. Beyond their immediate visual appeal, these plants play an active role in fostering biodiversity by providing habitats for various insects and birds that contribute to a balanced ecosystem. Furthermore, they serve as natural air purifiers, absorbing pollutants and releasing oxygen, thereby improving the overall air quality of the city. This harmonious coexistence of greenery and urbanity not only delights the senses but also creates a harmonizing effect that resonates with the aspirations of modern urban living.

Having a good insulation effect: Due to direct sunlight in summer, roofs without greenery have much higher temperatures than the outside. Moreover, due to the color and material of the roofs, the heating rate varies, with some roofs reaching a heating rate of over 80%. However, on a roof with green vegetation, the surface temperature of the roof can be effectively reduced due to the blocking of heat by leaves and the emission of heat by transpiration. Therefore, the indoor temperature of the building can be effectively controlled in the hot summer [22]. If the roof is arranged with a carpet-like lawn and with a certain number of crawling plants placed on the walls, it can effectively reduce indoor temperature and mitigate a lot of electricity consumption. Plants' ability to act as natural coolants during sweltering summers is facilitated through their shading effect, which reduces solar heat gain on rooftops. This not only directly contributes to lower indoor temperatures but also translates into reduced energy consumption for air conditioning. Moreover, these plants play a pivotal role in stormwater management by absorbing rainwater, thereby reducing runoff and the strain on drainage systems. In stark contrast, in winter, this covered roof can provide excellent insulation. The dynamic role of rooftop landscape plants as thermal regulators underscores their significance in moderating indoor temperatures. By forming a protective layer against heat loss, they contribute to energy savings by reducing the need for excessive heating. This dual-season insulation effect aligns with the ethos of sustainability and resource optimization, further reinforcing the instrumental value of rooftop landscape plants in contemporary urban design.

2.4. Computer Visual Design Techniques

Computer visual design techniques encompass various methods and tools used to create and manipulate visual elements in digital environments. Two key technologies in this realm are 3D modeling and virtual reality (VR). Three-dimensional modeling involves the creation of three-dimensional digital representations of objects or spaces, allowing for a realistic and interactive visualization. VR, on the other hand, immerses users (or the design team responsible for creating and implementing the rooftop garden design) in a simulated environment, enabling them to interact with and experience a virtual world [23].

In computer vision, image processing refers to the analysis and manipulation of digital images using algorithms and computational methods. It involves tasks such as image enhancement, segmentation, feature extraction, and object recognition. By extracting meaningful information from images, computer vision techniques enable the understanding and interpretation of visual data. The data-preparation stage of the computer vision system is shown in Figure 2.

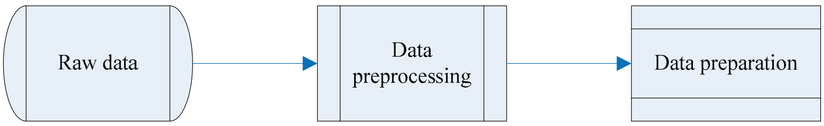


Figure 2. Computer vision system's data-preparation phase.

The method of computer vision image processing is shown in Figure 3.

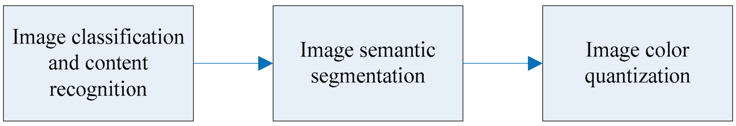


Figure 3. Methods of computer vision image processing.

Computer visual design techniques refer to the utilization of advanced software tools, often based on computer vision technology, to create and manipulate visual elements in a digital environment. These techniques enable designers and architects to simulate, model, and visualize various aspects of landscapes, structures, and objects in a highly detailed and interactive manner.

In this thesis, highlighting the application of computer visual design techniques, specifically using software like 3DMax, in the field of rooftop garden landscaping. This involves using the capabilities of such software to digitally model and visualize rooftop garden layouts, plant arrangements, and other landscape elements. The software's computer vision capabilities can assist in various ways:

Three-dimensional modeling: Computer visual design software like 3DMax allows designers to create detailed three-dimensional models of rooftop landscapes. This modeling can encompass everything from the layout of plants and structures to the overall spatial arrangement, providing an accurate representation of how the final garden would look.

Realistic visualization: These software tools enable the creation of high-fidelity visualizations that closely resemble real-world conditions. Designers can incorporate realistic textures, lighting, and environmental factors, giving stakeholders a clear and vivid understanding of the proposed rooftop garden's appearance.

Simulation and analysis: Computer visual design software often includes simulation features that can be used to analyze different scenarios. For rooftop garden landscaping, this could involve simulating the growth of plants over time, assessing factors like sunlight exposure, wind patterns, and how the garden might evolve seasonally.

Iterative design: The digital nature of these techniques allows for quick and easy modifications to the design. Designers can experiment with various plant placements, materials, and layout configurations, rapidly refining their ideas to achieve the desired outcome.

Stakeholder communication: These visualizations can serve as effective communication tools between designers, clients, and other stakeholders. By providing a realistic preview of the proposed rooftop garden, these techniques facilitate better understanding and decision making.

In essence, this thesis underscores the potential of utilizing computer visual design techniques to enhance the process of rooftop garden landscaping. By harnessing software equipped with computer vision technology, such as 3ds Max, designers can advocate for a more efficient and effective approach to designing, visualizing, and refining rooftop gardens, ultimately contributing to the advancement of sustainable urban landscapes.

2.5. The Landscape Design Process for Roof Gardens

The landscape design process for roof gardens involves a series of systematic steps aimed at conceptualizing, planning, and creating green spaces on the rooftops of buildings. This paper emphasizes the utilization of computer visual design techniques, particularly software with computer vision technology like 3ds Max, to enhance and facilitate this process. The following is an overview of the typical steps in the landscape design process for roof gardens:

Site analysis and assessment: The process begins with a comprehensive evaluation of the rooftop's characteristics. This includes assessing factors such as sunlight exposure, wind patterns, structural integrity, load-bearing capacity, and existing utilities. Computer visual design techniques can aid in creating accurate digital models of the rooftop, allowing designers to analyze these factors in detail.

Conceptualization and ideation: Designers brainstorm and develop initial ideas for the rooftop garden. This phase involves considering the client's preferences, functional requirements, and aesthetic goals. Computer visual design software enables the creation of digital sketches and preliminary visualizations that help translate conceptual ideas into tangible representations.

Design development: The chosen concepts are refined and developed further. This involves specifying plant selections, hardscape elements (such as pathways and seating areas), and other design elements. Computer visual design techniques allow for the creation of detailed 3D models that provide a realistic preview of the garden's layout, helping designers and clients visualize the final outcome.

Visualization and simulation: This step involves using computer visual design tools to create high-quality visualizations and simulations. Designers can apply realistic textures, lighting, and environmental effects to the digital models. Additionally, simulations can be used to predict how plants will grow over time, how shadows will change during different times of the day, and how the garden will evolve with the changing seasons.

Refinement and iteration: Computer visual design software allows for easy modifications to the design. Designers can experiment with various plant arrangements, colors, materials, and spatial configurations. Iterative refinement ensures that the design aligns with the client's vision and functional requirements.

Documentation and communication: Detailed plans, sections, and elevations are generated using the software tools. These documents serve as crucial references for construction and installation. Additionally, the high-quality visualizations facilitate effective communication with clients, stakeholders, and contractors, ensuring a shared understanding of the design intent.

Implementation and maintenance: Once the design is finalized, the actual construction of the rooftop garden takes place. Proper installation of plants and hardscape elements follows the detailed plans and specifications generated during the design phase. Ongoing maintenance ensures the garden thrives and continues to contribute positively to the urban environment.

2.6. Benefits and Applications in Interaction Design

The application of computer visual design techniques, specifically 3D modeling and VR, offers numerous benefits and applications in the field of interaction design, particularly in rooftop gardens [24].

Enhanced visualization: 3D modeling enables designers and users to visualize rooftop gardens in a realistic and immersive manner. It allows for a better understanding of spatial arrangements, plant placements, and design concepts. Users can explore the garden from different perspectives, fostering a deeper connection with the space and facilitating informed design decisions [25].

Interactive exploration: VR technology provides an unparalleled opportunity for users to interact with rooftop gardens. By simulating the experience of being in the garden, users can virtually walk through the space, interact with plants, and experience various design elements. This interactive exploration promotes engagement and enables users to envision the potential of the rooftop garden [26].

Iterative design process: Computer visual design techniques facilitate a more iterative and collaborative design process. Designers can create, modify, and refine 3D models of the rooftop garden, allowing for quick prototyping and testing of different design iterations. Users can provide feedback and actively participate in the design process, resulting in more user-centered and optimized designs.

Educational and informative experiences: Computer visual design techniques can be leveraged to create educational and informative experiences in rooftop gardens. Through 3D modeling and VR, users can learn about different plant species, their characteristics, and their ecological relationships [27]. This interactive learning experience fosters environmental awareness and promotes sustainable practices.

User engagement and well-being: The immersive and engaging nature of computer visual design techniques enhances user experiences in rooftop gardens. By incorporating interactive elements such as touch-based interactions or gamified activities, users can actively engage with the environment, fostering a sense of well-being, curiosity, and connection with nature.

Computer visual design techniques, including 3D modeling and VR technologies, offer numerous benefits and applications in the field of interaction design for rooftop gardens. They enable enhanced visualization, interactive exploration, iterative design processes, educational experiences, and increased user engagement. By leveraging these technologies, rooftop gardens can provide immersive and engaging experiences that promote sustainable design and improve the overall well-being of users [28].

3. A Case Study of the Application of Computer Visual Design to Green Rooftop Landscapes in Marine Cities

The Alibaba office building headquarters is a landmark building located in Hangzhou, China, and is home to the headquarters of Internet giant Alibaba. The building was designed by the internationally recognized architectural firm, Foster + Partners, and is an office and a commercial, cultural, and recreational complex. There are 15 roof gardens in the overall park, with a minimum area of 390 square meters and a maximum area of 878 square meters (As in Figure 4).

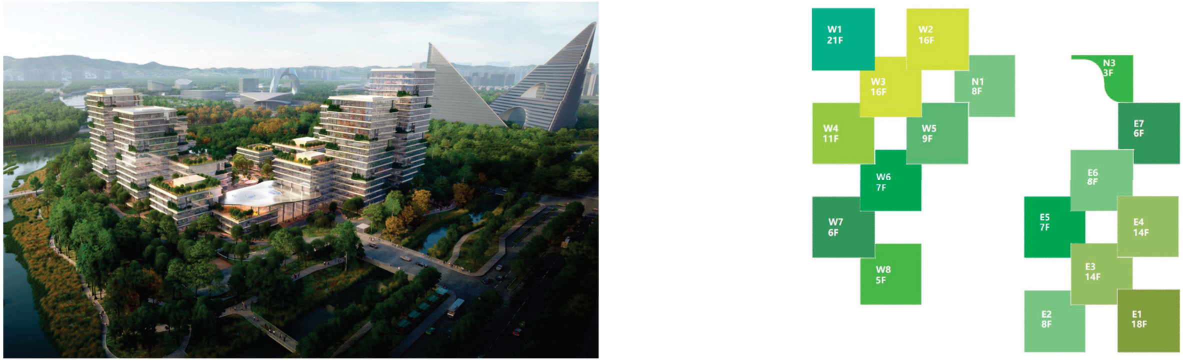


Figure 4. Location Map of Alibaba Corporate Headquarters Building and Roof Garden.

This paper takes the rooftop garden of Alibaba's headquarters building as a case study to conduct in-depth research on the application of computer visual design techniques, specifically computer vision and 3D rendering, in the intelligent interaction design of green roof landscape plants in ocean cities. The aim is to explore the potential of these technologies in optimizing the integration of green roof landscape plants and improving the overall landscape design.

To begin, computer vision techniques were employed to analyze and process images of the rooftop garden. By capturing high-resolution images and utilizing image-processing algorithms, various aspects of the rooftop garden, such as plant composition, spatial arrangement, and overall greening rate, were measured and evaluated. Computer vision enabled efficient and accurate data collection, providing valuable insights into the effectiveness of green roof landscapes in marine cities. Next, 3D rendering techniques were utilized to create detailed and realistic representations of the rooftop garden. By translating design drawings and plant simulations into three-dimensional models, designers are able to visualize and analyze the interactive design aspects of the plant landscapes. Herein, this included evaluating the placement of different plant species, assessing their visual impact, and understanding the ecological relationships within the rooftop garden.

The research focuses on several key aspects. Firstly, the greening rate of plants in the rooftop garden was measured and analyzed using computer vision techniques. By quantifying the coverage and distribution of plants, the effectiveness of the green roof landscape in providing environmental benefits, such as heat insulation and carbon sequestration, was able to be assessed. Furthermore, the composition of the rooftop garden's plant species was examined. Computer vision techniques aided in identifying and categorizing the various plants present in the rooftop garden. This analysis provided valuable information on the biodiversity and ecological balance of the green roof landscape. It also enables designers to make informed decisions regarding plant selection, considering factors such as adaptability to marine climates, resistance to saltwater exposure, and compatibility with the overall design concept. The interactive design of the plant landscapes was explored based on the 3D rendering models. By virtually experiencing the rooftop garden through VR technology, designers, users, and stakeholders can engage in interactive exploration and provide feedback on the design. This user-centered approach fosters participatory design, allowing for adjustments and improvements to be made based on user preferences and needs.

3.1. Simulation Experiment of Green Roof Landscape Plants in Marine Cities under Computer Vision

Ocean city data and computer technology have become important sources and methods for measuring landscape quality [29]. With the continuous progress and application of computer vision algorithms, landscape preference research has now developed towards large-scale, quantitative, and high-precision directions. The use of computer vision algorithms to measure landscape spatial quality and public perception preferences has been explored in multiple fields and scales, and various attempts have been made in the application of different algorithms [30]. At present, there is relatively little research in this field, and the research direction is mostly focused on the measurement of the green vision rate. There are also some shortcomings in the application and innovation of algorithms. Therefore, it is necessary to study a multi-dimensional landscape image quantification measurement method based on public perception and to use various computer vision algorithms to parameterize green roof landscape plant images. By extracting various landscape features from images and summarizing the dimensional structure of landscape images from multiple perspectives, the public's perception preferences can be analyzed.

Machine learning is often used in computer vision algorithms. Machine learning utilizes the set Q as training data. The best assumption in the assumed space is h, and N(h) is used to represent the initial probability of hypothesis h before the untrained dataset Q, while P(Q) reflects the probability of hypothesis h holding after setting the training data Q. The calculation method for probability is shown in Formula (1):

$$\mathrm{P(Q)} = \frac{\mathrm{N(h)}}{\mathrm{h}} \tag{1}$$

In the process of machine learning, the assumption of maximum likelihood is called the maximum posterior hypothesis, and the calculation method is shown in Formula (2):

$$\mathrm{h} = \arg\min \mathrm{P(Q)} \tag{2}$$

By combining Formulas (1)–(3), the following can be obtained:

$$\mathrm{h} = \arg\min \frac{\mathrm{N(h)}}{\mathrm{h}} \tag{3}$$

Computer vision techniques offer a powerful means to extract valuable landscape features through the utilization of image segmentation algorithms. One particularly useful metric is the green view index (GVI), which provides a quantitative measure of the greening level in ocean cities' landscapes. By quantifying the panoramic green view rate, it is possible to assess the aesthetic value of these cities and understand the significant impact of greening rates on people's overall life satisfaction and well-being [31]. And the study of greening rates also contributes to the refinement and development of interactive landscaping [32].

Figures 5 and 6 provides a visual representation of the numerical distribution of the green visibility rate across all samples of green roof landscape plants in marine cities. This data visualization offers valuable insights into the effectiveness of these rooftop gardens in increasing the overall greening rate, further highlighting the significance of intelligent interaction design and computer visual design techniques in optimizing the integration of green roof landscape plants in ocean cities. By utilizing computer vision algorithms to extract landscape features and quantify the greening rate through the green view index, this research highlights the vital role of intelligent interaction design and computer visual design techniques in optimizing the integration of green roof landscape plants in ocean cities.

The analysis of the data presented in Figure 6 provided insightful observations regarding the distribution of green landscape plant samples based on their greening rates. It is evident that the sample group with a greening rate of 0.2 represents the largest proportion, accounting for a significant 38% of the total samples. Additionally, the green landscape plant samples with a greening rate of 0.2 make up 22.5% of the overall samples. In contrast, the differences in proportions among the samples with greening rates ranging from 0.6 to 0.8 are not statistically significant. Remarkably, when the greening rate reaches 1, the sample proportion is the smallest, comprising only 4.8% of the total.

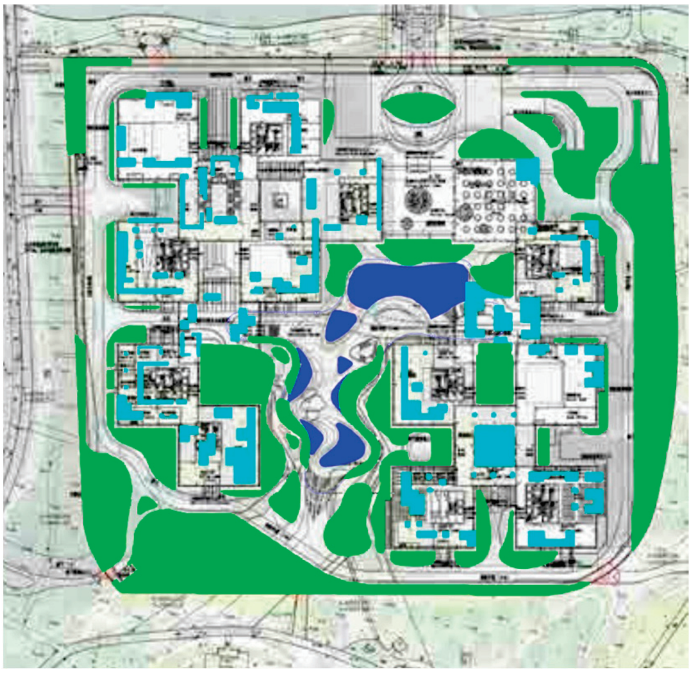


Figure 5. Roof garden green space map.

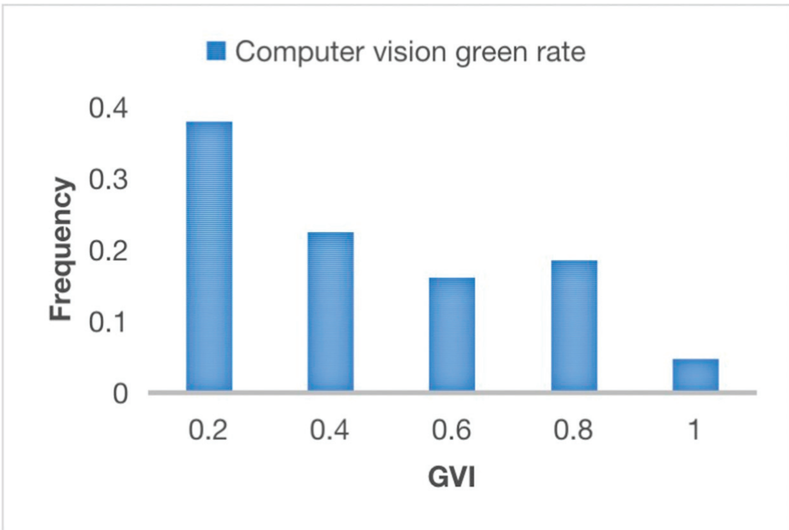


Figure 6. Distribution of green apparent rate of samples of green roof landscape plants in the rooftop garden of the Alibaba corporate headquarters building.

These experimental findings shed light on the greening rates of green roof landscape plants in the Alibaba corporate headquarters building roof garden, indicating a moderate level of greening. The results highlight the effectiveness of computer vision in observing and evaluating the greening levels of ocean city rooftop landscapes through advanced image-processing techniques and other technologies. This reflects the success of intelligent interaction enabled by computer vision, which played a significant role in obtaining relatively accurate greening rate measurements.

The experiment's outcomes further emphasize the significance of intelligent interaction design and computer visual design techniques in optimizing the integration of green roof landscape plants in ocean cities. By leveraging computer vision, designers can interact intelligently with the rooftop landscape, gaining precise measurements of greening rates. This intelligent interaction allows designers, users, and stakeholders to make informed decisions regarding landscape design, fostering the creation of aesthetically pleasing and environmentally beneficial green roof environments.

3.2. Analysis of Plant Landscape Interaction Design for Rooftop Garden of Alibaba Corporate Headquarters Building

3.2.1. Overall Analysis

The analysis of the roof gardens' ornamental intensity reveals that among the studied samples, there are four roof gardens categorized as having strong ornamental qualities, nine classified as medium, and two classified as weak (As shown in Figure 7). The areas with strong ornamental roof gardens exhibit a relatively high level of greening, aligning with the greening rate analysis discussed in the previous section.

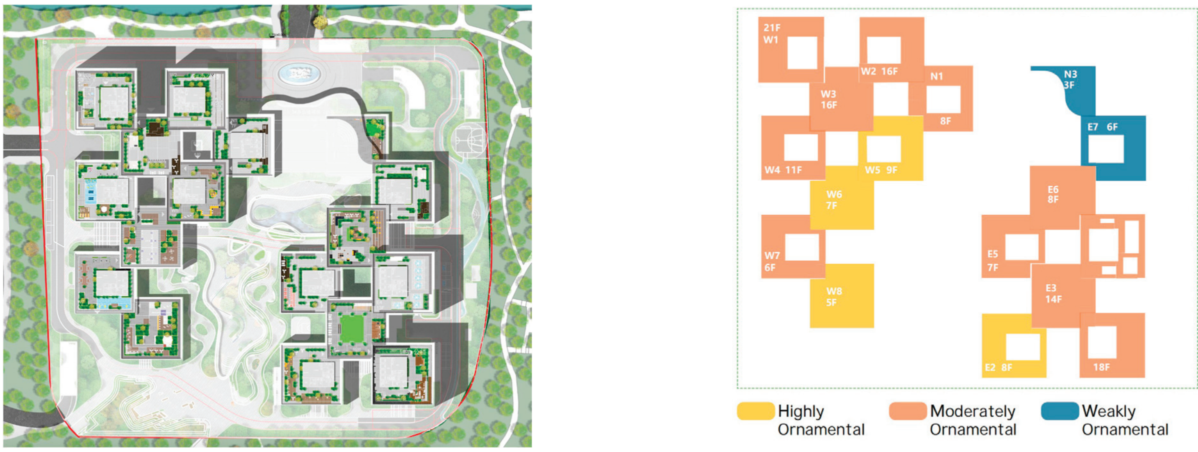


Figure 7. Three-dimensional floor plan and ornamental analysis diagrams.

The roof gardens encompass diverse spatial types, including multifunctional composite integrated spaces, public open spaces, semi-public open spaces, and private spaces. By distinguishing the characteristics of these roof gardens, they can be primarily categorized into four functional modules: negotiation spaces, observation decks, multi-person party areas, and VR virtual experiences. The careful arrangement and pairing of each functional module contribute to enhancing the interaction between individuals and the green roof landscape plants.

The negotiation space serves as a gathering area where people can engage in discussions and collaborative activities while being surrounded by the soothing presence of plants. The observation deck provides an elevated vantage point for individuals to appreciate the panoramic view of the green roof landscape, fostering a deeper connection with nature. The multi-person party area offers a social space where people can come together, socialize, and enjoy the vibrant ambiance created by the greenery. Finally, the inclusion of VR virtual experiences allows users to immerse themselves in virtual simulations of the rooftop gardens, providing an interactive and engaging platform to explore and interact with the plant landscapes.

3.2.2. Interactive Plantscape Design

Hangzhou, situated in the subtropical monsoon zone, experiences distinct seasons, abundant rainfall, and a wide variety of plant species suitable for growth. The greening efforts in Hangzhou follow a people-oriented approach, emphasizing ecological diversity, scientific principles, and artistic aesthetics. The selection of landscape tree species with ornamental value aims to meet functional needs such as accessibility, line-of-sight permeability, boundary richness, and interactivity. The design of rooftop gardens focuses on simplicity, aligning with the natural and functional requirements of green spaces. Attention is given to the interdependence between plants, ensuring a harmonious and visually appealing plant composition that incorporates color coordination, shapes, textures, and sounds to create a captivating landscape effect. The open entrance space of the rooftop garden employs ecological treatments to create a sense of grandeur. The tree species chosen should meet the requirements of the roof garden in terms of load bearing and maintenance management. Shaded activity areas are created through large trees with high points of support. The shrub groundcover is carefully trimmed to follow a natural curvature, which helps to soften the undulating and staggered heights, thereby mitigating the stark lines of the building. Comfortable lawns and natural flower paths are utilized to establish a serene leisure space and a tranquil resting area. Along the street, the display surface prominently features tall, straight, and large trees that serve as structural elements for the entire space. Combined with the building's visual interface, this creates a cohesive and expressive landscape, leaving a powerful visual impression on observers. Through the curved pruning of shrubs and ground cover, the building boundary is softened, and there is no lack of rich changes in the sense of sequence, which highlights the nobility and sophistication.

There are also shrubs, ground covers, and trees, as shown in Table 1.

Table 1. Proportion of park landscape color carriers.

Type	Name	Description	Benefits	Pictures
Shrubs	Dwarf Pomegranate (*Punica granatum* 'Nana'):	Dwarf pomegranates are small shrubs with glossy leaves and vibrant orange-red flowers that resemble miniature pomegranate blossoms.	These shrubs add a burst of color to rooftop gardens, and some varieties even produce small edible fruits. They thrive in full sun and can be pruned to maintain a compact size suitable for containers.	
	Lavender (*Lavandula* spp.)	Lavender is a fragrant herb with slender leaves and spikes of purple or blue flowers.	Lavender adds a delightful aroma and attracts pollinators like bees and butterflies. It thrives in sunny, well-drained locations and can be used for culinary purposes or for crafting aromatic products.	
	Rosemary (*Rosmarinus officinalis*)	Rosemary is an aromatic herb with needle-like leaves and small blue flowers.	Rosemary is drought-tolerant and well-suited for rooftop gardens. It adds fragrance and culinary versatility, and its evergreen foliage remains attractive year-round.	
Ground Covers	Blue Oat Grass (*Helictotrichon sempervirens*):	Blue oat grass is an ornamental grass with striking blue-gray foliage that forms neat clumps.	This grass offers a unique color contrast in rooftop gardens. Its compact size and drought tolerance make it suitable for containers. The foliage sways gracefully in the wind, adding movement to the landscape.	
	Creeping Jenny (*Lysimachia nummularia*)	Creeping Jenny is a trailing perennial with round, bright yellow-green leaves.	Creeping Jenny forms a lush ground cover that spills over edges, softening the look of containers. It is excellent for preventing erosion and adds a pop of color to your rooftop garden.	

Table 1. *Cont.*

Type	Name	Description	Benefits	Pictures
	Japanese Forest Grass (*Hakonechloa macra*)	Japanese forest grass is a low-growing ornamental grass with cascading, arching foliage.	This grass adds a graceful and flowing element to rooftop gardens. Its shade tolerance makes it suitable for partially shaded areas, and its texture creates a soothing contrast with other plant types.	
Trees	Japanese Maple (*Acer palmatum*)	Japanese maples are small trees known for their delicate, finely divided leaves and stunning fall colors.	Japanese maples bring elegance and architectural interest to rooftop gardens. They are available in various sizes and leaf colors, allowing for customization. Their foliage provides shade and their vibrant hues add seasonal beauty.	
	Dwarf Olive Tree (*Olea europaea* 'Little Ollie')	Dwarf olive trees are small, evergreen trees with silvery leaves and a classic Mediterranean appearance.	These trees bring a touch of the Mediterranean to rooftop gardens. They can be grown in containers and provide a timeless and sophisticated aesthetic. The silvery leaves reflect sunlight, helping to reduce heat absorption.	
	Dwarf Weeping Cherry (*Prunus subhirtella* 'Pendula')	Dwarf weeping cherry is a compact tree with cascading branches and delicate pink or white blossoms.	This tree brings a touch of elegance and romance to rooftop gardens with its pendulous branches and beautiful spring flowers. Its smaller size is suitable for containers, and it can be pruned to maintain its shape.	

The open activity space adopts a planting pattern that combines comfortable sparse forests and lawns, resulting in a leisurely landscape along the pathways. This design not only prioritizes walking comfort but also encourages people to engage with nature and participate in outdoor activities. The selection of large-crowned and shade-providing camphor trees creates pleasant, shaded areas where visitors can seek shelter from rain and engage in communication activities. The semi-open waterfront space accommodates the growth of lotus and cattails, creating a beautiful and natural water landscape. Along the shore, a wide variety of aquatic plants are planted to soften the water's edge and purify the water body. Additionally, the strategic placement of reeds around the artificial wetland allows visitors to have an up-close view of the garden without obstructing their line of sight, enhancing visual interaction (as shown in Figures 8 and 9).

The semi-open space features sparse forests dominated by green plants such as zelia and calamus, allowing visitors to experience the ever-changing charm of natural plant growth along their walking path and providing a closer connection to nature. The addition of other native tree species enriches the diversity of the landscape, creating a suitable habitat for birds to survive and forage. This in turn attracts birds and offers visitors a pleasant visual interaction experience, accompanied by the sounds of bird calls for an enhanced auditory experience. In the semi-enclosed space, plants like yew, magnolia, and camphor are planted densely, forming a hidden landscape that tantalizes visitors' curiosity (as shown in Figure 10).

Figure 8. Three-dimensional rendering of roof garden entrance.

Figure 9. Rendering of Rooftop Observation Deck.

Figure 10. Roof garden 3D effect.

The rooftop garden of Alibaba's headquarters building uses solar energy, wind energy, and other low-carbon and environmentally friendly new energy to increase the utilization rate and utilizes permeable paving, green roofing, soil and water conservation plants, etc. In terms of the selection of materials for the structures, paving, and facilities, Bengoshi stone, wood, and other materials are used to create a comfortable and pleasant environment and effectively protect the ecological environment. In the selection of materials for structures, paving, facilities, and sketches, the Bengoshi materials were selected to create a pleasant environment and effectively protect the ecological environment and to comprehensively utilize rainwater resources, conserve water, and improve the ecological environment with the use of innovative technology and techniques that are in line with the sustainability of the ecological environment and with local characteristics that are more harmonious and natural (as shown in Figure 11).

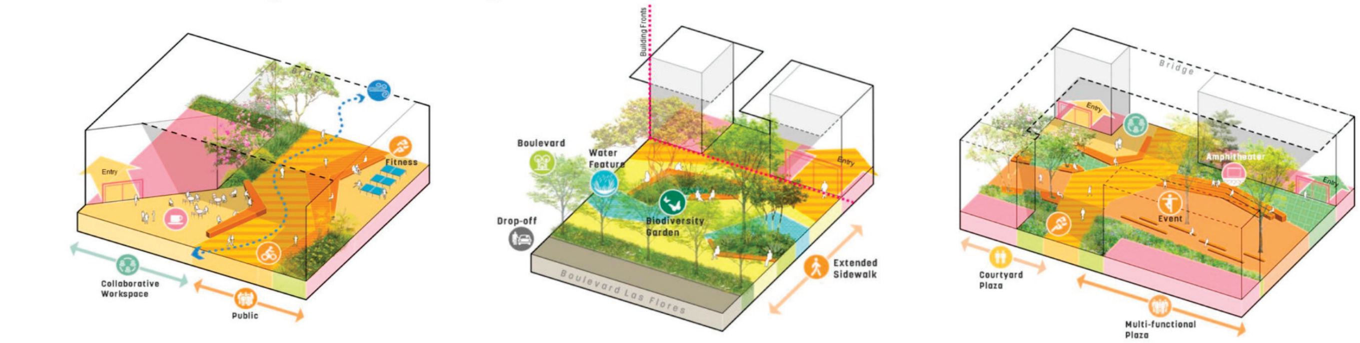


Figure 11. Schematic diagram of the ecological diversity of rooftop gardens.

The overall design of the rooftop garden emphasizes interactive plant landscapes, allowing people to experience the dynamic changes and charm of plant growth during their restful walks or conversations throughout different seasons. The characteristics of the plant landscape are harnessed to stimulate visual, tactile, auditory, and behavioral interactions, igniting human imagination and increasing visitors' interest in getting closer to nature. This design approach fosters a stronger connection between humans and nature, creating a more intimate relationship. Figure 12 provides a plant analysis diagram to further illustrate the diverse plant composition and layout within the rooftop garden.

Figure 12. Roof garden plant analysis chart.

3.2.3. Interactive Landscape Lighting Design

In the context of the rooftop garden at Alibaba's corporate headquarters building, the plant landscape lighting design plays a crucial role in enhancing its interactivity with people, especially during nighttime hours. The lighting design aims to highlight the unique characteristics of the plant landscape while creating a captivating environmental atmosphere. Various factors such as plant height, overall texture, branches, leaves, and the positioning of lamps and light sources are considered in the design process. By employing suitable lighting methods, the desired visual effects were achieved, transforming the rooftop garden into an artistic and decorative space. The roof garden plant landscape lighting design analysis diagram is shown in Figure 13.

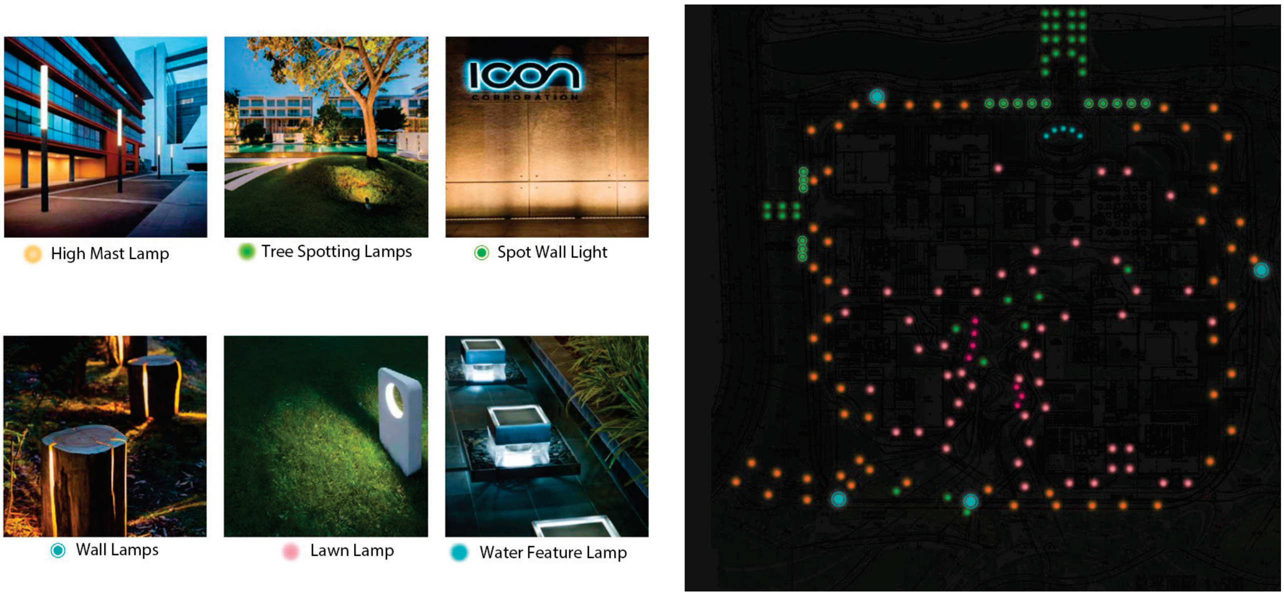


Figure 13. Rooftop garden plant landscape lighting design analysis diagram.

The landscape lighting at Alibaba's headquarters utilizes techniques such as light superposition, flow, translucency, and refraction to craft a highly imaginative sensory experience. Lamps are strategically concealed using techniques such as plant shading, light trough hiding, and low-level covering, creating an enchanting play of light that connects the area with nature. Suspended or silhouetted lighting effects further add to the magical ambiance of the rooftop garden.

A critical aspect of the plant lighting design is the choice of light source color. Different light sources can elicit varying color appearances and details in plants, evoking distinct emotions and sensations. The design team carefully selected colors to harmonize with each plant's inherent color and form, taking into account the unique structure of each tree. For spreading branches, up-lighting is used to illuminate the trunk and branches effectively, creating stunning effects for species like camphor and magnolia. In contrast, coniferous species with dense crowns near the ground require spotlights to illuminate their canopies from the periphery, showcasing seasonal changes throughout the year.

The plant landscape in the rooftop garden undergoes transformations in appearance with varying weather, seasons, and time of day. This dynamism was thoughtfully embraced in the lighting design, with corresponding adjustments made to highlight specific elements of the garden based on the season. During spring, summer, and fall, the focus may be on showcasing the lush crowns and foliage, while in winter, the emphasis shifts to the striking branches and tree trunks. This approach enhances the interactivity between visitors and the ever-changing plant landscape, allowing people to immerse themselves in the garden's unique atmosphere and the visual spectacle presented by different seasons.

To achieve a human-centric design, the lighting plan takes into account human physiological and psychological characteristics. The composition of light in the landscape design was carefully considered to evoke emotions and interactions, making visitors feel more connected to the plants and the environment. By thoughtfully combining technological prowess with a deep understanding of human needs, the rooftop garden at Alibaba's corporate headquarters exemplifies the integration of intelligent interaction design and computer visual design techniques, resulting in an engaging and visually captivating green roof landscape in the context of an ocean city. The lighting design not only enhances the user experience but also contributes to the overall well-being of urban dwellers, providing insights for future green roof landscape projects in ocean cities seeking to incorporate intelligent technologies for sustainable urban development.

3.3. Chapter Summary

Through computer vision image-processing techniques, the greening rate of the rooftop garden at Alibaba's headquarters building was accurately determined. These findings demonstrate the effectiveness of computer vision in accurately assessing and quantifying the greening rate of green roof landscape plants in ocean cities. The intelligent interaction of computer vision in image processing has proven to be highly beneficial in evaluating and optimizing the integration of green roof landscape plants, leading to a more sustainable and aesthetically pleasing urban environment. The specific results of the analysis are as follows:

(1) Analysis of Plant Landscape and Human Interaction:

The rooftop garden of Alibaba's headquarters building features a diverse plant landscape carefully curated to provide both aesthetic value and functional benefits. The designers employed 3D modeling and VR technology to create an immersive experience for users and stakeholders. By conducting in-depth case studies, the analysis revealed a strong alignment between computer vision and green rooftop landscape plant design in marine cities, further emphasizing the significance of intelligent interaction design and computer visual design techniques [33].

(2) The plant landscape design in the rooftop garden incorporates four functional modules: negotiation space, observation deck, multi-person party area, and VR virtual experience zone. Each module is strategically placed to enhance the interaction between visitors and plants, fostering a deeper connection with nature. The rooftop garden features a variety of plant species, including weeping willow, camphor trees, magnolia, cattails, and more, each chosen to create a specific ambiance and offer a range of sensory experiences.

The design also considers the rooftop garden's accessibility, line-of-sight permeability, boundary richness, and interactivity. For instance, the semi-open waterfront space is adorned with water's-edge plants like lotus and cattails, creating a beautiful and natural water landscape that allows for close interaction with the garden. Meanwhile, the semi-enclosed space is densely planted with yew, magnolia, and camphor trees, forming a hidden and secluded landscape, providing visitors with a sense of tranquility and enclosure.

(3) Plant Landscape Lighting Design and Human Interaction:

The rooftop garden's plant landscape lighting design significantly contributes to the interactivity between people and the environment, particularly during nighttime hours. This lighting design takes into account human physiological and psychological characteristics, emphasizing a human-centric approach. By thoughtfully selecting light sources and lamp positions based on plant height and characteristics, the lighting design effectively showcases the rooftop garden's unique features [34].

Using light superposition, flow, translucency, and refraction, the plant landscape lighting design creates a mesmerizing visual experience that captivates visitors. The lighting fixtures are strategically hidden through various methods, allowing the light to flow through the foliage or create enchanting silhouettes, fostering a harmonious connection between light and nature.

The lighting design also adapts to the changing seasons and weather conditions, allowing visitors to experience the rooftop garden's different scenes throughout the year. During spring, the focus is on illuminating lush crowns and leaves, while winter highlights the striking branches and tree trunks. This thoughtful adjustment enhances the rooftop garden's interactivity, making visitors feel closer to nature and creating a sense of wonder and awe.

In conclusion, the application of computer visual design techniques, 3D modeling, and VR technology in the intelligent interaction design of green roof landscape plants in ocean cities offers numerous benefits. From accurately assessing the greening rate to curating a diverse and interactive plant landscape and employing sophisticated lighting design, these intelligent technologies enhance the overall experience of green rooftop gardens. As urbanization continues, these findings provide valuable insights for designers, policymakers, and researchers seeking to create sustainable and engaging green spaces in ocean cities.

4. Comparative Analysis of Design Effects: A Case Study of Three-Dimensional Technology in Green Roof Landscapes of Coastal Cities

4.1. Case Selection Criteria and Analytical Methods

In line with current design trends for green roof landscapes in coastal cities, the dominant approach is visual design using new 3D2020 software. Through analysis of the climate conditions in marine cities, we aimed to understand the optimal design of roof gardens, including spatial requirements and plant arrangements. We used interactive software to simulate visitors' movements within the garden and generate ideas for an interactive experience. Abbreviations are defined on first use. In this paper, we examine the process of designing green roof landscapes using 3D software. We focus on two representative cases and conducted a comparative analysis with three additional cases to enhance the results. To gather information for the 3D design, we conducted a literature survey and used a specialized program design. According to the research cases presented in the previous section, this section analyzes the three-dimensional effects of various forms of green roofs. The following Table 2 contents are organized accordingly.

Table 2. Case information.

No	Device Name	Located in a City
A	Alibaba Headquarters Landscape Design	Shanghai, China
B	Roof Garden Landscape Program Of Xiamen 361 Office Building	Xiamen, China
C	Roof Garden of Qingdao Central Business District	Qingdao, China

4.2. Landscape Plant Analysis after Applying 3D Technology

This papers analyze four representative green roofs for their three-dimensional effects and uses 3D and VR technology for further explanation. Table 3 shows the design of Alibaba's roof garden landscape plants.

The rooftop garden landscape design for the 361° office building in Xiamen is as displayed in Table 4.

As indicated in Table 5, the landscape design of the rooftop garden in Qingdao Central Business District was created.

Table 3. Alibaba Headquarters Landscape Design.

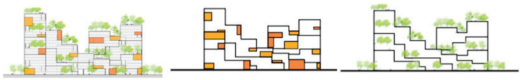
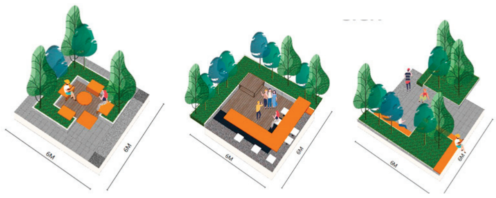
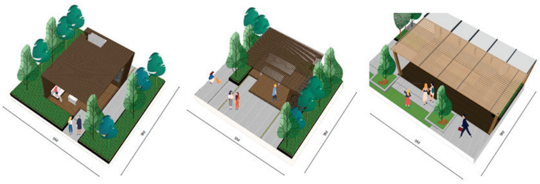
<table>
<tr><th colspan="3">Overview</th></tr>
<tr><td colspan="3">Setting up a green space that is distinctively characterized by a landscape corridor, theater area, and leisure space in the rooftop garden can provide the city landscape with a living-room function. Various plantings can be combined and echoed to provide green spaces that promote the sustainable development of the ocean city.</td></tr>
<tr><td>Photograph</td><td colspan="2"></td></tr>
<tr><td colspan="3">Application characteristics of 3D technology</td></tr>
<tr><td>Color</td><td></td><td>The green roof space was functionally divided with various colors representing different functions paired with different types of plants.</td></tr>
<tr><td>Shape</td><td></td><td>According to the various sizes and orientations of green roof spaces, the morphological design satisfies both mobility and ornamental needs, utilizing plant shading to divide the area.</td></tr>
<tr><td>Proportion</td><td></td><td>The green roof's planting ratios were determined by the space proportions of the site, accompanied by corresponding decorative proportions for each area.</td></tr>
<tr><td>Texture</td><td></td><td>Through the use of plant texture matching, ground pavement, installation styles, wall decorations, and other textures, the embodiment of different effects of three-dimensional technology was achieved.</td></tr>
</table>

Table 4. Roof Garden Landscape Program of Xiamen 361° Office Building.

<table>
<tr><th colspan="2">Overview</th></tr>
<tr><td colspan="2">The 361° Building is situated in Xiamen, China, a typical seaside city. In general, it employs a new Chinese style of landscaping, incorporating various types of flora based on population usage, emphasizing a more upscale and tasteful ambiance, and showcasing Zen influences.</td></tr>
<tr><td>Photograph</td><td></td></tr>
</table>

Table 4. *Cont.*

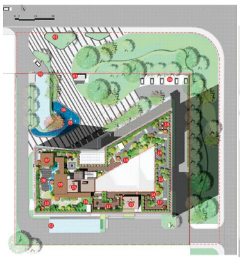
Application characteristics of 3D technology		
Color	 	Computer software was utilized to differentiate the colors on the roof plan according to their respective functions. The vegetation colors can also contribute to the division of space as well as the paving materials.
Shape		Based on the building's brand image, a stylized plant design was implemented in the rooftop garden. The planting space was designed to reflect the brand's colors and shapes.
Proportion		The design of the plants and the spatial layout of the rooftop garden must adhere to ergonomic principles. The size of the plants and the spatial scale should be proportional to achieve a harmonized design.
Texture		In the hardscaping section of the rooftop garden, it is important to maintain an overall unity in texture style. Combining hard slate and soft plants creates an intriguing and beautiful textural contrast.

Table 5. Roof Garden of Qingdao Central Business District.

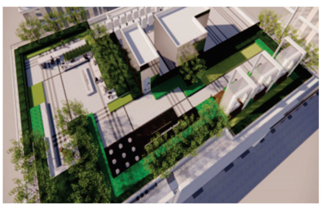
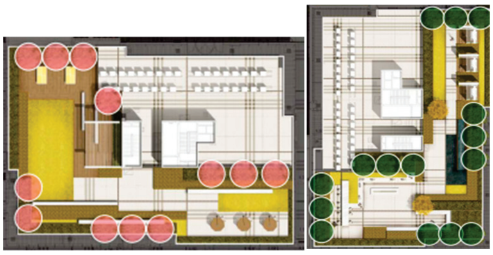
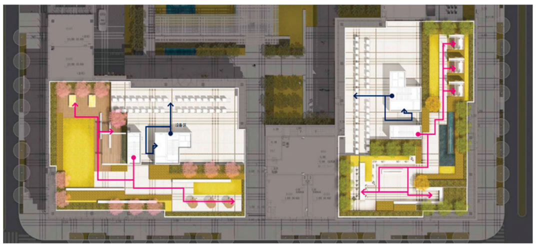
Overview	
The rooftop garden design at Qingdao Central Business District is based on the concept of small scale. The combination of compact space and foliage creates an ideal walking and leisure area.	
Photograph	  

Table 5. *Cont.*

Application characteristics of 3D technology		
Color		The rooftop garden design in Qingdao's Central Business District is based on the concept of a smaller scale, featuring proportionate space and plants that together create a rooftop garden suitable for walking and leisure.
Shape		The design of the plant layout for the roof garden space is based on the image of sparse and dense urban transportation networks, resulting in a rhythmic plant network with an irregular shape.
Proportion		The design of green roof plants fully takes into account the size ratio of plants, utilizing it to create varying smaller spaces. No changes necessary.
Texture		The floor paving texture in the rooftop garden complements the texture of the plants, contributing to the harmonious spatial design.

4.3. Summary of Analysis

As presented in Table 6, a comparative analysis was conducted to examine the impact of 3D technology in the three primary scenarios. The analysis summarizes the application space, advantages, and drawbacks for each case.

The three case studies of green roof development yield the following conclusions:

(1) It is necessary to enhance the theory of roof garden design by adhering to correct design.

First, the concept of appropriate ecological design is based on the climatic conditions of the region and selecting vegetation that suits the roof's planting site. Second, the concept of sustainable development design is also important. Rooftop garden landscape design is a viable option, as shown by Alibaba's success story. However, it is not necessary to adopt all popular foreign elements, which can increase costs and be an imprudent behavior. It is important to consider the impact on expenses before making such decisions. To ensure the seamless integration of such imported goods into China's urban development, it is also essential to implement a sustainable development strategy for rooftop gardening. This must be carried out in a progressive and steady manner, taking into account national conditions and economic development.

(2) It is crucial to carefully select plants that are suitable for the region's growth and development.

Firstly, the high location of the roof suggests the choice plants that thrive in direct sunlight and have a well-developed root system. Secondly, given the limited weight-bearing capacity, it is advisable to opt for lightweight flowers or herbaceous plants. Thirdly, since the soil layer on the roof is shallow and lacks water-storage capacity, drought-resistant vegetation is a suitable choice.

(3) Computer-aided three-dimensional technology can be utilized to optimize the landscape design in accordance with the building's form and function.

The landscape design for the roof garden failed to consider the building group's shape and did not establish clear design standards beforehand. To enhance the design program, it is recommended to lay out the landscape design in accordance with the building group's shape and function. The intention of this approach is to adapt to the local conditions. Combined with the form and function of the building complex, a garden landscape must be designed that is harmonious with the surrounding environment and fully reflects the functional characteristics of the building. It must adopt a natural layout that reflects the coordination and integration of the building with the garden landscape or adopt a conventional approach that emphasizes landscape decoration and arrangement to enhance the landscape level and compensate for spatial constraints. However, in selecting garden vignettes, weight and volume restrictions due to the roof's load-bearing capacity necessitate a considered approach. Alternatively, the designer may change the materials used for garden vignettes, such as employing lighter volcanic rock for rockeries. Adjusting the landscape of the roof garden can be achieved through manipulating color, shape, proportion, and texture by means of a computer.

Table 6. Comparative analysis of rooftop garden 3D technology application cases.

	Case	Application Space Type	Advantage	Insufficient
A	Alibaba Headquarters Landscape Design	Office building roof garden	Public space; large site scale; rich plant mix.	The ornamental value is average; the plant space is fragmented.
B	Roof Garden Landscape Program Of Xiamen 361° Office Building	Roof garden of sports brand building	Chinese cultural elements have a strong sense of experience; there are many types of plants, and the design effects are rich.	The dredging and discreteness are weak; large green plants cannot be planted.
C	Roof Garden of Qingdao Central Business District	Rooftop garden in business district	Strong sense of ecological experience; strong sense of plant design.	The ornamental value is single; the planting of some plants in the northern region is limited.

4.4. Analysis of Results

(1) Generalization and General Design of Analytical Studies:

A fundamental consideration in research involving case studies represents the extent to which the findings can be extrapolated to wider contexts, thereby contributing to universal design principles and practices. In the context of the study titled "Computer Vision Interaction Design in Sustainable Urban Development: A Case Study of Roof Garden Landscape Plants in Marine Cities", it is pertinent to address the generalizability of the case study findings.

The case study focused on the rooftop garden of the Alibaba headquarters building, examining the integration of computer visual design techniques, 3D modeling, and VR technology in the intelligent interaction design of green roof landscape plants. While this case study is insightful and provides a specific example of effective integration, it is essential to discuss the potential for broader applicability. Therefore, this study comparatively analyzes the roof gardens of two other ocean cities. The study of three cases makes the research conclusion more rigorous and scientific.

Universal design implications: The insights derived from the case study hold potential implications for the broader domain of green roof landscape design in ocean cities. The principles and methodologies employed, such as accurately assessing greening rates, curating diverse plant landscapes, and employing sophisticated lighting design, can serve as foundational concepts applicable to other similar projects. At the same time, comprehensive design is carried out from aspects such as color, shape, proportion, texture, and so on.

Key considerations for generalization: It is crucial to recognize that the success and generalizability of case study findings depend on various factors, including the context, scope, and specific characteristics of the target projects. The generalizability of our findings rests on the alignment of factors such as climate, geographical location, urban planning regulations, and user preferences.

While our case study offers a specific example of intelligent interaction design in a green roof landscape, its generalizability to universal design principles requires careful consideration of contextual factors. Our study serves as a foundation, and its findings can be interpreted alongside existing research to ascertain their broader applicability in enhancing green roof landscapes in various marine cities.

(2) Analysis of the Spatial Structure Presented in the Case Study:

Landscape typology of the rooftop garden: The landscape typology of the rooftop garden can be categorized as a "Multifunctional Urban Oasis". This typology encapsulates the fusion of ecological, aesthetic, and interactive elements within an urban context. The garden serves as a retreat within the bustling city, offering not only visual delight but also functional benefits such as temperature regulation, air purification, and biodiversity enhancement. The negotiation spaces, observation deck, party area, and virtual experience zone each contribute to this multifaceted typology, providing opportunities for relaxation, connection with nature, and engagement.

The case study centers around the rooftop garden of the Alibaba headquarters building, a landmark in Hangzhou, China. This case is compared with the other two cases. This garden showcases a thoughtfully designed spatial structure that integrates various functional modules, plant species, and interactive elements. The spatial arrangement exhibits a purposeful division of zones, each contributing to the overall user experience and interaction with the green roof landscape.

Scope of application of the case study: The scope of this case study is centered around showcasing the integration of intelligent technologies, specifically computer visual design techniques, in the design and interaction of green roof landscapes in ocean cities. While the case study's primary focus is on the rooftop garden of the Alibaba headquarters building, its implications extend beyond this specific location. The principles, methodologies, and findings presented offer valuable insights for designers, researchers, and policymakers seeking to enhance green roof landscapes in diverse marine cities facing similar urbanization and sustainability challenges.

By utilizing computer vision and 3D rendering techniques, the study addresses key aspects of green roof design: greening rate assessment, plant species composition, interactive design, and lighting considerations. The case study's scope of application encompasses not only rooftop gardens in marine cities but also potentially any urban environment that aims to leverage intelligent technologies for sustainable and engaging green spaces.

5. Discussions

Prior this study, existing research has explored various aspects of green roof landscapes and their benefits in urban environments. Many studies have focused on the environmental advantages of green roofs, such as their ability to mitigate heat-island effects, improve air quality, and reduce stormwater runoff [35]. Additionally, some research has investigated the impact of green roof landscapes on the well-being and mental health of urban dwellers, highlighting the importance of incorporating nature into urban settings. Moreover, previous works have discussed the role of technology, including computer vision and 3DMAX modeling, in landscape design and urban planning. These technologies have been applied in different contexts, such as simulating urban environments, visualizing architectural designs, and assessing the performance of green spaces [36]. However, there is a gap in the literature regarding the specific application of computer visual design techniques, 3D modeling, and VR technology in the intelligent interaction design of green roof landscape plants in ocean cities. This study seeks to bridge that gap by exploring the novel use of these technologies in the context of rooftop gardens. This study stands out from the existing research in several key aspects [37]. Firstly, it addresses the specific context of green roof landscapes in ocean cities, which presents unique challenges and opportunities compared to other urban settings. Ocean cities face distinctive climate conditions, and their rooftop gardens must be carefully designed to withstand saltwater exposure and other environmental factors [38]. This paper acknowledges these challenges and proposes intelligent interaction design solutions that cater to the marine city context.

Secondly, this research places a strong emphasis on the integration of intelligent technologies, particularly computer visual design techniques, 3D modeling, and VR technology, in the design process. By leveraging these tools, designers can interact intelligently with the rooftop landscape, leading to more informed decisions and better outcomes. This integration of technology and design aligns with the growing trend of smart urban development and highlights the potential for creating innovative and sustainable green roof landscapes [39].

While this study provides valuable insights into the application of computer visual design techniques and intelligent interaction design in green roof landscapes, there are certain areas that warrant further exploration. Firstly, the research primarily focuses on the case study of the Alibaba headquarters building. Although there are also comparative analyses of two other cases, this may limit the generalizability of the findings. Future research could include a broader range of case studies from various ocean cities to enhance the comprehensiveness of the results.

Additionally, the study primarily emphasizes the greening rate and aesthetic aspects of rooftop gardens. Future research could delve deeper into the functional aspects of green roof landscapes, such as their role in providing habitat for biodiversity, supporting urban agriculture, and contributing to energy efficiency and building performance. Understanding the multifaceted benefits of rooftop gardens will enable a more holistic approach to their design and integration into urban environments. As technology continues to evolve, there may be opportunities to explore emerging computer visual design techniques and other intelligent technologies that could further enhance the interaction design of green roof landscapes. Integrating advancements in artificial intelligence, data analytics, and sensor technologies could open new avenues for optimizing the performance and user experience of rooftop gardens.

6. Conclusions

The conclusions drawn from this research are well defined within a focused and referenceable research scope. Through a comprehensive analysis of the rooftop garden at the Alibaba headquarters building and a comparative analysis of the other two cases, this study effectively demonstrates the applicability and benefits of integrating computer visual design techniques, particularly 3D modeling and virtual reality, in the intelligent interaction design of green roof landscape plants in marine cities. This article studied the intelligent interaction of green rooftop landscape plants in marine cities using computer vision technology. This can enable more reasonable design of landscape plant layout. This article tested the distribution of greening rates of various rooftop landscapes under computer vision through experiments. These greening rate data can provide a reference for landscape design. This research delves into the realm of intelligent interaction design of green roof landscape plants in ocean cities, leveraging the power of computer visual design techniques and 3D modeling. The rapid urbanization and the growing demand for sustainable development have given rise to the emergence of green roof landscapes, which not only provide significant environmental benefits but also contribute to the overall well-being of urban dwellers.

The integration of intelligent technologies is paramount in optimizing the design and interaction experience of green roof landscapes. Through case studies and extensive analysis, we have established that computer vision, particularly in the image processing of rooftop landscapes, offers remarkable accuracy in assessing and quantifying the greening rate of green roof landscape plants. This valuable information empowers designers and policymakers to create more effective and sustainable urban environments.

The application of 3DMAX modeling and VR technology enriches the design process by providing designers, users, and stakeholders with immersive and engaging experiences. By simulating and visualizing the rooftop gardens, designers can interact intelligently with the space and make well-informed decisions to enhance the landscape design effectively. The compatibility between computer vision and green rooftop landscape plant design in marine cities underscores the potential of these technologies in shaping aesthetically pleasing and functional green spaces.

The specific conclusions obtained within this scope include the following:

Effectiveness of computer vision design aids: The efficiency of computer vision design technology is prominently demonstrated through its utilization in the analysis of greening rates via 3DMAX renderings. This approach offers a precise and dependable method for assessing and quantifying the extent of greenery within rooftop landscape plants. Moreover, within the domain of plant landscape design, the versatility of this technology allows for real-time adjustments to design schemes in alignment with specific requirements. As a result, the overall efficacy of the design process is significantly enhanced.

Alignment with design: The alignment between computer visual design techniques and green rooftop landscape plant design in marine cities is clearly demonstrated. Through in-depth case studies, we highlight the significance of intelligent interaction design and computer visual design techniques in enhancing user experiences with green rooftop gardens.

Scope of application: Our study's conclusions are specifically applicable to the integration of computer visual design techniques, 3D modeling, and VR technology in green roof landscaping within ocean cities. The findings provide valuable insights for designers, policymakers, and researchers working on sustainable urban development in similar marine environments.

Enhanced interaction design: Through in-depth case studies, the study affirms a strong alignment between computer visual design techniques and the effective design of green rooftop landscapes in marine cities. The utilization of 3D modeling and virtual reality facilitates immersive experiences for designers, users, and stakeholders. This finding underscores the potential for intelligent technologies to enhance human interaction with green spaces.

Ecological considerations: The research recognizes the importance of plant species composition and ecological balance in green roof landscape design. The study's application of computer vision in identifying and categorizing plant species informs the selection process for plants that thrive in marine climates, thus contributing to sustainable and resilient designs.

User-centered approach: The investigation underscores the significance of a human-centric approach in landscape lighting design. By thoughtfully adapting lighting to seasonal changes and physiological factors, the research showcases the potential of computer visual design techniques to create captivating visual experiences that foster a stronger connection between visitors and the natural environment.

Applicability to ocean cities: The study's scope is clearly defined within the context of marine cities, catering to the specific challenges and opportunities posed.

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Cross-Compatibility in Interspecific Hybridization of Different *Curcuma* Accessions

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Abstract: *Curcuma* is extensively cultivated as a medicinal and ornamental plant in tropical and subtropical regions. Due to the bright bract color, distinctive inflorescence and long blooming period, it has become a new favorite in terms of the urban landscape, potted flowers and cut flowers. However, little research on breeding new cultivars using traditional plant breeding methods is available on the genus *Curcuma*. In the present study, pollen viability and stigma receptivity evaluation were performed, and the genetic relationship of 38 *Curcuma* accessions was evaluated, then 5 *C. alismatifolia* Gagnep. (Ca), 2 *C. hybrid* (Ch), 2 *C. sparganiifolia* Gagnep. cultivars and 4 *Curcuma* native species were selected as parents for subsequent interspecific cross-breeding. A total of 132 reciprocal crosses were carried out for interspecific hybridization, including 70 obverse and 62 inverse crosses. Obvious discrepancies among fruit-setting rates were manifested in different combinations and in reciprocal crosses. Results showed that the highest fruit-setting rate (87.5%) was observed in the Ca combinations. There were 87 combinations with a fruit-setting rate of 0%, which meant nearly 65.9% was incompatible. We concluded that *C. alismatifolia* 'Siam Shadow' (Ch34) was suitable as a male parent and *C. petiolata* Roxb. (Cpet) was suitable as a female parent to improve the fruit-setting rates. The maximum number of seeds per fruit (45.4) was obtained when *C. alismatifolia* 'Chiang Mai Pink' (Ca01) was used as a female parent followed by *C. attenuata* Wall. ex Baker (Catt) (42.8) and *C. alismatifolia* 'Splash' (Ca63) (39.6) as male parents. The highest germination rate was observed for the Ca group followed by Catt and *C. sparganiifolia* 'Maetang Sunrise' (Csms). The germination rates of Ca accessions ranged from 58.2% (*C. alismatifolia* 'Siam Scarlet' (Ca06) as a male parent) to 89.3% (*C. alismatifolia* 'Sitone' (Ca10) as a male parent) with an average value of 74.0%. Based on the results of hybrid identification, all the individuals from the four combinations exhibited paternal-specific bands, indicating that the true hybrid rates of crossings were 100%. Our results would facilitate the interspecific hybridization and introduction of genetic variation from wild species into the cultivars in *Curcuma* in the future, which could be helpful in realizing the sustainable application in urban green areas.

Keywords: cross-compatibility; fertility evaluation; interspecific hybridization; urban landscape; Zingiberaceae

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1. Introduction

The genus *Curcuma* (family Zingiberaceae) comprises more than 110 native species and is distributed in tropical and subtropical regions [1–3]. The leaves and rhizomes of *Curcuma* accumulate considerable amounts of active components such as phenols, flavonoids and saturated fatty acids [4–7]. The flowers have a wide range of medicinal and ornamental uses [8–10]. *C. alismatifolia* Gagnep. (2n = 32), commonly known as Siam tulip or Patumma, is a perennial bulbous flowering plant native to Thailand and widely grown in China [11,12] (Figure 1). Patumma has a long flowering duration and blooms continuously from June to October in Guangdong province [13]. With the policies of beautiful countryside and high-quality development of agriculture, this special flower has promising applications for blossom oceans, urban park landscapes, flower-bed landscapes and potted flowers [14]. Moreover, the vase life of Patumma is as long as 15 d. Since the demand for the flower on the market is scarce in summer and autumn, Patumma has become a new favorite cut flower [15]. Other native species of *Curcuma* such as *C. petiolata* Roxb., *C. roscoeana* Wall. and *C. yunnanensis* N. Liu & S. J. Chen exhibit high plant architecture, long inflorescences and bright bracts, which are also known as novel and splendid urban plants [16]. Exploring the potential uses of these valuable resources for improving the ornamental characteristics such as flowering time, bract color and plant architecture is becoming a key question to be addressed in the breeding of *Curcuma*. So far, most *Curcuma* cultivars have been cultivated by foreign breeders [17]. An increasing number of cultivars have been bred for their excellent ornamental characteristics and resistance. Interspecific cross-breeding among *Curcuma* germplasm resources is a new, rising topic, but relevant research is still scarce in China. Because of the popularization of intellectual property protection, it is essential to develop such cultivars for different types of landscape applications.

Figure 1. Different types of landscape applications of *C. alismatifolia:* (**A**) Blossom ocean of beautiful countryside; (**B**) Fresh cut flower; (**C**) Greening-road or urban park landscape; (**D**) Flower-bed landscape; (**E**) Potted flower.

Unlike many plants, the genus *Curcuma* lacks a genetic transformation system, which makes it difficult to achieve feasible goals in molecular breeding [18,19]. Using traditional breeding methods such as conventional hybridization, radiation mutagenesis and chemical mutagenesis, many rapid improvements on ornamental traits have been achieved [20,21]. Abdullah et al. reported that 25 Gy of gamma irradiation was an effective dose of radiation [22]. After radiation mutagenesis, the bulb germination time, plant height, number of leaves and plant architecture were significantly improved. However, mutagenesis is random rather than directed breeding, and the induced mutations are frequently unstable, where the mutant traits disappear after several generations of reproduction [23,24]. Interspecific hybridization is a common method for breeding new cultivars [25,26]. With different hybrid combinations, new cultivars with stable excellent traits can be quickly obtained [27]. This method has been successfully applied in breeding programs of eggplant, loquat, azalea, tulip and other plants [28–31]. However, few reports have described the development of interspecific hybridization breeding in the genus *Curcuma*.

The genus *Curcuma* has a complex genetic background with different chromosome numbers, viz., *C. alismatifolia* (2n = 32), *C. thorelii* Gagnep. (2n = 34, 36), *C. parviflora* Wall. (2n = 24, 28, 34, 36, 56), *C. petiolata* (2n = 42, 64) and *C. roscoeana* (2n = 42) [32,33]. Many studies have been carried out to clarify the genetic relationships among the resources of *Curcuma* [34,35]. Taheri et al. used eight SSR markers to analyze the genetic diversity of five varieties and 25 lines of Patumma. Those five varieties were finally divided into two groups [36]. Záveská et al. analyzed the genetic evolution of 19 species in the genus *Curcuma* and explored the evolution of the genus in distant hybridization [37]. Many varieties of *Curcuma* that are bred by artificial crosses have many advantages in bract color and growth characteristics. However, their fertility is too poor to be used as parents for the next steps of breeding, which poses a substantial obstacle to interspecific hybridization. Ketmaro et al. measured the pollen viability of the hybrids *C. sparganiifolia* × *C. parviflora* and found the pollen was almost sterile, but the vigor was improved after colchicine treatment [38]. Saensouk et al. reported the pollen scanning information of 13 germplasm resources of *Curcuma*, which provided a good view for cross-breeding [39]. Yu et al. investigated the pollen storage and viability of 14 *C. alismatifolia* cultivars to provide a reference for *C. alismatifolia* and related species breeding programs [40]. Taking into account that precious genotypes are integral parts of breeding practice, it is pressing to set up a large number of hybrid combinations. The success rate of crossing may be enhanced by selecting parents with close genetic relationships and good fertility.

In this study, through genetic analysis and fertility assessment of *Curcuma* germplasm resources, 13 appropriate parents, including 5 *C. alismatifolia* cultivars (Ca), 2 *C. hybrid* cultivars (Ch), 2 *C. sparganiifolia* cultivars (Cspp and Csms), *C. petiolata* (Cpet), *C. attenuata* Wall. Ex Baker (Catt), *C. thorelii* (Ctho) and *C. yunnanensis* (Cyun), were selected for subsequent interspecific cross-breeding (Table S1). The aim of the study was to explore the cross-compatibility of interspecific hybridizations between *Curcuma* cultivars and wild species. The fruit-setting rate, seed number and germination rate were calculated in order to obtain numerous seedlings. The information on interspecific crossability is important in developing a comprehensive breeding strategy. The breeding materials employed in this program will help in further improvement of *Curcuma* particularly in bract color and inflorescence height breeding. Our results would facilitate the interspecific hybridization and introduction of genetic variation from wild species into the cultivars in *Curcuma* in the future, which could be helpful to realize the sustainable application in urban green areas.

2. Results

2.1. Fertility Evaluation of Curcuma Germplasm Resources

Based on the fertility evaluations of two methods, there were significant differences among species or cultivars (Figure 2A–F and Figure 3). In general, the *C. alismatifolia* (Ca) samples exhibited the strongest pollen viability. The mean value of fertile pollen and sterile pollen was 71.0% and 11.0%, respectively. The *C. hybrid* (Ch) cultivars showed low pollen viability where the mean fertile pollen accounted for 18.6%, but 59.9% of the pollen was sterile. For the other accessions, *C. petiolata* (Cpet) and *C. sparganiifolia* 'Pink Pearl' (Cspp) had excellent fertility, the viable pollen accounted for more than 50%. While the viable pollen of *C. sichuanensis* X. X. Chen (Csic), *C. kwangsiensis* S. G. Lee & C. F. Liang (Ckwa) and *C. yunnanensis* (Cyun) accounted for less than 10% and the inactive pollen was more than 60%. In terms of different groups, Ca accessions showed the best pollen viability, and fertile pollen was 91.3% in *C. alismatifolia* 'Siam Scarlet' (Ca06) and 89.6% in *C. alismatifolia* 'Holland Red' (Ca03). In the Ch group, the best pollen viability was recorded in *C. hybrid* 'Solo' (Ch35) (47.3%) and the weakest pollen viability was found in *C. hybrid* 'Linglongfen' (Ch16), *C. hybrid* 'Ban Rai Red' (Ch47) and *C. hybrid* 'DT602' (Ch54) (0%).

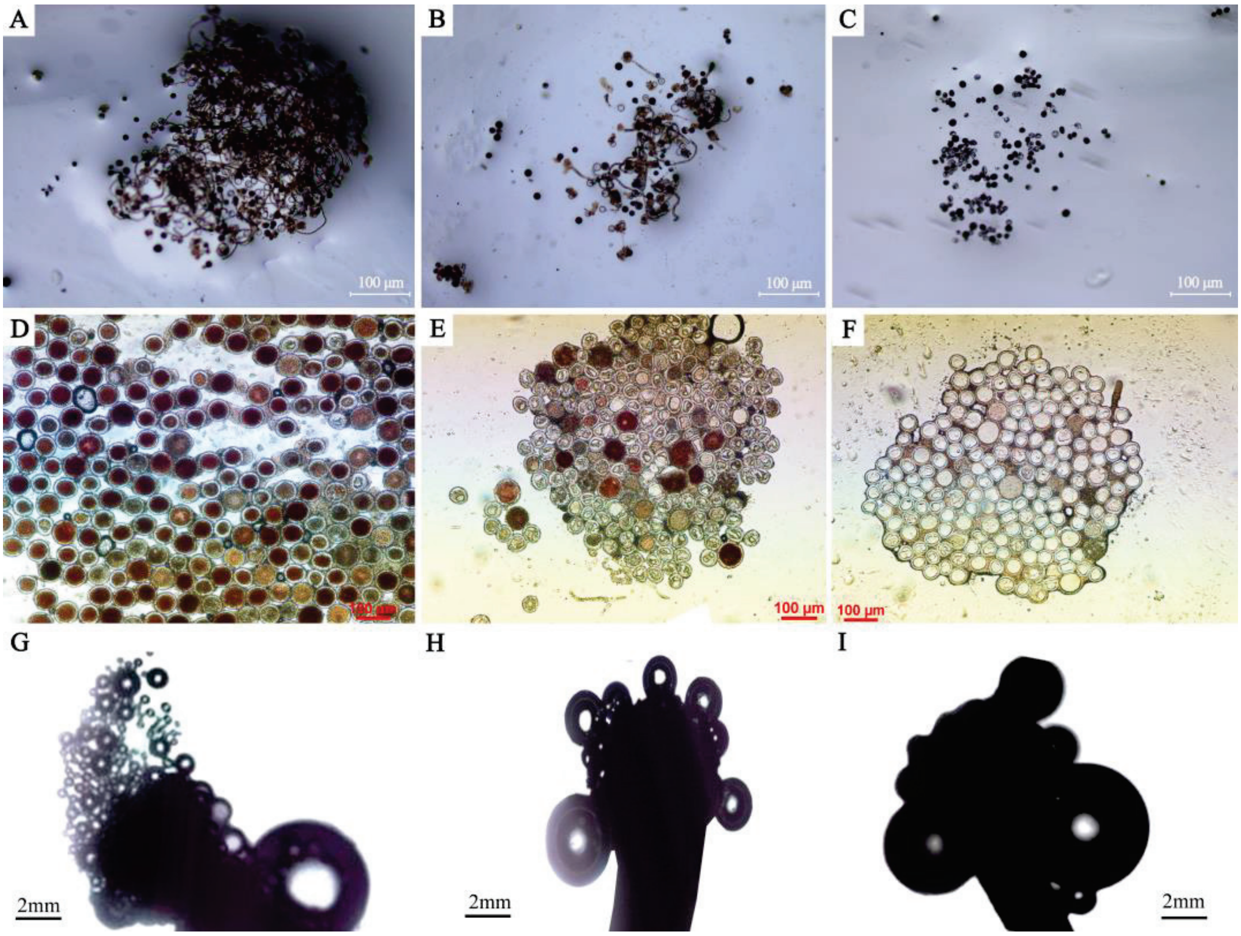

Figure 2. In the fertility evaluation of different *Curcuma* accessions, the selected samples are Ca01, Csms and Ch59 from left to right: (**A**–**C**) Pollen germinability test by in vitro germination on culture medium; (**D**–**F**) Pollen germinability test using TTC staining method; (**G**–**I**) Stigma receptivity evaluation.

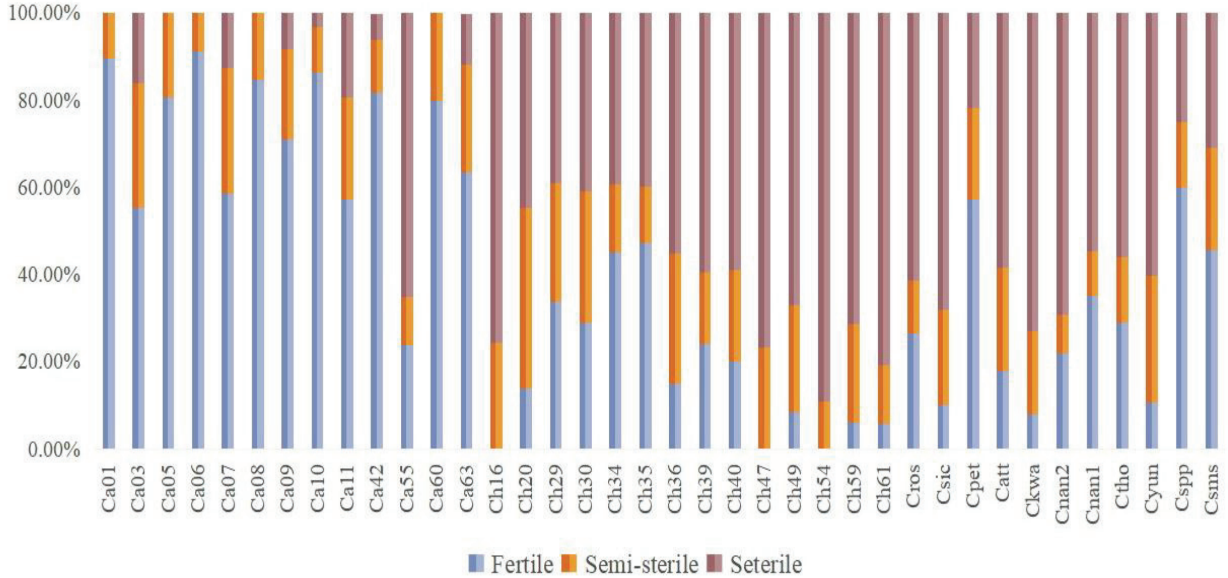

Figure 3. The pollen viability of 38 experimental *Curcuma* accessions.

The Ca accessions had the best stigma receptivity indicated by the bubbling test (Figure 2G–I). All other samples had strong stigma receptivity except *C. alismatifolia* 'Silk' (Ca42), *C. alismatifolia* 'Silk' (Gongfen) and *C. alismatifolia* 'Siam Solar' (Ca60). The stigma receptivity of Ch cultivars was less than Ca cultivars, whereas Ch47, Ch54 and *C. hybrid* 'Hong Bai' (Ch59) had lower stigma receptivity with almost no bubbles on the stigma. For the other *Curcuma* accessions, Cpet, Ctho, Cspp and *C. sparganiifolia* 'Maetang Sunrise' (Csms) showed strong stigma receptivity, while Csic, *C. nankunshanensis* N. Liu, X. B. Ye & Juan Chen (Cnan1), and *C. kwangsiensis* var. *nanlingenesis* (Cnan2) exhibited low stigma receptivity (Table 1).

Table 1. The Stigma receptivity evaluation of 38 *Curcuma* accessions.

Accessions	Stigma Receptivity	Accessions	Stigma Receptivity	Accessions	Stigma Receptivity
Ca01	+++	Ch16	+	Ch61	+
Ca03	+++	Ch20	++	Cros	++
Ca05	+++	Ch29	++	Cpet	+++
Ca06	+++	Ch30	++	Csic	+
Ca07	+++	Ch34	+	Ckwa	+
Ca08	+++	Ch35	+	Catt	++
Ca09	+++	Ch36	++	Cnan1	+
Ca10	+++	Ch39	+	Cnan2	+
Ca11	+++	Ch40	++	Ctho	+++
Ca42	++	Ch47	—	Cyun	++
Ca55	++	Ch49	+	Cspp	+++
Ca60	++	Ch54	—	Csms	+++
Ca63	+++	Ch59	—		

Note: +++ means stigmas have high receptivity; ++ means stigmas have medium receptivity; + means stigmas have low receptivity; — means stigmas have no receptivity.

2.2. Genetic Relationship Analysis

A total of 18 EST-SSR markers were selected to screen the polymorphism of 38 *Curcuma* accessions (Table S2). A total of 173 polymorphic loci were amplified with 9.611 polymorphic loci for each marker. The polymorphic information content (PIC) was the important index for evaluating the polymorphism of each locus where it ranged from 0.628 to 0.888 with an average value of 0.768, indicating that the highly polymorphic EST-SSR markers could be used for genetic analysis of *Curcuma* germplasm resources. According to the clustering results, the 38 germplasms were divided into three groups (Figure S1). The first group contained 17 germplasms, including 4 Ch and 13 Ca cultivars. The common characteristics of these germplasms were that they have long narrow leaves and good fertility. The second group contained 10 specimens, including 2 Cspa and 8 Ch accessions. The common characteristics of them were that they have large leaves and poor fertility. The third group contained 11 samples, of which 9 samples were native species. Based on the results of pollen viability and stigma receptivity, five Ca, two Ch, two Cspa cultivars and four *Curcuma* species were selected as parents for subsequent interspecific cross-breeding.

2.3. Fruit-Setting Rates of Different Hybrid Groups

A total of 132 reciprocal crosses were carried out for interspecific hybridization, including 70 obverse and 62 inverse crosses (Table S2). Based on the results of fruit-setting rates of different hybrid groups, the highest fruit-setting rate (87.5%) was observed in the Ca combinations (Figure S2). There were 87 combinations with a fruit-setting rate of 0%, accounting for 65.9% of the total number of cross combinations. Among the different hybrid groups, the combinations between *C. alismatifolia* interspecies (Ca × Ca) exhibited the highest fruit-setting rate. Besides, the Ca combinations with Ctho and Cpet exhibited low fruit-setting rates. Compared to Ca and other *Curcuma* species, Ch and Cspa preferred to make successful hybridizations with Ctho and Cspa cultivars. For the four native species, Ctho was regarded as the best parent with moderate fruit-setting rates when crossing with Ca, Ch and Cspa accessions. However, all the hybridizations failed when Cyun crossed with the other species or cultivars.

Obvious discrepancies among fruit-setting rates were manifested in different combinations and in reciprocal crosses (Figure 4). Overall, higher fruit-setting rates were observed from obverse crosses for Ca06, Ca09, Ch29, Csms and Cpet, while the fruit-setting rates from inverse crosses were higher than those from obverse crosses for Ca01, Ca10, Ca63, Ch34, Ctho, Cspp and Catt. Results indicated that most accessions could produce fruits as both parents, but there existed some exceptions. For the cross combinations Ca01 × Ch34, Ca01 × Ctho, Ca09 × Ch34, Ca09 × Ctho, Ca10 × Ch34 and Ca63 × Ch34, successful hybridizations were made only in obverse crosses, suggesting that Ch34 was suitable as a male parent for interspecific crossing. For the cross combinations Ca01 × Cpet, Ca06 × Cpet, Ca09 × Cpet, Ca63 × Csms and Ch34 × Ctho, fruits were produced only in inverse crosses, indicating that it was better to choose Cpet as a female parent to improve the fruit-setting rates.

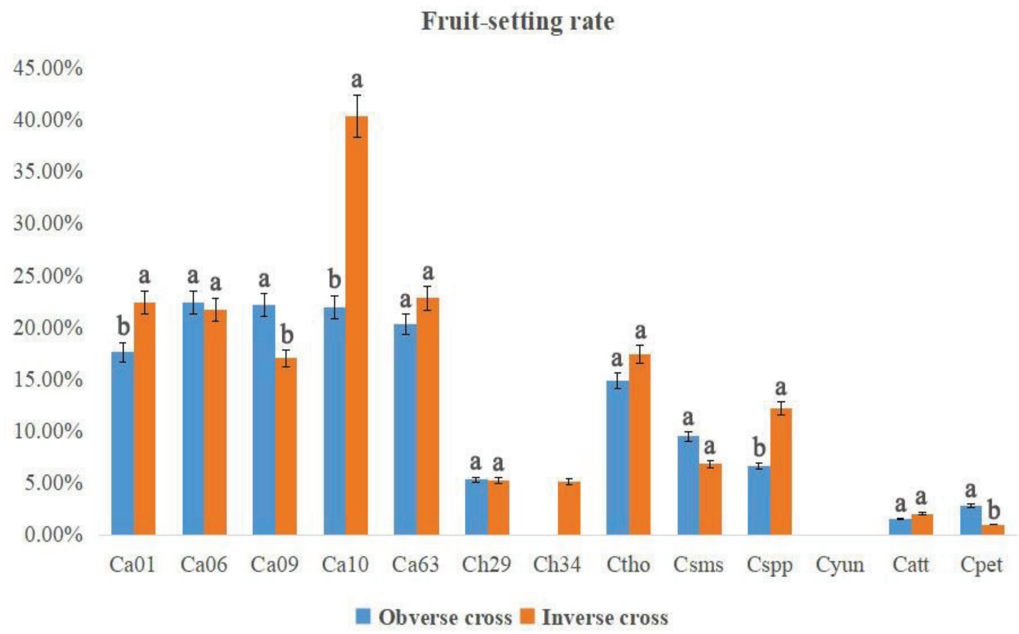

Figure 4. The fruit-setting rates in each cross combination of *Curcuma*. Different lowercase letters represent significant differences ($p < 0.5$).

2.4. Number of Seeds per Fruit and Germination Rates

The number of seeds per fruit and the germination rates of different hybrid combinations are shown in Figures 5 and 6, respectively. The maximum number of seeds per fruit (45.4) was obtained when Ca01 was used as a female parent followed by Catt (42.8) and Ca63 (39.6) as male parents. There existed significant differences in the number of seeds per fruit between obverse cross and inverse cross. As for Ca01, Ca06 and Csms, a greater number of seeds per fruit were observed in obverse crosses than those in inverse crosses. However, contrasting results were observed for Ca63, Ch29, Ch34, Ctho, Catt and Cpet. The degree of germination rates varied with different hybrid groups. The highest germination rate was observed for the Ca group, followed by Catt and Csms. The germination rates of Ca accessions ranged from 58.2% (Ca06 as a male parent) to 89.3% (Ca10 as a male parent), with an average value of 74.0%. As for Ctho, Cspp and Cpet, higher germination rates and a greater number of seeds per fruit were observed in obverse crosses than those in inverse crosses. For the cross combinations Ca01 × Ch34, Cpet × C01, Ctho × Ca06, Ctho × Ch34 and Cspp × Ctho, the seeds were obtained but did not sprout, indicating the seed development problem resulted from the cross compatibilities of some interspecific hybrids.

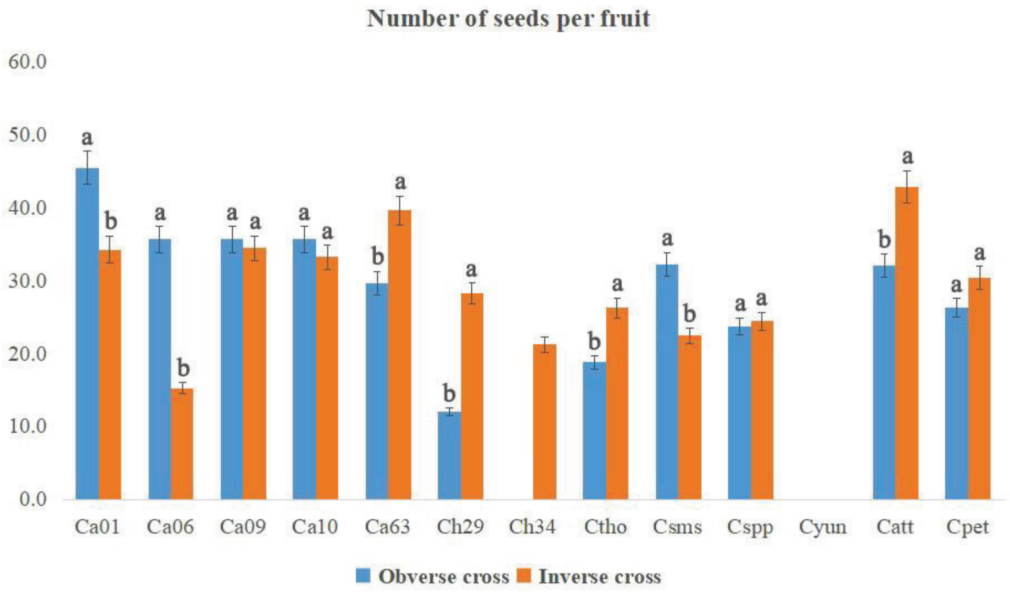

Figure 5. Number of seeds per fruit in each cross combination of *Curcuma*. Different lowercase letters represent significant differences ($p < 0.5$).

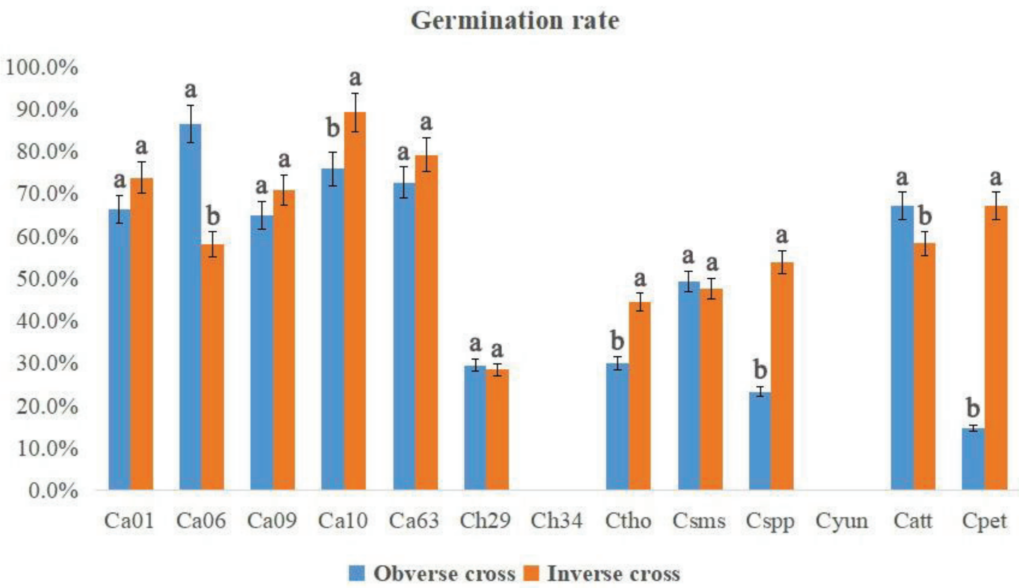

Figure 6. Germination rates in each cross combination of *Curcuma*. Different lowercase letters represent significant differences ($p < 0.5$).

2.5. Hybrid Identification

Six plants from each of Ca01 × Ca10, Ca06 × Ctho, Ctho × Csms and Catt × Cpet crosses were randomly selected for hybrid identification. The EST-SSR markers with clear bands and strong polymorphism were employed for analysis of the genetic polymorphism of the parents (Figure S3). The results showed that all individuals from four combinations exhibited paternal-specific bands, indicating that the true hybrid rates of crossings were 100% (Table 2).

Table 2. Results of amplification for parents and individuals using EST-SSR markers.

SSR Locus	Parent		F_1 Individual						Purity%
	Ca01	Ca10	Caa-1	Caa-2	Caa-3	Caa-4	Caa-5	Caa-6	100
JHH10	160/160	160/166	160/166	160/166	166/166	160/166	166/166	166/166	
	Ca06	Ctho	Cat-1	Cat-2	Cat-3	Cat-4	Cat-5	Cat-6	
JHH2	245/248	248/251	251/251	248/251	245/251	245/251	248/251	251/251	100
JHH21	146/155	146/149	146/149	146/149	146/149	149/155	149/155	146/149	
	Ctho	Csms	Cts-1	Cts-2	Cts-3	Cts-4	Cts-5	Cts-6	
JHH10	166/172	169/172	169/172	169/169	169/172	169/172	169/169	166/172	100
JHH2	248/248	248/251	251/251	248/251	248/248	248/251	251/251	248/251	
	Catt	Cpet	Cap-1	Cap-2	Cap-3	Cap-4	Cap-5	Cap-6	100
JHH15	130/133	130/139	130/139	130/139	139/139	139/139	130/139	130/139	

3. Discussion

Interspecies or intergeneric hybridization is one of the main methods for breeding new cultivars in plants [41]. Reports on the fertility of interspecies hybrids of *Curcuma* are scarce, although it is an excellent ornamental and edible medicinal plant with promising market potential. Until now, a large number of excellent cultivars have also been obtained through interspecific hybridization [11,42]. Parent fertility is one of the main factors affecting the seed-setting rate of interspecific hybridization [43,44]. It is easy to overcome the incompatibility of hybridization by using species or cultivars with strong stigma receptivity as female parents. Choosing varieties with high pollen vigor or germination rates as male parents can substantially increase the fruit-setting rate [45]. In this study, the fertility and stigma receptivity of Ca cultivars was generally higher than other *Curcuma* accessions, which could be used by both male and female parents. For some special parents such as Ch34, Ctho and Cpet, it is necessary to comprehensively compare the pollen viability and stigma receptivity of the parents to optimize the cross. Meanwhile, the ploidy level and the chromosome number of the parents may also affect the compatibility of the parents [46]. If the parents have the same ploidy and chromosome number, it would be easier to obtain hybrids. Previous reports found that most Ca cultivars and *Curcuma* native species were diploid, and the chromosome numbers were widely inconsistent [32,33]. Catt had the most chromosome numbers (2n = 84), followed by Cpet (2n = 42, 64), Ctho (2n = 34, 36) and Ca (2n = 32). Most hybridizations between Ca/Ch and *Curcuma* native species were incompatible, which may have been caused by different chromosome numbers. It was concluded that the poor fertility of Ch accessions might have been due to the unsuccessful pairing of chromosomes during meiosis, resulting from different numbers of chromatids and reproductive disorders. We confirmed the fertility of Ch cultivars and provided a view for subsequent interspecific hybridization. However, there were no reports on the chromosome numbers and karyotype analysis of different Ch cultivars. Whether the chromosome numbers are significantly related to fertility or not is still unknown, and the question should be further addressed by studying chromosome compression and karyotype analysis.

Due to the distant genetic relationship of germplasm resources, hybrid incompatibility exists for most *Curcuma* hybridizations. In this study, 18 EST-SSR markers with a mean value of 0.768 were used to assess the genetic relationships among 38 *Curcuma* accessions. Interestingly, the Ca and Ch cultivars and native species were divided together with a few exceptions, which were consistent with their origins and previous findings [12,17]. Combining with the results of the fertility evaluation, the suitable parents from different groups were selected in order to improve the success rates of crossing. A total of 132 interspecific crosses were carried out, which suggested the fruit-setting rates of the hybrids with close parent relationships were significantly higher than those with distant relationships. The four native species had very low success rates of crossing with Ca and Ch accessions, indicating that these species were less genetically related. Especially in Cyun, no fruits were observed for all the combinations. In terms of the low fruit-setting rates, we speculated

Ch cultivars have been crossed for multiple generations, which hence may harbor parts of the genome of the native species and Ca cultivars. The Ch cultivars would be suitable as intermediate materials for cross-breeding through introgression. However, due to the limited native species and interspecific hybrid combinations, it is necessary to investigate more into this topic in the future to further verify the influence of genetic relationships on cross-compatibility.

Different parental combinations of obverse and inverse crosses have a great influence on the success rates of crossing. It was found that in the distant hybridization of loquat (*Eriobotrya japonica* Lindl.), the obverse crosses of loquat with its related genera were almost incompatible [29]. When different species were used as male or female parents, the fruit-setting rates were quite different. As a female parent, azalea exhibited better compatibility with the same subgenus *Rhododendron* [30]. However, when the *Rhododendron ovatum* (Lindl.) Planch ex Maxim. was used as the female parent, it failed to cross with *Rhododendron ellipticum* Maxim. but had better crossing compatibility with other species of *Rhododendron*. Similar results were found for the interspecific hybridization of the *Rosa hybrida* E. H. L. Krause, *Iris sibirica* L. and *Prunus* [47–49]. For the Ca hybrid group, there were good seed-setting rates in both of the obverse and inverse crosses. Though Ch34 had low stigma receptivity, all the cross combinations failed when used as a female parent. For the native species, except Cyun, there existed significant differences in reciprocal crosses in the fruit-setting rate. The above results preliminarily indicated that the combination of obverse and inverse crosses had a certain effect on the success rates of crosses in *Curcuma*, but no obvious unidirectional hybridizations were observed. By setting up reasonable combinations of obverse and inverse crosses and choosing appropriate parents, there would be a chance to obtain superior hybrids [28]. Although some hybrid combinations showed lower success rates of crossing, there was no obvious fertilization disorder, suggesting that the number of hybrids could be increased by increasing pollination.

When Ch, Ctho and Cspa were used as parents, the number of seeds per fruit and the seed germination rates were lower than other hybrid combinations. Although these combinations produced fruits, the number of seeds per fruit was very little and there were fewer plump seeds. Some fruits of these crosses were even dropped after pollination, which indicated that the abnormal embryo development and incompatibility of pre-zygotic and post-zygotic stages might occur in the process of interspecific hybridization [50]. As for the low seed germination rates, it might have been caused by an interruption of seed development in the zygote stage or abnormalities in the endosperm that led to impaired nutrient supply for the embryo during germination [51]. In order to promote ovary enlargement and increase the fruit-setting rate, delaying pollination before the pollen is fully mature or applying pollen culture solution should be considered [52].

In summary, factors affecting cross-compatibility are complex and diverse. In addition to these objective reasons, environmental conditions such as temperature, humidity and light may also affect hybrid compatibility. To fully understand the causes of cross-compatibility of the genus *Curcuma*, in-depth studies on the physiological and molecular aspects are needed. It is easy to obtain hybrids by interspecific hybridization in which parents are closely related, but it may be difficult to acquire excellent traits. Therefore, it is necessary to try multi-generation backcrossing, selfing and distant hybridization, which will provide more probabilities to create new *Curcuma* germplasms and support breakthroughs in *Curcuma* breeding.

4. Materials and Methods

4.1. Plant Materials

A total of 38 *Curcuma* accessions were collected from the resource garden of the Environmental Horticulture Research Institute, Guangdong Academy of Agricultural Sciences, Guangzhou, China, which included 9 *Curcuma* native species, 13 *C. alismatifolia*, 2 *C. sparganiifolia* cultivars and 14 *C. hybrid* cultivars (Table S1).

4.2. Pollen Germinability Test

Fresh pollen samples were collected on a flowering day (9–11 a.m.) and placed onto glass slides. The pollen was then killed by heating to a high temperature and used as a control. Fresh pollen samples on glass slides were treated with 1–2 drops of 0.5% 2,3,5-triphenyl tetrazolium chloride (TTC) staining method, mixed evenly, covered with cover glasses, and incubated at 37 °C. The pollen vitality depended on the staining color, which indicated that the dark stain colors were categorized as strong vitality, light colors as medium or low vitality and unstained as no vitality. Meanwhile, the pollen viability above was estimated by in vitro germination on a culture medium referring to the method of Xing et al. [31]. Three flowers were used for each sample, and pollen from three microscope fields was counted for each combination. The total and germinating pollen grains were counted for each field. The pollen staining and germination were observed under a microscope (objective and eyepiece lenses 10×, respectively) (Olympus, CH-20i, Tokyo, Japan).

4.3. Evaluation of Stigma Receptivity

The stigmas were collected on a flowering day (9–11 a.m.), applied onto grooved glass slides and immersed into benzidine-H_2O_2 reaction solution (1% benzidine: 3% H_2O_2:H_2O, 4:11:22) [51]. The intensity of effervescence on stigmas was observed with a magnifier after 6 min. Color change and strong bubbling in the reaction solution indicated strong receptivity of the stigma. Less bubbling indicated lower receptivity, whereas no bubbling indicated no receptivity. Three replicates for each test were used.

4.4. Interspecific Hybridization

To select suitable parents to set up hybrid combinations, EST-SSR molecular markers were used to analyze the genetic diversity of 38 *Curcuma* accessions. The primer information, amplification procedure and genetic diversity analysis referred to the research of Ye et al. (Table S2) [17]. According to the results of fertility assessment and cluster analysis, five *C. alismatifolia*, two *C. hybrid*, two *C. sparganiifolia* cultivars and four *Curcuma* native species were selected as parents. The interspecific hybridization was conducted in all possible combinations with reciprocal crosses, including 70 obverse and 62 inverse crosses. Wilting florets and fertile bracts around the florets were removed before artificial pollination. Pollen from each male parent was collected and applied to the stigma of the female plant at 9–11 o'clock on the flowering day. The pollinated florets were bagged and labeled. Three days after pollination, the bags were removed, and pod set rate was determined after one month. The seeds in each fruit were harvested and counted after ripening. They were sown in March of the next year, and the germination rate of each combination was calculated (Figure 7).

4.5. Hybrid Identification

When the seedlings were at the two-leaf stage, four hybrid combinations were randomly selected, and six plants of each combination were chosen for DNA extraction. Their DNA was extracted using a new-type genomic DNA extraction kit (Tiangen Biotechnology Co., Ltd., Beijing, China). The integrity and quantity of DNA were evaluated by 1% agarose gel electrophoresis and a Nanodrop 2000 spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA), respectively. To perform the PCR amplification, the forward primer of EST-SSR markers was elongated from the M13 primer appended to the 5'-end [17]. PCR amplifications were conducted on 15 μL volumes containing 7.5 μL of 2× *Taq* mix, 0.2 μL of forward M13 primer (1 μM), 1.2 μL of reverse primer (1 μM), 1.2 μL of M13 fluorescent primer (1 μM), 2.5 μL of template DNA (10 ng/μL) and 2.4 μL of ddH_2O. The thermal cycling program consisted of pre-denaturation at 94 °C for 5 min, 30 cycles at 94 °C for 30 s, 55 °C for 30 s and 72 °C for 1 min, followed by 13 cycles at 94 °C for 30 s, 53 °C for 30 s and 72 °C for 1 min, and a final extension at 72 °C for 10 min. The marker bands in the parents were screened using the polyacrylamide gel electrophoresis, and approximately 0.5 μL of

PCR products with four different fluorescent labels (FAM, HEX, ROX and TAMRA) and sizes were pooled and detected using a DNA analyzer. Finally, the hybrids with paternal bands were identified as true hybrids.

Figure 7. The schematic process of cross-breeding: (**A**) The stamen and pistil of *C. alismatifolia*; (**B**) The pollinated floret after one week; (**C**) The pollinated floret after three weeks; (**D**) The pollinated floret after five weeks; (**E**) The seeds of *C. alismatifolia*; (**F**) The seedlings of *C. alismatifolia*.

5. Conclusions

As promising urban plants for different types of landscape applications, it is pressing to breed new *Curcuma* cultivars with excellent ornamental characteristics and resistance. In this research, a total of 132 reciprocal crosses were conducted among 13 *Curcuma* germplasm resources by assessing the fertility and genetic relationship. Significant differences among fruit-setting rates were manifested in different combinations and in reciprocal crosses. Results showed that the highest fruit-setting rate (87.5%) was observed in the Ca combinations. The maximum number of seeds per fruit (45.4) was obtained when Ca01 was used as the female parent followed by Catt (42.8) and Ca63 (39.6) as the male parent. The highest germination rate was observed for the Ca group followed by Catt and Csms. All the seedlings obtained from the crosses were true hybrids through hybrid identification. The present study was performed to explore the crossability behavior of different *Curcuma* accessions and to develop innovative cultivars with desirable traits. Our results would facilitate the interspecific hybridization and introduction of genetic variation from wild species into the cultivars in *Curcuma* in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/plants12101961/s1, Figure S1: The cluster analysis of 38 *Curcuma* accessions based on 18 EST-SSRs; Figure S2: The fruit-setting rates in each hybrid group of *Curcuma*; Figure S3: The polyacrylamide gel electrophoresis of JHH10 among 8 samples in Ca01 × Ca10; Table S1: The *Curcuma* accessions used in this study; Table S2: Polymorphic information of 18 EST-SSRs in 38 *Curcuma* accessions; Table S3: The results of interspecific hybridization between different *Curcuma* accessions.

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plants

Article

Salt Tolerance of *Limonium gmelinii* subsp. *hungaricum* as a Potential Ornamental Plant for Secondary Salinized Soils

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Abstract: Secondary salinization caused by climate change is a growing global problem. Searching for plants that can survive in areas with high salt content and even have decorative value was the focus of our research. Thirty plants of *Limonium gmelinii* subsp. *hungaricum* were planted in clear river sand; another thirty plants were planted in Pindstrup, a growing substrate enriched with 40% clay. With the latter, we modeled the natural soil. In addition to the control tap-water treatment, plants received 50, 125, 250, 375, and 500 mM NaCl solution irrigation twice a week. The leaf sizes of plants planted in sand decreased proportionally with the increasing NaCl concentration, and their dry matter content increased. In the clay-containing medium, leaf sizes increased, even at a concentration of 375 mM, although the dry matter content increased only at high concentrations. Carotene content in both media became higher, due to the higher NaCl concentrations, while proline content in the plants grown in sandy media increased, even with the 125 mM concentration. With our present experiment we proved the salt tolerance of the taxon, and even the soil's great importance in supporting the plant's salt tolerance.

Keywords: *Limonium*; saline; salt stress; proline; NaCl; chlorophyll

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1. Introduction

Land salinization is a global problem that affects a significant portion of the world's irrigated farmland. According to estimates, the globe loses at least 0.5–1% of arable land each year due to salinization [1], and by 2050 half of the world's arable land may be gone if current trends continue [2]. The primary symptoms of salt toxicity in plants include ion damage, osmotic stress, and oxidative stress [1]. These pressures negatively impact plant growth and development. Salinization can also cause physiological drought, which occurs when a plant's roots respond to environmental stimuli such as a lack of water or an abundance of salt ions in the soil [3]. This lack of water has detrimental impacts on plants, including the accumulation of reactive oxygen species and oxidative stress, and reduced photosynthetic rates [3]. Plant cells have sodium receptors that detect increases in sodium, which elevates cytosolic calcium and triggers adaptation responses [4]. Through the SOS pathway, the extra cytosolic sodium is either sequestered in vacuoles or evacuated from the cell [5,6]. Growing traditional crops in areas with high salt content is uncertain, as most plants cannot survive in such environments. Using molecular biology and genetic engineering to create salt-tolerant plants is a possibility, but it can be costly and time-consuming. An alternative solution is to cultivate naturally salt-tolerant plants in these areas, as it is more affordable, sustainable and cost-effective [7].

Halophytes are able to thrive and carry out their entire life cycle in regions where the concentration of NaCl is above 200 mM [8] and could be optimized to minimize the salinity of salty soils [9]. *Limonium* is a biodiverse halophyte taxon within the *Plumbaginaceae* family, known for its remarkable characteristics, and has the ability to thrive in saline environments. This taxon comprises around 370 species with high adaptability to such conditions [10]. Continental climates are ideal for the growth of *Limonium* species [11]. Nearly all species of *Limonium* are endemic to salty environments, and several of them can thrive in extremely salty conditions [12]. *Limonium gmelinii* subsp. *hungaricum*, also known as Hungarian sea lavender or Hungarian statice, is a perennial herbaceous plant of the genus. The species is indigenous to the coastal areas of Eastern Europe and Asia and is known for its tolerance to salt and drought. It typically grows to a height of 30–60 cm, and has a woody base with branching flower stems. The leaves are linear-lanceolate, sessile, and fleshy, and range in size from 15 to 30 cm long and 5 to10 cm wide. The flowers are small, pinkish-purple and arranged in dense spikes. They bloom in late summer and early fall [13]. The plant has developed a tolerance for high levels of salt in the soil, which allows it to thrive in environments such as coastal dunes, salt marshes, and sandy soils, making it a potential ornamental plant for secondary salinized soils [14].

Halophytic plants, which possess the ability to thrive in environments with high salinity, exhibit various modifications in terms of morphology, physiology, biochemistry, and molecular structure [15]. The adaptation mechanisms of halophytic plants in response to salinity stress include: preservation of the photosynthetic system through enhanced chlorophyll synthesis [16], adjustment of carotenoid levels [15], modulation of reactive oxygen species (ROS) levels, stimulation of enzymatic antioxidant activity [17], and increased production of non-enzymatic antioxidants such as proline [18].

Limonium sp. or recretohalophytes are distinctive halophytes that possess specialized structures on their epidermis, such as salt bladders and salt glands, which allow them to cope with salt-rich environments [19]. Recretohalophytes secrete excess salt ions through their salt glands in order to maintain ionic balance [20,21]. The studies by Daraban et al. and Rozentsvet et al. [22,23] have shown that the salt glands play a crucial role in the adaptation of the czrynohalophyte *L. gmelinii* (Willd.) to high-salt conditions; crynohalophytes are plants that secrete excess salt on their leaves' surface [24]. According to the findings of Leng et al. [25] *L. gmelinii*'s salt glands show a distribution pattern that suggests an optimal concentration of 50 mM NaCl for its growth. In contrast, a study by [21] showed that the salinity threshold of *L. gmelinii* can reach up to 400 mM. Under environmental stress conditions, plants typically exhibit a reduction in growth, as they prioritize activating their defense mechanisms using their metabolic precursors and energy resources rather than allocating them towards biomass accumulation, according to Munns and Tester [1]. An investigation by Ghanem et al. [26] discovered that the buildup of proline was connected to a decrease in biomass, chlorophyll a/b ratio, and carotenoid levels in *Salicornia europaea* when exposed to high salinity. According to MI et al. [21], *Limonium* species subjected to saline stress exhibited a positive correlation between their total fresh weight and variables such as total dry weight, chlorophyll content, and intercellular CO_2 concentration. Additionally, many *Limonium* species have been found to contain proline or osmolytes, which are important in preserving osmotic equilibrium and safeguarding plants against stress, especially at elevated levels of NaCl, serving as protectors of plasma membrane integrity, ROS scavengers, or signaling molecules during severe stress [8,27].

Additionally, salinity can be controlled through the implementation of appropriate soil amendments and effective water management techniques [28]. The physical characteristics of the soil, such as texture and structure, can also impact the growth and performance of halophytic plants, as they affect the soil's nutrient retention, ventilation, water retention and drainage capacity [29]. In this study, we aim to examine the response of *Limonium gmelinii* subsp. *hungaricum* to saline conditions and the influence of soil type on its salt tolerance.

2. Results

2.1. Effect of NaCl Stress on the Growth and Development of Limonium gmelinii subsp. hungaricum in Sandy and Clayey Soil

The results of *Limonium gmelinii* subsp. *hungaricum* grown in sandy and clayey soil were analyzed to determine the effect of NaCl treatments on the plant's growth and development. The treatments were given in various concentrations of 50 mM, 125 mM, 250 mM, 375 mM, and 500 mM. In addition, the control treatment was given in the form of normal irrigation or tap-water irrigation, which represented the plant's growth without stress (Figure 1).

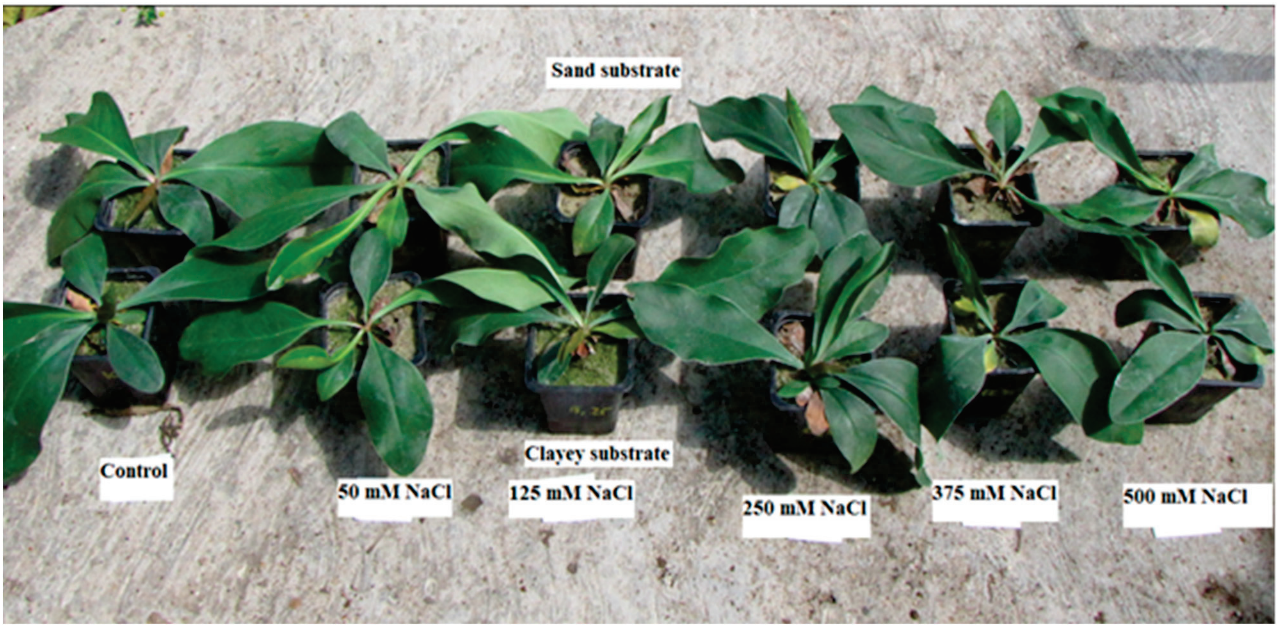


Figure 1. Effect of NaCl stress on morphological characters of *Limonium gmelinii* subsp. *hungaricum* under sandy soil and clayey soil.

In the sandy soil, the fresh weight of *Limonium gmelinii* subsp. *hungaricum* showed a decrease of about 17.4% to 57% compared to the control treatment. Similarly, the dry weight showed a decrease of about 10.1% to 39.3% compared to the control treatment (Figure 2A), with NaCl concentrations ranging from 50 mM to 500 mM. On the other hand, the relative dry weight (g/100 g) in sandy soil increased by about 9% to 41% compared to the control treatment with NaCl concentrations, ranging from 50 mM to 500 mM (Figure 2B). The length of the leaves was also significantly affected by the NaCl treatments, with a decrease of approximately 4% to 31% compared to the control treatment, with NaCl concentrations ranging from 50 mM to 500 mM. The width of the leaves showed a similar pattern, with a decrease of approximately 6% to 29% compared to the control treatment, with NaCl concentrations ranging from 50 mM to 500 mM (Figure 2C).

In the case of clayey soil, the results showed that the relative dry weight increased with the increase in the NaCl concentration, with the highest value at 500 mM (43 g/100 g) (Figure 2E). However, the fresh weight showed an increasing trend until 250 mM, where it showed an increase of 12% compared to the control and then decreased at 375 mM by 23% and at 500 mM by 10% compared to the control. The same trend was observed in the dry weight, with an increase until 375 mM, where it showed an increase of 12% compared to the control. However, at 500 mM NaCl treatment, the dry weight decreased by 19% compared to 375 mM treatment and by 9% compared to the control (Figure 2D). This suggests that the plants in the clayey soil were able to withstand the salt stress to some extent but showed reduced growth and biomass production as the salt concentration increased beyond 375 mM.

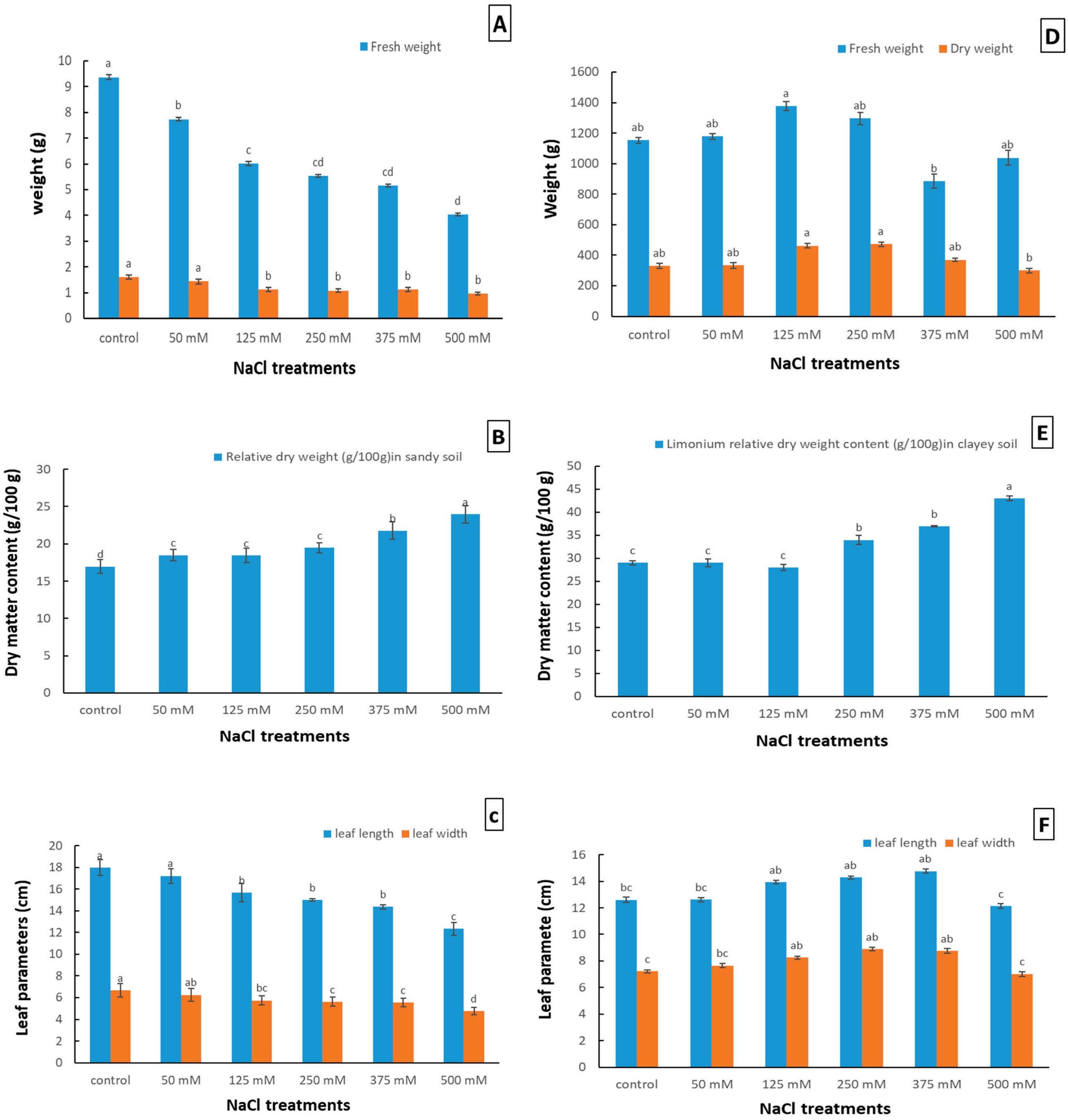


Figure 2. Effect of NaCl stress on morphological characters of *Limonium gmelinii* subsp. *hungaricum* under sandy soil and clayey soil. Leaves' fresh weight and dry weight (g) in sandy soil (**A**), dry matter content (g/100 g FW) in sandy soil (**B**), and leaf parameters (cm) in sandy soil (**C**) of *Limonium gmelinii* subsp. *hungaricum* under different NaCl levels (Mm). Leaves' fresh weight and dry weight (g) in clayey soil (**D**), dry matter content (g/100 g FW) in clayey soil (**E**), and leaf parameters (cm) in clayey soil (**F**) of *Limonium gmelinii* subsp. *hungaricum* under different NaCl levels (Mm), data represent averages of ten replications ± SD. The various letters indicate a significant variance between treated plants. $p < 0.05$ from Tukey's multiple-range test.

The leaf length and width of plants grown in the clayey soil showed varying responses to the NaCl treatments (Figure 2F). The leaf length initially increased with increasing NaCl concentration, reaching its maximum at 375 mM by 17% compared to the control. However, the leaf length decreased significantly at 500 mM NaCl concentration, by 4% compared to the control. On the other hand, the leaf width gradually increased with increasing NaCl concentrations up until 375 mM, compared to the control (Figure 2F). However, the leaf width decreased by 3% with a 500 mM NaCl treatment, indicating that there is an optimal range of NaCl concentrations for *Limonium gmelinii* subsp. *hungaricum* to grow optimally. These observations suggest that NaCl stress has a differential effect on the different morphological characteristics of plants grown in clayey soil.

2.2. The Effects of NaCl Concentration on Chlorophyll and Carotenoid Content in Limonium gmelinii subsp. hungaricum Grown in Sandy and Clayey Soils

The pigment content of *Limonium gmelinii* subsp. *hungaricum* was subjected to varying levels of NaCl in both sandy and clay soils. In sandy soil (Figure 3A), the results indicated that the control group exhibited a relatively constant level of chlorophyll, with a modest reduction observed at 50 mM NaCl, followed by an increase at 125 mM NaCl. The highest chlorophyll concentration was recorded at 375 mM NaCl, demonstrating a 14.4% increase compared to the control group, before experiencing a slight decrease at 500 mM NaCl, and a slight increase at 250 mM NaCl. On the other hand, the carotenoid content in sandy soil (Figure 3B) exhibited a divergent trend, with a modest reduction observed at 50 mM NaCl, followed by a slight uptick in carotenoid concentration at 125 mM NaCl, and then a significant increase observed with higher NaCl concentrations, peaking at 375 mM NaCl with an increase of 16.4% compared to the control group. This increase was further amplified at 500 mM NaCl, where the concentration of carotenoids reached an 18.6% increase compared to the control group.

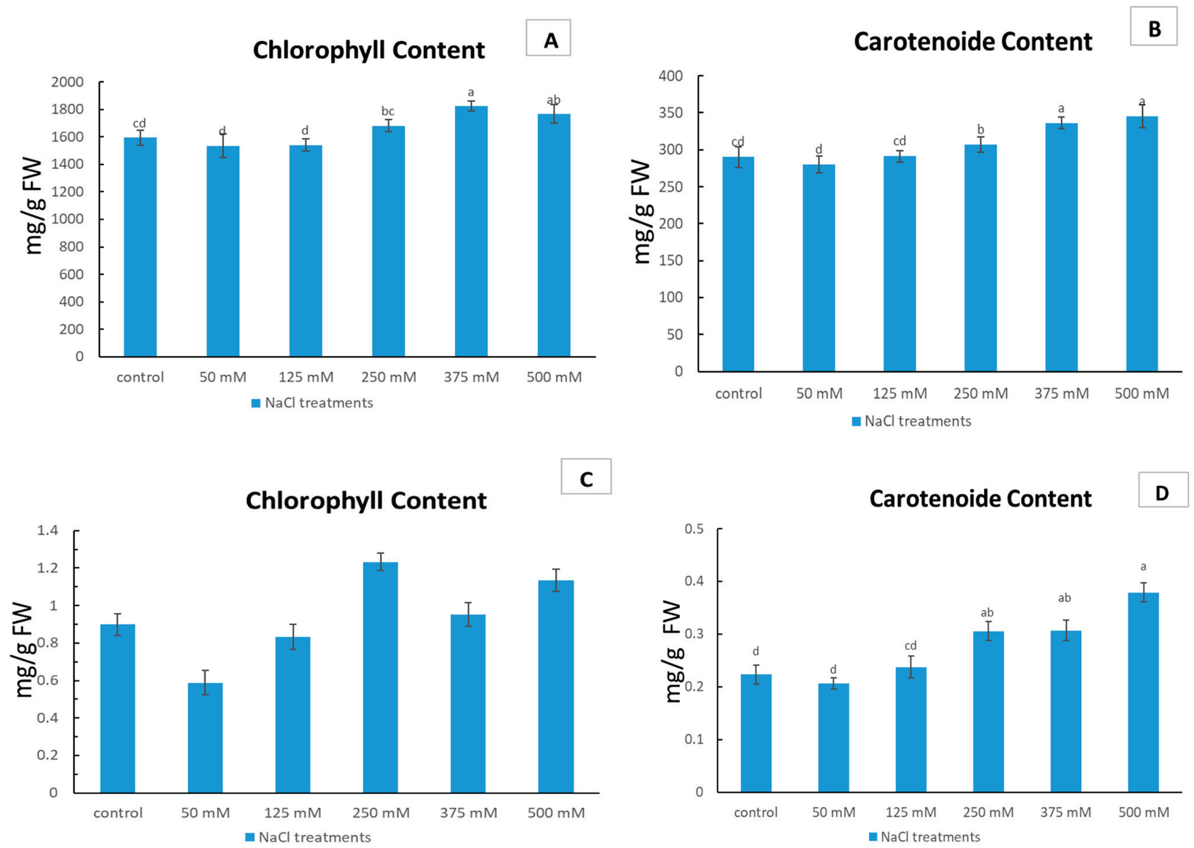


Figure 3. Effect of NaCl stress on *Limonium gmelinii* subsp. *hungaricum* under sandy soil and clayey soil. Total chlorophyll content mg/g FW (**A**) and carotenoid content mg/g FW (**B**) in sandy soil and total chlorophyll content mg/g FW (**C**) and carotenoid content mg/g FW (**D**) in clayey soil of *Limonium gmelinii* subsp. *hungaricum*, under different NaCl levels. Data represent averages of ten replications ± SD. The various letters indicate a significant variance between treated plants. $p < 0.05$ from Tukey's multiple-range test.

In clayey soil, the results indicated that the control group had a moderate concentration of chlorophyll (Figure 3C), which was diminished at 50 mM NaCl. However, this reduction was followed by an increase in chlorophyll concentration at 125 mM NaCl. The highest concentration of chlorophyll was recorded at 250 mM NaCl, where the concentration increased by 38% compared to the control group, before experiencing a decrease at 375 mM NaCl, and a slight increase at 500 mM NaCl. Similarly, the carotenoid content in clayey soil (Figure 3D) showed a decrease at 50 mM NaCl, followed by an increase at 125 mM NaCl. The highest concentration of carotenoids was observed at 500 mM NaCl, where the concentration increased by 70% compared to the control group, followed by a stable level at 375 mM NaCl and 250 mM NaCl.

2.3. Effect of NaCl Levels on Sodium Content in Limonium gmelinii subsp. hungaricum Leaves

The data in Figure 4 provide valuable information on the effect of increasing NaCl levels on the sodium (Na) content in the leaves of *Limonium gmelinii* subsp. *hungaricum* grown in sandy substrate. The control treatment recorded an average Na content of 1.13 g/100 g fresh weight. With a steady increase in NaCl levels, the Na content in the leaves also increased. At the highest NaCl level of 500 mM, the average Na content reached 3.47 g/100 g fresh weight, representing a 205% increase on the control treatment. This result demonstrates the remarkable ability of *Limonium gmelinii* subsp. *hungaricum* to regulate its internal Na levels in response to changing external conditions.

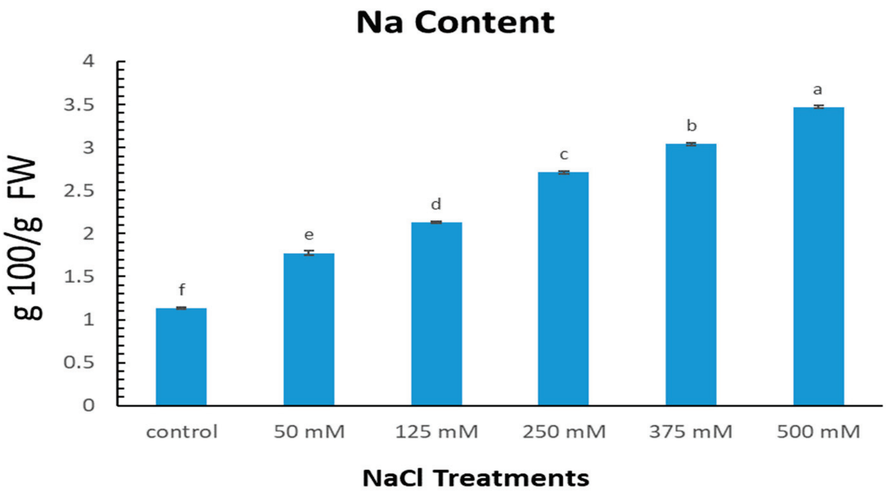
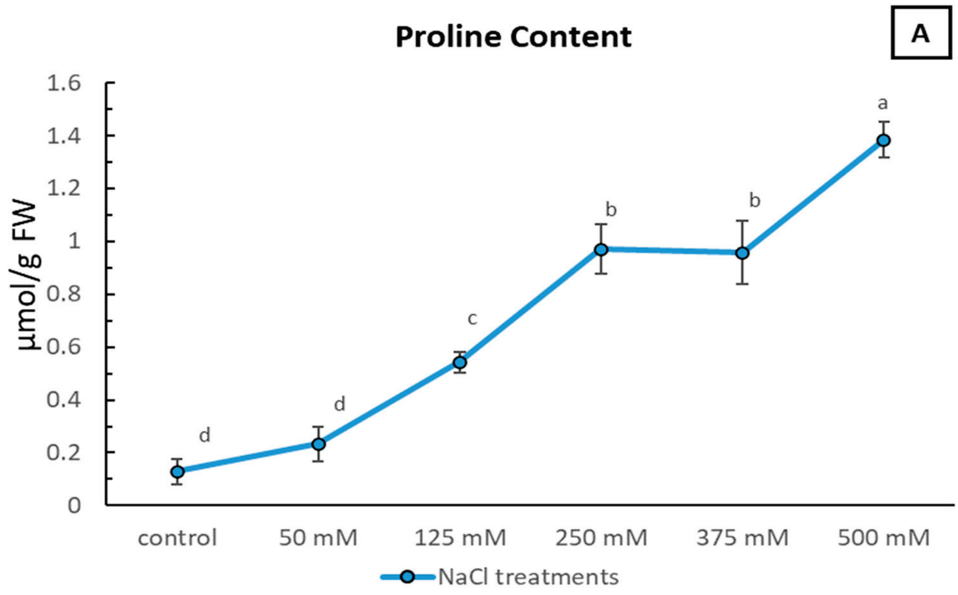


Figure 4. Leaves' Na content of *Limonium gmelinii* subsp. *hungaricum* in sandy soil under different NaCl levels (mM). Data represent averages of ten replications ± SD. The various letters indicate a significant variance between treated plants. $p < 0.05$ from Tukey's multiple-range test.

2.4. Proline Content Response of Limonium gmelinii subsp. hungaricum Leaves to Increasing NaCl Concentrations in Sandy and Clayey Soils

In sandy soil (Figure 5A), the proline content of *Limonium gmelinii* subsp. *hungaricum* leaves was observed to increase significantly with increasing NaCl concentrations. The control group, with no added NaCl, had a proline content of 0.128 μmol g^{-1} FW. However, when exposed to 50 mM of NaCl, the proline content increased by over 80%. This trend continued with even higher concentrations of NaCl, with the proline content reaching a peak of over 1100% greater than the control group at 500 mM. Interestingly, at 375 mM, the proline content dropped slightly, but still remained well above the control group.

In clayey soil (Figure 5B), the proline content also increased with increasing NaCl concentrations, but to a much lesser extent than in sandy soil. The control group in clayey soil had a proline content of only 0.005 μmol g^{-1} FW. Even at the highest concentration of 500 mM, the proline content only increased by over 200%. The proline content in clayey soil was consistently lower than that of sandy soil at each NaCl concentration. Overall, it can be inferred that *Limonium gmelinii* subsp. *hungaricum* leaves are better adapted to handling salt stress in sandy soil than in clayey soil.



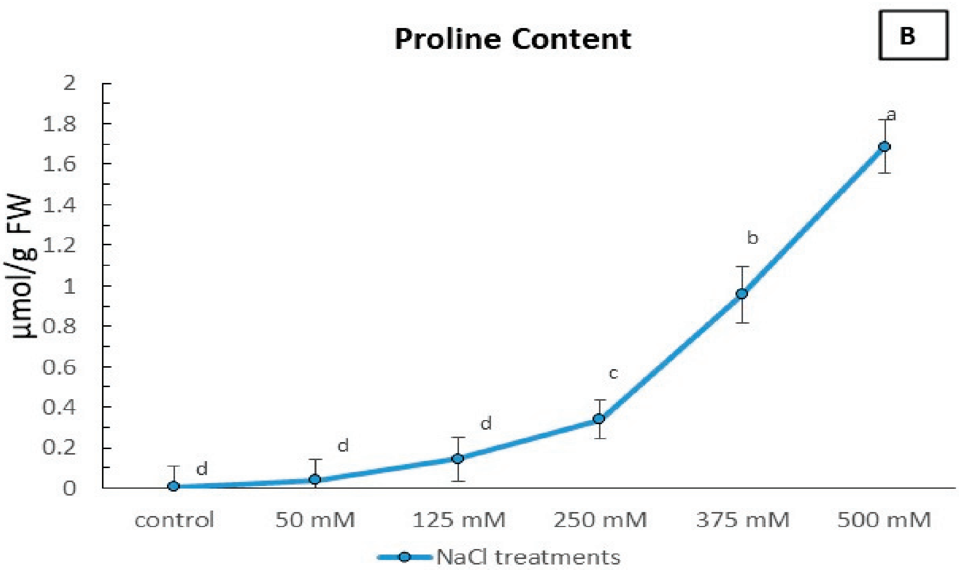


Figure 5. Effect of NaCl stress on proline content under sandy soil and clayey soil. Proline content of *Limonium gmelinii* subsp. *hungaricum*, under different NaCl levels in sandy soil (**A**) and clayey soil (**B**); data represent averages of ten replications ± SD. The various letters indicate a significant variance between treated plants. $p < 0.05$ from Tukey's multiple-range test.

3. Discussion

Salt stress induced by NaCl is one of the most frequent and widely studied abiotic stresses in controlled and natural environments [30]. Plants are subjected to high-salt conditions, which might impair photosynthesis, and diminish the fresh weight and dry matter accumulation in the plant [21]. The detrimental effects on the formation of plant biomass are attributed to osmotic stress, nutritional insufficiency, and ionic toxicity induced by NaCl, which impacts physiological status [31,32]. This is compatible with findings that NaCl inhibits the plant's capacity to absorb water, resulting in delayed growth; additionally, when there is an excessive amount of salt present in the transpiration stream, it can eventually lead to damage to the cells in the leaf that is undergoing transpiration, thereby further inhibiting growth [1].

Understanding how halophytes respond to salt is crucial to their further evolution and practical application. It is possible to extrapolate a plant's salt tolerance from its threshold of salt tolerance. In this investigation, we examined to what extent *L. gmelinii* subsp. *hungaricum* can tolerate salt stress and the vital role of soil texture in ameliorating the negative impact of saline conditions.

According to the findings illustrated in Figure 2, NaCl treatments had a significant impact on the growth and development of *Limonium gmelinii* subsp. *hungaricum* in both sandy and clayey soil. In the sandy soil (Figure 2A–C), the fresh weight and dry weight of the plants decreased with increasing NaCl concentration, ranging from 17.4% to 57% and 10.1% to 39.3%, respectively, compared to the control treatment. This decrease in fresh weight and dry weight was accompanied by a decrease in the length and width of the leaves. Likewise, Mi et al. noticed a significant reduction in the fresh weight of all four Limonium species, namely *L. aureum*, *L. gmelinii (Willd.) Kuntze*, *L. otolepis*, and *L. sinuatum* Mill., when exposed to a concentration of 400 mM NaCl. Among these species, *L. gmelinii* showed the least reduction in leaf fresh weight, with only 49% of that of the control [21]. Low or moderate salinity stimulates growth in a few salt-tolerant halophytes, whereas salt above a species-specific concentration threshold inhibits growth [33]; hence, the growth parameter is a vital indicator for assessing the degree of salt tolerance of the plant [34]. Likewise, Jangra et al. [35] observed that salinity reduced the fresh weight, dry weight, and leaf area of *Sorghum* plants. In a comprehensive study by González-Orenga et al. [14] on different *Limonium* species (*L. albuferae*; *L. dufourii*; *L. girardianum*; *L. narbonense*; *L. santapolense*; *L. virgatum*), it was investigated that growth was enhanced at 200 and even 400 mM NaCl, and was only suppressed at higher salt levels. Mi et al. [21] determined the salinity-tolerated threshold of *L. gmelinii* at 420 mM NaCl, while our work reached 500 mM in most estimated parameters. Therefore, our results suggest that the optimal growth of *L. gmelinii* is under low NaCl levels, and it could maintain their survival under moderate and high NaCl levels (250 and 500 mM).

On the other hand, in the clayey soil (Figure 2D–F), the relative dry weight increased with increasing NaCl concentration up until 375 mM, where it showed an increase of 12% compared to the control treatment. Beyond 375 mM, the dry weight decreased by 19%. The leaf length and width showed varying responses to the NaCl treatments in the clayey soil, with the leaf length reaching its maximum at 375 mM and the leaf width gradually increasing up until 375 mM. However, beyond 375 mM, both the leaf length and width decreased, suggesting that there is an optimal range of NaCl concentrations for *Limonium gmelinii* subsp. *hungaricum* to grow optimally. The different effects of NaCl treatments on the growth and development of *Limonium gmelinii* subsp. *hungaricum* in sandy and clayey soil are likely due to differences in soil properties, such as water-holding capacity, nutrient availability, and ion toxicity. Similarly, [36], the absence of plant biomass losses in a clayey medium implies that finer textures mitigate salinity stress compared to a coarser soil texture (sandy soil).

Photosynthesis is a useful physiological metric for assessing plants' response to salinity stress and determining stress-tolerant species, as it directly represents the plants' photosynthetic capacity. Salinity stress is a known inhibitor of plant photosynthesis [37], and, consequently, biomass accumulation [21]. As non-enzymatic antioxidants, carotenoids are essential in preserving the photosynthetic system and regulating plant growth, in which plants synthesize abscisic acid from carotenoids via the mevalonic acid pathway under stressful conditions [38]. Our results in both soil types suggests that the salt tolerance of *L. gmelinii* evaluated in this work is primarily attributable to variations in the degree of photosynthetic pigment damage caused by increasing salt concentration (Figure 3A–D). In sandy soil, the results showed that the control group had a constant level of chlorophyll, with a modest reduction observed at 50 mM NaCl and then an increase at 125 mM NaCl. The highest concentration of chlorophyll was recorded at 375 mM NaCl, showing a 14.4% increase compared to the control group. On the other hand, the carotenoid content in sandy soil exhibited a divergent trend, with an increase observed with higher NaCl concentrations, peaking at 375 mM NaCl with an 18.6% increase compared to the control group.

In clayey soil, the results showed that the control group had a moderate concentration of chlorophyll, which decreased at 50 mM NaCl, but then increased at 125 mM NaCl. The highest concentration of chlorophyll was recorded at 250 mM NaCl, where the concentration increased by 38% compared to the control group. The carotenoid content in clayey soil showed a similar trend, with the highest concentration observed at 500 mM NaCl, where the concentration increased by 70% compared to the control group. This is further supported by the findings of [39], who reported that halophytes utilize specific mechanisms to protect themselves from photo-damage, such as dissipating excess energy generated during photosynthesis. Additionally, [40] found that the levels of Chl a, Chl b, total chlorophyll, Chl a/b, and carotenoids in *S. maritima* seedlings were unchanged in response to salinity stress, further supporting the importance of these pigments in halophyte tolerance to salt. A comparable study confirmed a correlation between the increase in carotenoids in two types of halophytes, *Arthrocnemum macrostachyum* and *Sarcocornia fruticose*, and enhanced salt tolerance, as a method to maintain chlorophyll amount, along with different NaCl levels [26].

In halophytes species, the salt accumulation of the plants' aerial part sections matched their salt-tolerant strategy [22]. By secreting extra sodium and potassium salts, *L. gmelinii* plants can adjust their salt level [23]. The findings from the study of *Limonium gmelinii* subsp. *hungaricum* grown in sandy substrate reveal the plant's capability of regulating its internal sodium (Na) content in response to external conditions. As observed in Figure 4, the control treatment recorded an average Na content of 1.13 g/100 g fresh weight. With the progressive increase in NaCl levels, the Na content in the leaves also increased, reaching a maximum of 3.47 g/100 g fresh weight at 500 mM NaCl, a 205% increase on the control treatment. This result is in agreement with previous studies that have demonstrated the ability of plants to respond to salinity stress by adjusting their internal Na levels. For instance, a study by [25] showed that increasing NaCl concentrations resulted in a significant increase in Na content in the leaves of halophytes, including *Limonium bicolor* and *Limonium gmelinii*. Several studies have explored the underlying mechanisms of Na uptake and transport in plants. For example, a study by [41] found that the expression of genes involved in Na uptake and transport was regulated in response to increasing NaCl levels in the leaves of the halophyte *Suaeda salsa*. Additionally, halophytes, specifically recretohalophytes, have a unique advantage over other halophytes and non-halophytes in maintaining cellular ion homeostasis. They are able to directly secrete high levels of salt ions onto the leaf surface through specialized structures called salt glands. This makes them exceptional in handling the challenges of salinity compared to other classes of plants [22,42]. Salty glands regulate osmotic pressure and promote salt tolerance by preserving ion equilibrium [43]. Sodium glands regulate the leaf's internal ionic composition in the chloroplast and cytosol, which prevents leaf cell dehydration and enhances photosynthesis [14].

Proline is a non-essential amino acid that can adjusts osmotic pressure and act as an osmoprotectant, helping the plant to maintain its water balance in the face of high salt concentrations [44]. It is also a powerful antioxidant, helping the plant to protect itself against the damage caused by high salt concentrations [27]. In halophytes, osmotic equilibrium is accomplished by accumulating uncostly energy ions, such as Na^+ and Cl^-, and osmolyte solutes with low molecular weight [45].

In sandy soil, the leaves were able to produce a significantly higher amount of proline, a molecule known to help protect plants from the damaging effects of salt (Figure 5A). As NaCl concentrations increased, the proline content in the leaves of these plants skyrocketed, reaching levels over 1100% higher than the control group, in the most extreme condition.

In contrast, the proline content in clayey soil was much lower, and despite increasing with higher NaCl concentrations, it never reached the same levels as in sandy soil (Figure 5B). This suggests that *Limonium gmelinii* subsp. *hungaricum* leaves are adapted to handle salt stress in sandy soil. Similar results have been found in numerous halophyte species, where proline content increased in response to salt stress [46]. Additionally, the substantial accumulation of proline observed at a high NaCl level in irrigation water compared to unstressed conditions and the observed fluctuations in proline content may be caused by subsequent mitochondrial damage and repair during the pro-oxidation process [47,48]. *Limonium* species' tolerance to salinity was mainly based on the active transport and buildup of ions in the leaves, along with the simultaneous production of soluble sugars and proline as compatible solutes for osmotic regulation. The halophyte cytoplasm's synthesis and the accumulation of osmolytes maintain osmotic equilibrium under stress, to compensate for inorganic ion accumulation in vacuoles [14].

The results from the study of *Limonium gmelinii* subsp. *hungaricum* in clayey soil were quite intriguing. The plants showed a slight improvement in growth and development, even when subjected to increasing salt concentrations (Figure 2D–F), and the lower proline content with increasing NaCl level until 375 mM compared to that in sandy soil (Figure 5B), despite the same concentrations of NaCl being applied. This may indicate that soil structure is closely connected to the soil's ability to adsorb or desorb chemical ions [49], so a portion of the Na^+ in the salty water was likely absorbed and accumulated by clayey soil particles and became less accessible to the plant, due to the clayey soils' lower leaching rate and larger soil surface area, which can help to reduce ion toxicity and improve plant growth [50]. As a result of their role as sites of cation exchange for soils, clays also serve as a source of extra exchangeable Na^+ [49]. Thus, clayey soil with finer texture retains more water, reducing drought-related salinity stress and production losses, as the ionic components of finer-textured soils are regarded as macronutrients, a feature attributed to their response to specific ion impacts [36]. On the contrary, sandy soils have limited nutrient- and water-holding capacity and high infiltration rates [29]. In general, sandy soils would be preferred for irrigation at highly saline levels [51]; however, more essential plant nutrients leached from the sandy substrate than from clay-textured media during the applied irrigation [50]. Panta et al. [50] hypothesized that soil texture and nutrient-holding ability may have played a role in the increase in chlorophyll content and stomatal conductance, as well as the naturally high nutritional content of the clay soil, which may have benefited plant growth. However, beyond a certain concentration, the accumulation of ions in the soil can become toxic and result in reduced growth and development, as seen in the decrease in dry weight and leaf length and width of the plants grown in both soils at 500 mM NaCl treatment (Figure 2).

This is the first study of *Limonium gmelinii* subsp. *hungaricum* in clayey soil and it has exhibited the ability to survive and grow better than in sandy soil, despite increasing salt concentrations. However, further research is needed to confirm these findings and to determine the mechanisms behind these changes.

4. Materials and Methods

4.1. Material, Cultivation Conditions, and Trial Layout

Seeds of *Limonium gmelinii* subsp. *hungaricum* were collected in the Apajpuszta region, Hungary, in October 2019. A total of 3–4 leaf-containing plugs were grown from these seeds in 104-hole Teku® trays in Pindstrup Blond Gold substrate (Figure 6). A total of 180 plants were potted in pure river sand in 7 × 7 × 8 cm black Teku® containers, in order to model the salt tolerance of the species. Another 180 plants were potted in 40% clay containing Pindstrup Blond Gold substrate in 7 × 7 × 8 cm black Teku® containers, in order to model the original soil. The experiment was carried on in a glasshouse, with day temperature 20 ± 5 °C, night temperature 16 ± 5 °C, and relative air humidity 60 ± 5%. Based on the experiment of Geissler et al. (2009), plants of both groups were irrigated with different concentrations of NaCl as follows: control with tap water, and further groups with 50, 125, 250, 375 and 500 mM NaCl solution twice a week, in a 50 mL container. The treatment solution of plants grown in sand was enriched with 2 g/L Yara Mila Ferticare 14:10:18 NPK fertilizer. The experiment was set up in a random block layout, with 6 repetitions, 5 plants per repetition, and each pot containing 1 plant.

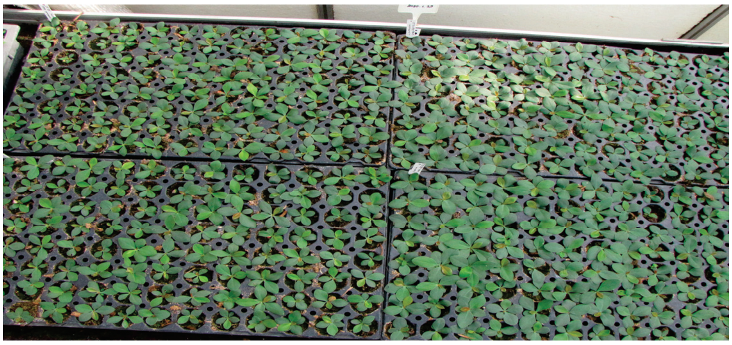


Figure 6. 3–4 leaf-containing plugs in Teku® trays in Pindstrup Blond Gold substrate.

4.2. Morphological Characteristics

After 12 weeks, the morphological parameters of the plants were measured: leaf length, plant diameter and leaf diameter were estimated using a measuring tape. Since the plant diameter is roughly twice the leaf length, this parameter was not measured in the experiment planted in sand. The fresh weight of 10 randomly chosen plants per treatment was calculated. The root and shoot were then placed in separate paper bags and dried in an oven. The dry weight of the root and shoot was recorded after the samples were dried at 105 °C for 15 min and 75 °C for three days [52]. The dry matter content was determined by dividing the dry weight of the leaves by the fresh weight, and expressed as a percentage [53]. The height of the plants was measured using a tape measure.

4.3. Chlorophyll, Carotenoid and Proline Determination

Leaves of the same position were taken from 6 × 5 plants per treatment; an average sample was prepared from them and used for the following determination:

The measurement of photosynthetic pigments involved grinding 0.1 g of fresh weight (FW) of leaves in 80% cold acetone and centrifuging the mixture at 5000× *g* for 10 min. The absorbance of the purified chlorophyll samples was then recorded using a UV–VIS Spectrophotometer (Genesys 10S, Waltham, MA, USA) at 470, 646, and 663 nm. The chlorophyll and carotenoid contents were calculated based on the method described by [54].

The impact of the treatments on the stress state of the plants was assessed by determining the level of proline, using a method described in Reference [55]. This involved grinding 300 mg of fresh leaves in a solution containing 3% aqueous sulfosalicylic acid and filtering the mixture through Whatman no. 1 filter paper. The resulting filtrate was mixed with acid ninhydrin and glacial acetic acid and heated at 100 °C for 1 h, then cooled on ice for 15 min. Toluene was added, and the mixture was vortexed for 20 s before measuring the absorbance of the upper phase at 520 nm, using a spectrophotometer. The proline concentration was then calculated and reported as $\mu mol g^{-1}$ FW.

4.4. Determination of Sodium Content in Leaves Grown in Sand

The condition of the leaf samples grown in sand was determined using a flame photometer, following the method outlined by [56]. A dry plant sample of 2 g was ground to a particle size of 2 mm and incinerated in a muffle furnace at 600 °C for 4 h. The ashes were treated with 40 mL of 30% HCl and 5 mL of HNO_3, filtered and cooled, and the resulting solution was diluted with deionized water to a volume of 250 mL. The sodium (Na^+) content was then determined, using the flame photometer Na^+ content in leaves.

4.5. Statical Analysis

The experiment was set up in a completely randomized design. The Two-Way MANOVA followed by UNIANOVA for the variables with Bonferroni's correction was run for all dependent variables, between factors at two levels: 1.Treatments (control, no salinity stress) and NaCl treatments (50, 125, 250, 375 and 500 mM); 2. Soil type: sandy and clayey. It was assumed that the normality of the residuals for all dependent variables were accepted by the Kolmogorov–Smirnov test ($p > 0.05$) [57]. The homogeneity of variances established by Leven's F test was satisfied for all dependent variables $p > 0.05$ [58]. Tukey's post hoc test was used for factor level comparisons [59,60]. Pairwise within-subject effects were compared using Bonferroni's method. All statistics were conducted using the software IBM SPSS27, Armonk, NY, USA [60].

5. Conclusions

In conclusion, the effect of NaCl stress on the growth and development of *Limonium gmelinii* subsp. *hungaricum* in sandy and clayey soil was analyzed. The results showed that the plant's growth and development were impacted by the NaCl treatments in varying ways. In the sandy soil, the plant's fresh weight and dry weight decreased, while its relative dry weight increased. The leaf parameters of length and width were also impacted, with a decrease observed in both. The decrease in biomass coincide with increases in proline concentration and leaf NaCl content with higher salt stress. In the clayey soil, the relative dry weight increased with increasing NaCl concentration, while the fresh weight showed a peak at 250 mM NaCl and decreased thereafter. The parameters of the leaves (length and width) increased until 375 mM NaCl and decreased thereafter. Additionally, a significant proline accumulation increment was seen only with the higher NaCl levels in clayey soil. The pigment content of the plant was also impacted by the NaCl treatments, with a moderate reduction observed at 50 mM NaCl, followed by an increase at higher NaCl concentrations, peaking at 375 mM NaCl for both chlorophyll and carotenoid content in sandy soil, and 250 mM NaCl for chlorophyll content and 500 mM NaCl in clay soil. These results suggest that there is an optimal range of NaCl concentrations, ranging from 50 to 125 mM, for *Limonium gmelinii* subsp. *hungaricum* to grow optimally, while 500 mM NaCl had the most negative effect on *L. gmelinii* growth, and that substrate texture also plays a role in the plant's response to salt stress.

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Multimodal Interaction of MU Plant Landscape Design in Marine Urban Based on Computer Vision Technology

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Abstract: At present, there is a growing focus on the landscape and environment of ocean cities, with an increasing demand for improved ecological sustainability and aesthetic appeal. With the emergence of computer vision design technologies such as 3D and VR, people have overcome the limitations of traditional paper-based design materials. Through the use of computer software, various forms of expression, such as drawings and animations, can be produced, thereby meeting the diverse demands for showcasing plant landscapes. The purpose of this paper is to study the design of marine urban (MU) botanical landscapes based on computer vision technology (CVT) and multimodal interaction design (MID) theory, so that the design of MU botanical landscape can meet people's psychological behavior and visual needs, and at the same time enable people to participate in and experience the landscape, so as to better meet people's needs for viewing, leisure, and entertainment. At the same time, it is hoped that the research of this paper will play a role in promoting the innovation and development of the concept of MU landscape design (LD) in the future, specifically from two levels of theoretical and practical significance. First, at the level of theoretical research: Based on the theory of MID, this paper explores the application of communication and interaction among humans and between humans and the landscape in the design of MU planting, and tries to explore and summarize the content and methods of interactive LD in marine cities with a theoretical basis and research value. The goal is to both enhance the theoretical level of interactive LD, and also provide new reference for future marine city (MC) LD. Second, at the level of practical application: In the field of LD, the new concept of computer vision is introduced to fully understand the visual needs of people and increase the practicality and pleasantness of the MU landscape, hoping to attract more people to come to play and rest. Through the attraction of MU landscapes to tourists, the design and construction of the landscape no longer focus on its appearance, but rather on the participation and experience of people.

Keywords: marine city; plant landscape; computer vision technology; multimodal interaction; five-view plant system

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1. Introduction

Botanical landscaping is the only way to create a beautiful visual effect of nature's plants, whether in single or group form, so that people can experience the beauty of this effect from the inside out. Plantscaping includes not only the naturally formed plantscape, but also artificial pruning and landscaping to create the perfect plantscape. At present, many gardening companies benefit from the VR industry and have realized its application. Australian architect Beau B. Beza's team used interactive experience technology to capture and represent the famous botanical landscape of Geelong's eastern coastal reserve in Australia. At present, most of the research and applications of multi-modal interactive technology in landscape architecture focus on planning and design, and less attention is paid to garden plant landscaping. At the same time, the existing research also lacks the distinction and summary of applying modal interaction technology to landscape architecture. In terms of practical application, it is mainly used to display and communicate the scheme, analyze the design process, teach garden plant landscaping, etc. The use of aspects is also rare.

Many scholars in China have started to discuss what kind of marine urban (MU) landscape environment is the most ideal environment for recreation and play. In the process of MU planting design, the direction of research has shifted to the analysis of low-carbon and ecological landscape environment design, but they are still inseparable from human participation. In China, there are a large number of relevant theoretical studies on interaction design, marine cities, and planted landscape design (LD), but relatively few research institutions and researchers are engaged in multimodal interactive LD research [1]. With the increasing demand for tourism, MU landscaping as an important part of urban planning has become the highlight of urban landscaping, and people's love for marine nature makes people more inclined to approach marine landscapes. People pay increased attention to the needs of tourists in the construction of marine cities, and they pay attention to the enjoyment and experience of environmental recreation. However, most of the current research on the design of MU planting focuses more on the form and visual impact, while ignoring the communication and interaction among people and between people and scenery [2,3]. Therefore, it is necessary to analyze its importance to plant LD from the perspective of interactive design.

Based on plant design, this paper points out the necessity of plant LD in marine cities by describing the research background of plant LD in marine cities. A design analysis of the four functional areas of a marine city is then carried out with a case study of the coastal plants in Sanya Bay, China. Finally, the design interaction effect of computer vision technology and the multimodal interactive design on the plant landscape of the marine city is analyzed through interviewees' evaluation of the multimodal interactive design effect based on computer vision technology. We discuss the multi-modal interactive design of marine city plant landscaping through analysis and research on the relationship between interactive design and maritime city plant landscaping. Integrating the concept of multi-modal interaction into plant landscaping maximizes the role of plants in improving the environment to further the sustainable development of ocean cities. The resulting innovative value is mainly reflected in the expansion of design performance tools and display methods, the incremental innovation of traditional thinking methods, and the diversification of landscaping effects. Through the interactive design concept combined with the current situation of local plant landscaping in Sanya City, the corresponding scientific improvement methods and optimization methods are proposed to create a beautiful marine city plant artistic image and local style characteristics, which have particular theoretical research significance and practical value.

2. Basic Overview

2.1. Concept Introduction

(1) Features of MU plant LD

Coordination: Plant LD should consider the cooperation among individual plants and between individuals and the whole, so that the landscape reflects mutual integration and comfortable and pleasant aesthetics. Determining the similarities and similar characteristics among plants so that the plants match will make people feel coordinated. On the contrary, the contrast effect can be reflected by differences between plants, so that the whole space has contrast, giving people a feeling of excitement and stimulation. This technique is often used in plant landscaping to highlight the theme of a certain area or to draw people's attention to something [4].

Recreation: Recreation includes play and rest, and the design of MU planting should not only meet the playful nature of visitors, but also provide resting places. Recreational activities need to be realized with the help of a certain external environment, the same activity subject in a different external environment, and different recreational experiences [5].

Ornamental: Ornamental MU plants are plant species with a landscape ornamental function as the main feature and ecological benefits as a supplement. The ornamental nature of MU plants is mainly reflected in the rich colors, different forms, and distinct textures of plants.

(2) CVT

Computer vision technology includes the fields of image recognition, target detection, vision-based simultaneous localization and map building, depth estimation, etc. It is an emerging technology that involves many disciplines, is comprehensive, and has broad application prospects [6].

The binocular depth estimation algorithm captures binocular images after polar alignment correction using a stereo matching algorithm to calculate a reference image. The most commonly used conventional algorithm for binocular vision is the SGBM algorithm (semi-global block matching) known as the semi-global algorithm. The SGBM algorithm first preprocesses the image using the Sobal operator and afterwards calculates the matching cost. The matching cost consists of two parts: the first part is to calculate the BT (Birchfield Tomasi) cost for the preprocessed image and the second part is to calculate the BT cost for the original. The BT cost is developed on the basis of the AD (absolute differences) cost. The AD cost is the absolute value of the pixel gray value difference, and the AD surrogate value of the pixel I_R(x, y) in the left pixel and the pixel with parallaxd in the right image is:

$$e(x, y, d) = |I_R(x, y) - I_T(x + d, y)| \tag{1}$$

The BT cost is similar to the AD cost; the difference is that the BT cost uses the grayscale information of sub-pixels to reduce the effect of noise. the formula of BT cost is shown in Equations (2) and (3), where, represent the pixel intensity functions of the left and right cameras, respectively; x_i and y_i are the two pixels in the left- and right-eye images for which the dissimilarity is to be calculated; I_L represents the linear interpolation of the left pixel function and I_R represents the linear interpolation of the right pixel function. The calculation result of Equation (2) represents the dissimilarity between pixel x_i and the pixel in the region near y_i, and the dissimilarity between the final pixels is determined by this value and the minimum value of the dissimilarity with its symmetry:

$$\overline{d}(x_i, y_i, I_L, I_R) = \min_{y_i - \frac{1}{2} \le y \le y_i + \frac{1}{2}} \left| I_L(x_i) - \hat{I}_R(y) \right| \tag{2}$$

$$d(x_i, y_i) = \min\left\{ \overline{d}(x_i, y_i, I_L, I_R, \overline{d}(y_i, x_i, I_R, I_L) \right\} \tag{3}$$

(3) Multimodal interaction

People's feelings about a landscape are multifaceted, and in the process of experiencing and participating in LD, the landscape stimulates different human senses. In MU interactive LD, human senses are stimulated by different degrees of interactive landscapes, triggering associative effects and prompting a good landscape experience [7]. The MU plant landscape multimodal interactive design concept mainly includes visual, auditory, olfactory, and tactile interaction, while gustatory interaction, although not the main marine correctional plant LD interaction concept, also contributes to multimodal interaction, as shown in Figure 1.

Visual interaction: People feel differences in color, shape, distance, and movement of things through visual perception, which has an impact on their thinking and psychological feelings. In MC interactive LD, visual interaction is used as the main means to attract people to participate in interaction. A clever shape design can mobilize the active participation of visitors. The use of different colors also stimulates people's vision and brings different feelings to their psychology. The use of colors with higher brightness stimulates the visual senses and generates visual interaction [8].

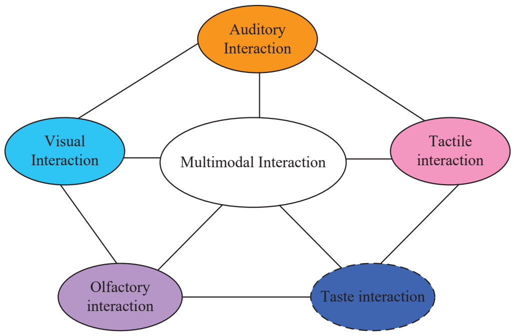


Figure 1. MID concept.

Auditory interaction: In the interactive LD of marine cities, auditory senses play a large role. Sounds of nature, such as the sound of waves, the chirping of birds, and the sound of wind blowing leaves in the MC, increase the vitality of the MC while visitors can experience physical and psychological relaxation. The sound of various landscape facilities and modern art media as well as people's conversations stimulates people's auditory senses and causes different emotional behaviors [9].

Olfactory interaction: Smell is mainly transmitted through scent, and a good smell can elicit a pleasant feeling. In marine cities, the elements that can convey scents are soil, flowers, trees, etc., and artificially added scents. In MC interactive LD, scent is used to influence the viewers' perceptions and then expand the scope of the interaction between humans and the landscape. Scent can be used to induce people to interact with the landscape; for example, the fragrance of flowers can induce people to come closer to smell them. However, the transmission of smell has certain limitations; generally, the perceptible distance does not exceed 3 m. Based on the different characteristics of each person's sense of smell, the principle of moderation should be employed during the design [10].

Tactile interaction: touch is the feeling produced by skin receptors in contact with mechanical stimuli, which is one of the most real feelings of human contact with things. In the interactive LD of marine cities, facilities of different materials and plants of different textures are set up to let people get close to the landscape through touch.

2.2. Literature Review at Home and Abroad

In October 2018, the Chinese State Council emphasized its commitment to further promoting the development of China's new generation of artificial intelligence (AI). As a result, many high-tech companies are gradually entering the AI industry. The rapid development of digital media technology in the context of smart city construction has promoted urban information exchange, enhanced connectivity, and promoted intelligent design and innovation. This development is moving towards system coordination and resource consolidation [11]. Technologies such as the Internet of Things, cloud computing, big data, and mobile Internet have enabled different functional structures in cities to coordinate with each other, resulting in intelligent, digital, and intensive urban management and operations. These advancements have provided people with more convenient services. Interactive landscapes embody the characteristics of intelligent cities, specifically the intelligent provision of services and interactive experiences. This facilitates collaborative and innovative development between the landscape and the intelligence of the city, as well as the provision of intelligent urban services [12]. The application of interactive technology in landscape design strengthens the connection between the landscape and people, space, and city. The use of digital media technology enhances the effect of the landscape and satisfies diverse needs of people.

The term "human–computer interaction" was first proposed in 1975, and its concept was popularized by the book The Psychology of Human-Computer Interaction by Card in 1983. The term "interaction design" was first proposed in 1984 by Bill Moggridge, one of the founders of IDEO [13]. Since then, scholars around the world have started to research and pay attention to this field. In 1997, Hiroshi Ishii and Brygg Ullmer from the MIT Media Lab proposed the concept of Tangible Bits, which involves coupling bits with everyday physical objects to allow users to directly grasp and manipulate them [14]. In 2013, Israeli scholars Oren Zuckerman and Avelet Gal-Oz concluded that due to the rich physical feedback information and more advanced forms of interaction brought by TUI (tangible user interfaces), it is recommended to promote the use of TUI-based interaction methods for human–computer information interaction [15]. Since then, many landscape architects, artists, and architects involved in human–computer interaction have been engaged in scientific research and design practices in this field, and research on interactive design of landscapes has followed.

Alan Cooper mentioned in his book The Road to Interactivity Design-Bring High-Tech Products Back to Humanity that combining scientific technology and digital media content with landscape design can provide people with a fresher experience [16]. In addition, Alan Cooper proposed in his book Software Concept Revolution: *The* Essence of Interaction Design that the core of interactive landscape design should focus on the relationship between people and the landscape [17]. His research emphasizes the leading role of people in landscape and interaction processes, which has become a core issue in later research.

Integrating the concept of "interaction design" into landscape design, using modern science, theory, and materials, and integrating new technological methods and artistic forms, can create landscapes that are in line with the characteristics of the site and meet usage needs. By involving people as components in landscape design, communication and interaction between people and the landscape can be achieved [18]. This facilitates the concentration of functions, the sharing of information, the integration of resources, and the participation of human intelligence. As part of urban construction, the research and development of interactive landscapes should constantly reshape the relationship between people and the world, provide new methods for addressing the shortcomings of traditional landscapes, and offer new pathways for fully integrating landscapes into urban systems. Applying the concept of intelligent design, interactive landscapes should continue to be developed with deeper research and broader applications.

2.3. The Necessity of Combining the Characteristics of MC Plant LD, CVT, and Multimodal Interactive Design

By analyzing the concepts of MU LD features, computer vision and multimodal interactive design, we find that there are similarities between these three.

Through the design of interactive landscapes in marine cities, landscapes and people can establish an organic connection, so as to effectively achieve the objectives of use and promote understanding and communication between people. To achieve this, however, it is important to follow the usability goals of interactive landscapes as well as the goals of good participant experience [19].

At this stage, marine cities are becoming more and more important in people's daily lives, and the main purpose of MC plant LD is to provide tourists with places to visit and rest, so that the process of their experience can enrich their sensory experience and give them great satisfaction in both physiological and psychological aspects [20].

The two goals of usability of plant LD and good participant experience together serve the interactive LD of marine cities. The usability goal focuses more on the landscape product itself, while the participant experience goal considers the ideas and needs of people, and the two together promote the application and development of interactive LD in marine cities [21].

This paper selects computer vision software suitable for plant landscaping in ocean cities and proposes a general process for applying intelligent interactive technology to plant landscaping in ocean cities. This provides a certain supplement and improvement to the theoretical research in related fields and provides reference for the practice of multimodal interactive design of plant landscaping in ocean cities in the information age. Thus, it promotes the application of multimodal interactive technology in the landscape architecture industry. Practically, more research on the integration of the three has to be conducted:

(1) Beneficial for designers to refine their design proposals. Through the use of 3D and virtual reality (VR) interactive technology, designers can observe their design proposals in multidimensional virtual environments. This benefits them in conducting further analysis, deduction, and refinement of their design works, enabling them to promptly identify issues and reduce design flaws.
(2) Beneficial for presenting design proposals. Multimodal interactive technology has brought about a revolution in the field of landscape design representation. Viewers can not only intuitively experience the effects of the scene after construction, but also obtain more information from the scene through human–computer interaction, achieving information interaction. Moreover, virtual reality (VR) interactive technology supports demonstrations on both computers and mobile devices, greatly expanding the channels for presenting and communicating design proposals.
(3) Beneficial for communication between designers and decision makers. Through the use of computer VR multimodal interactive technology, property owners can view design proposals from multiple angles in virtual scenes according to their preferences, experience the site environment firsthand, and intuitively understand the designer's design intentions. This is something that cannot be achieved with renderings, sand table models, or animations. After fully understanding the design intentions, property owners can communicate and negotiate more effectively with designers, and their opinions are also more targeted.

With the coming of the 5G era, intelligent design will further integrate and develop with global research and development, manufacturing, module, and other resources, enabling maximum information sharing and communication among all parts of the city. It will continue to evolve towards a more information-based, digitalized, and intelligent system. The most essential attributes of the landscape in ocean cities are interactivity and publicness. Therefore, the development of interactive landscapes plays an important role in the research and development of plant landscape design in ocean cities. Urban plant landscape design guided by interactive concepts always incorporates interactive thinking throughout the entire process, from conception to presentation. The rapid development of technologies such as big data, the Internet of Things, cloud computing, and artificial intelligence provides great possibilities for the realization of smart landscapes, promoting the development of the "smart" concept. Future explorations of smart spaces based on sustainable development principles will become an important trend in the development of ocean urban landscapes [22].

2.4. MU LD Based on Multimodal Interaction

(1) Interactive water body LD

The water body LD of marine cities takes interactive design as the core, considers the relationship between water body landscape and terrain, people, and roads, and coordinates the relationship between them to achieve good communication and an interactive experience between people and the water body landscape.

Relationship between the water landscape and the site: When designing the water landscape of the ocean city, the topography, soil, climate, and water table of the ocean city will be surveyed and investigated in the field to determine whether the location is suitable for developing the waterscape and how to design the waterscape. Secondly, we should focus on how the water feature is related to human recreational activities, and combine human behavior and psychological needs to design a reasonable interactive water landscape.

Relationship between water landscape and roads: There is also a close relationship between water landscape and roads in urban parks. Roads are the main way for people to enjoy waterscapes, as they connect all waterscapes in the city [23]. Based on the concept of interactive design, people are guided to carry out hydrophilic activities through landscape facilities such as plank roads and Tingbu, so that visitors can have a relaxing and pleasant experience in the ocean city.

Relationship between water landscape and people: It is human nature to be hydrophilic and to be close to water. Therefore, landscape planners should increase opportunities for interaction between people and the water landscape, such as wading, playing in water, being hydrophilic, and watching water. As shown in Figure 2, when people enter the water to experience it, this is considered wading activity. When the distance between people and water is $0 < s \leq 2$ m, it is playing in water activity. When the distance between people and water is $2 < s \leq 50$ m, people are considered to be hydrophiliced, and if the distance between people and water is >50 m, people are engaging in water-viewing activity. These activities can make people have a variety of waterscape experiences and can narrow the distance between people and the waterscape.

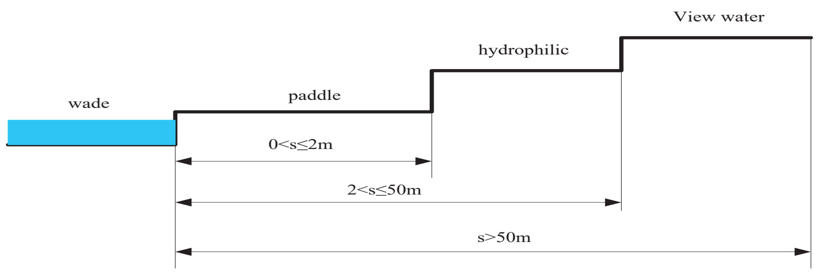


Figure 2. The effect of distance on human hydrophilicity.

(2) Interactive landscape facilities design

The concept of interactive design is introduced into the design of landscape facilities, adhering to the principle of interactive participation, providing quantitative services for someone visiting the marine landscape, and promoting a good interaction between people and facilities [24].

First, the design of interactive landscape facilities should be human-centered. In the design, designers should always consider the functional use by people, so that people's needs are satisfied through the landscape facilities. For example, guiding signs and advertising boards of the ocean city guide visitors on tour routes and provide science education, and ocean sunscreen chairs provide opportunities to rest.

Second, the design of interactive landscape facilities should be universal. Generic designs should mainly consider disadvantaged groups, e.g., the mobility and hearing impaired, pregnant women, or individuals with chronic diseases, among other groups of people, and they should be concerned about taking care of their psychological emotions and increasing their use of landscape facilities.

Next, the design of interactive landscape facilities should be easy to use. First, the spatial scale should both meet the psychological and usage needs of people and be scientific and reasonable. For example, seats or platforms for resting should be set up along longer roads and at corners in marine cities to buffer the flow of people. Second, human scale refers to the corresponding design for people of different ages; for example, there is a great difference in height and ability between children and adults; therefore, the design cannot consider only adults and ignore the use of landscape facilities by children.

(3) Interactive plant LD

The interactive design is introduced into the MC plant LD to meet the basic psychological needs of people at the core, to create a landscape space with a sense of hierarchy and richness for visitors, and to increase the chances of visitors interacting with marine plants and animals or other elements [25].

Plant LD should be pleasant. In the selection of plants, plants of different sizes are planted according to the size of the activity site. For example, at a site where visitors are concentrated, large-sized trees should be planted, which can provide shade and shelter for visitors and a good interactive environment.

3. Case Design of Coastal Plants in Sanya Bay, China

3.1. Assessment and Analysis of Marine Eco-Economic Zoning in Sanya Region

3.1.1. Analysis of Spatial Heterogeneity

As shown in Table 1 below. Considering the sub-indexes of the three subsystems in the Sanya marine eco-economic system—namely, marine ecology, marine economy, and marine society—an evaluation index system for marine eco-economic zoning was built and the marine ecological economy of Sanya was evaluated via zoning using comprehensive factor evaluation and analysis. Briefly, this process was divided into three steps. First, a zoning evaluation index system was built. Second, the weight of each index was calculated and determined by issuing questionnaires and scoring by experts. Third, rational values were assigned to concrete indexes for each region according to the evaluation criteria. Finally, the evaluation index was obtained via calculations and the zoning evaluation was made.

Table 1. Evaluation index system of marine ecological suitability.

Target Layer	Criterion Layer	First-Level Indicators	Secondary Indicators	Element Layer	Direction	Required/ Not Required
Marine ecological suitability	Suitability of marine ecological environment	Biological environment structure	Environmental quality	Eutrophication index	Negative indicator	●
			Natural shoreline integrity	Natural shoreline retention rate	Positive indicators	●
			Marine disaster risk distribution	Marine risk intensity index	Negative indicator	○
			Community structure	Biodiversity index	Positive indicators	●
		Biological environment function	Important protection value	Ecological sensitive areas and important protected objects	Positive indicators	●
			Landscape type	Ecological disturbance degree	Negative indicator	●
			Production supply	Net primary productivity	Positive indicators	●
	Suitability of marine social environment	Current situation of space utilization	Deepwater shoreline resources	Available deep-water shoreline length	Negative indicator	●
			Mudflat resources	Available mudflat area	Negative indicator	●
			Landscape cultural resources	Rating coefficient of scenic spots	Negative indicator	○
	Suitability of marine economic environment	Socio-economic conditions	Marine economy	Total output value of marine industry	Negative indicator	●
			Coastal population	Population density	Negative indicator	●
			Geographic conditions	Accessibility of important nodes	Negative indicator	●

● means that this option is a mandatory choice for the Evaluation index system of marine ecological suitability.
○ means that this option is a non-mandatory option of the Evaluation index system of marine ecological suitability.

3.1.2. Data Source

The research data used in this study primarily included Google satellite images, previous urban master plans for Sanya, other specialized plans, and social and economic development plans. Amid studies on the urban form of Sanya City, our work mainly referred to the compilation year of the latest version of Sanya's urban master plan, and we processed data using three main reference pictures that depended on the data collection time of the Google satellite map; that is, the status quo image from 2014 (Figure 3).

Figure 3. Map of Sanya.

3.2. Case Study of Coastal Plants in Sanya Bay—Anaya Community

3.2.1. Design Ideas

Major goals of design ideas are to adhere to the people-oriented concept, carry out interactive landscape design of the ocean city, pay attention to how the landscape is integrated into people's life and environment, have landscape usability and good user experience as the goal, and promote good communication and interaction among people and between people and the environment. Based on the design goal of a multi-modal interactive landscape of the ocean city, this design project carries out reasonable planning and layout for the functional zoning, road system, water landscape, landscape facilities, and plant configuration of the Sanya Bay Anaya community, providing people with different functional requirements and bringing different viewing experiences, as shown in Figure 4.

Figure 4. Landscape distribution of Sanya Anaya community.

3.2.2. Functional Zoning Design Based on Tourists' Needs

The word "Aranya" comes from the Sanskrit word "Aranjo", which means "a quiet, idle, remote, or secluded place for spiritual practice away from the hustle and bustle of human activity" [26]. Aranya has also come to Sanya, advocating for an aestheticism that believes "life can be more beautiful," and arousing a great deal of curiosity among the people living in the mountains and seas of Sanya about the aesthetics of life. Combined with the development of the MC and the needs of tourists, based on the distribution of marine natural resources, the MC is divided into four functional areas: the entrance landscape area, the ornamental tour area, the water-friendly landscape area, and the quiet rest area.

(1) Entrance landscape area

As shown in Figure 5, The entrance landscape area is also the service management area of the Sanya Anaya scenic spot. It is located in the axis of the scenic spot and connects all functional zones, so that visitors can enter the scenic spot as soon as possible to carry out their favorite activities in the area. This area also includes ecological parking lots, visitor service centers, and other landscape facilities to meet the physical and psychological needs of visitors. The design of the entrance is such that by minimizing the entrance of the scenic area, when visitors enter the scenic area, they are met with a large and open space. This contrast reflects the image of “small entrance, large landscape”, giving visitors a visual impact, with rich visual level changes to guide visitors to interact with the landscape. Electronic guidance devices are also set up at the entrance, and VR panoramic photography is carried out for the whole scenic area, so that visitors can scan it on their cell phones and experience all the scenery of the scenic area, making it convenient for them to choose the functional area they want to go to.

Figure 5. Sanya Anaya Entrance.

(2) Viewing tour area

As shown in Figure 6, the Aranya in Sanya is full of tropical plants with a distinctive Middle Eastern ‘flavor’. The architecturally designed buildings are reminiscent of Tuscan-style estates, and the garden is filled with exotic cacti. Visitors entering the Ocean City Scenic Area can immerse themselves in the ocean culture and the wonderful ocean scenery, creating an immersive experience for visitors with multi-sensory means. By utilizing plant landscape design, visitors’ attention can be focused on interacting with the scenery, achieving mutual communication between people and plants. Different plants are in varying growth states, resulting in different visual effects and leading to multimodal visual expression.

Figure 6. Anaya Scenic Area.

(3) Water-friendly landscape area

As shown in Figure 7, according to the topographic characteristics of the ocean city, water-friendly landscape areas are set up in areas with large water surfaces, advocating the “close to the ocean nature” way of touring to meet the needs of tourists. Visitors can reach various spots through water stacks and circular walkways, which have good hydrophilicity and experience, and guide visitors to interact with the water body landscape tactilely. Specific strategies include, firstly, improving accessibility and enhancing the transportation connection between coastal plants and water. The second strategy is to enhance visual accessibility and minimize the obstruction to the water views by plants, as unobstructed views are another important means of increasing the water-friendly environment. The third strategy is to bring water ashore and introduce water into the interior of the waterfront space for landscape shaping, achieving a coordinated and harmonious effect between the interior and exterior spaces and greatly enhancing the waterfront space’s affinity with water.

The fourth strategy is to enhance the psychological experience of being near the water. When designing the plant layout, elements related to water, such as aquatic creatures, wave shapes, boat shapes, and color elements, can be used in the surrounding landscape facilities to enhance the psychological experience of visitors being near the water [26].

Figure 7. Anaya Water Plank Path.

(4) Quiet rest area

As shown in Figure 8, The quiet rest area is designed especially for visitors, to provide people with quiet rest and interaction activities. This area includes the marine hotel area and a camping area. The marine hotel provides a resting place for visitors, and the beautiful scenery around the hotel stimulates visitors' vision and offers a good viewing experience. The camping area is on the open beach, providing visitors with space for casual activities. They can freely contact the sea breeze, waves, and the surrounding environment, and feel the good experience of contact between humans and nature, thus creating a behavioral interaction.

Figure 8. Anaya vegetation area.

3.2.3. Five-View Plant System

When using plants to create an ocean resort landscape, it is essential to consider the physical and psychological sensitivity of the experience [27]. By selecting and using different plants through scientifically rigorous design, human experiences can be incorporated to create a plant landscape that excels in the five senses of "sight, sound, smell, taste and touch". Only then can a maritime landscape space be created that combines aesthetic taste with leisure and entertainment functions, as shown in Figure 9, which presents a statistical summary of the five sensory modes of plants.

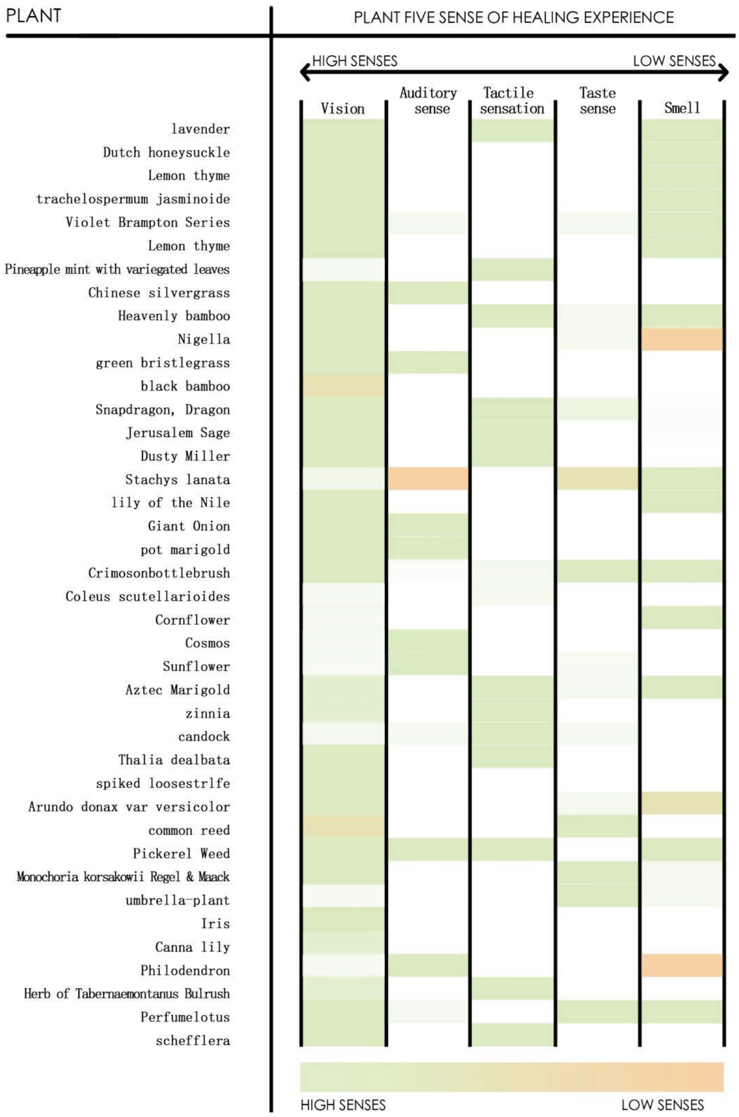


Figure 9. Statistical Diagram of Plant Five Sensory Modes.

- Visual effect

Plants with warm tones can create a sense of warmth and evoke positive emotions, while plants with cool tones can help calm down individuals who are feeling restless or anxious. When designing plant landscapes, a diverse selection of species should be considered to meet various landscape preferences. As for plant variety, the crown, color, season, and form of cultivation should be comprehensively considered to create a rich visual effect.

- Auditory effect

In 1929, Finnish geographer Grano first proposed the concept of "Soundscape" to research the audience-centered sound environment [28]. Different sounds bring completely different feelings, so a design should try to isolate noise and make more use of natural sounds to create a favorable auditory landscape. Natural sounds such as pine-soughing valleys, fine rain in a bamboo forest, windy lotus in a winding courtyard, and rain drops drumming rhythmically against banana leaves create classic auditory landscapes. A special area can be designated as a meditation space in the ocean vacation area to plant a bamboo forest. Visitors can relax and alleviate their anxiety while experiencing the rustling sound of bamboo leaves swaying in the wind within the bamboo groves.

- Smell effect

Using the fragrance emitted by plants or creating an atmosphere with their scent can create a healthy and clean landscape environment with a therapeutic effect. There are two types of plants: sterilizing, air purifying plants and external treatment functional plants.

- Gustatory effect

The taste effect is usually achieved by combining the landscape environment with experiential activities. Small tourist orchards and agricultural parks can be built, where various fruits and vegetables can attract the elderly to leisurely taste and enjoy the produce, thereby adding a taste experience and relaxing their mood.

- Tactile effect

Among the five senses of sound, sight, smell, taste, and touch, touch is the most difficult to grasp. It requires people to experience an area through touch in order to stimulate their physiological responses and convey emotions. This effect often needs to be achieved through plants with good texture.

In the plant landscaping of marine cities, the modal configuration of different sensory systems produced by plants is summarized as follows, as shown in Figure 10.

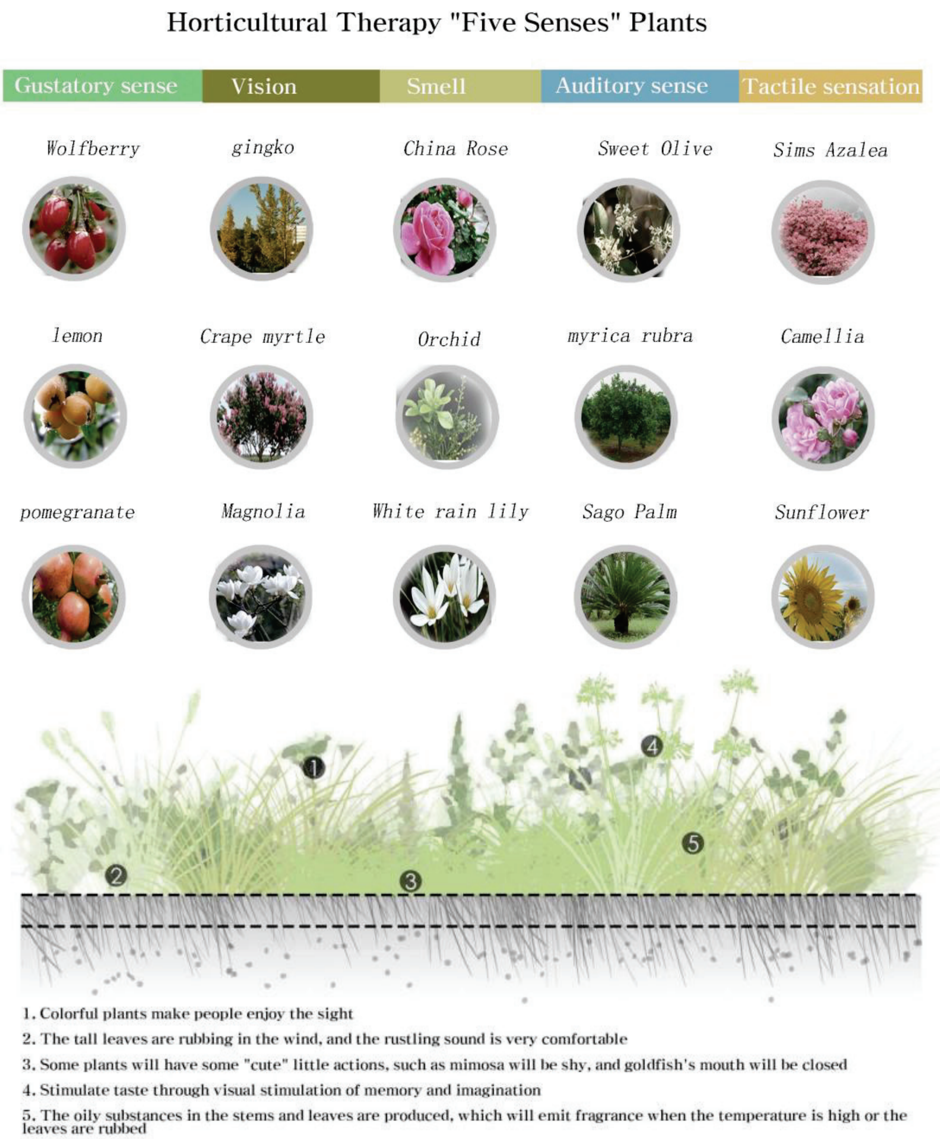


Figure 10. Multimodal configuration of plants.

4. Evaluation of the Interactional Impact between CVT, MC Planting, and MID

4.1. Respondents' Occupational Distribution

As shown in Table 2 below.The respondent population was divided into three parts: working professionals, students studying landscape architecture, and non-landscape architecture professionals. As far as possible, a certain sample size was ensured for different groups of people to better analyze and compare the views of different respondents and to ensure more objective and accurate results.

Table 2. Distribution of Respondents.

	Professionals Already Working	Landscape Architecture Students	Non-Landscape Gardening Professionals
Number of people	20	50	30
Proportion	18%	55%	27%

4.2. Evaluation Analysis of the Effect of Computer Vision-Based MID

When evaluating the effectiveness of the design approach in this paper, the evaluation degree was divided into "strongly disagree", "disagree", "not sure", "agree", and "strongly agree", with scores of 1, 2, 3, 4, and 5, respectively. This method was used to quantify and analyze the respondents' answers.

As shown in Table 3 and Figure 11, the respondents' ratings for each item exceeded 4.00, indicating that the respondents were satisfied with the effectiveness of computer vision-based MID. Among them, the respondents agreed more on "Computer vision-based MID is interactive" and "Computer vision-based MID is ornamental", with mean scores of 4.73 and 4.74, respectively. The lowest score is "rich content of plant scenery", with an average score of 4.32. There are two main reasons for this: first, the current common modeling software has a limited ability to restore the scene, and the realistic feeling of plant models is not strong, which is the main reason for the low score; second, the accuracy of the case scene modeling still needs to be improved.

Table 3. Respondents' evaluation of the effectiveness of computer vision-based MID.

	Professionals Already Working	Landscape Architecture Students	Non-Landscape Gardening Professionals
High interactivity	4.78	4.67	4.74
Highly enjoyable	4.82	4.69	4.71
Rich plant scenery	4.26	4.33	4.38
Physical and mental pleasure	4.57	4.48	4.60

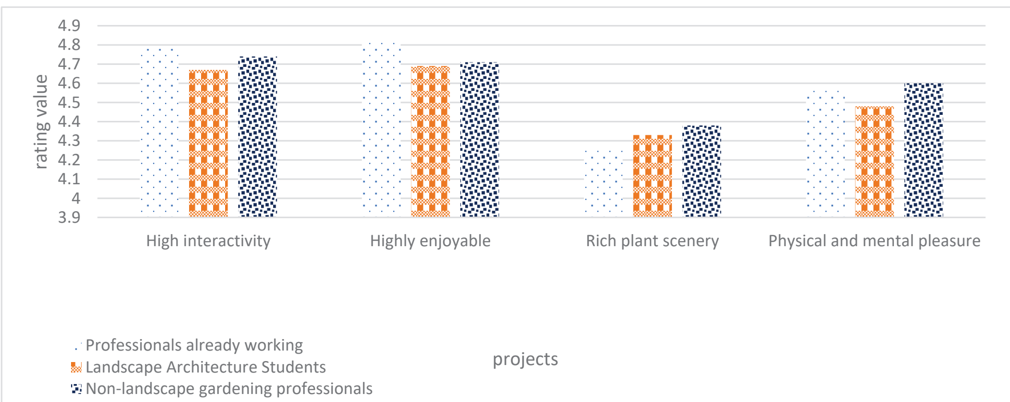


Figure 11. Evaluation of design effects.

Among the three groups of people interviewed, the scores given by landscape architecture students were generally low, probably because of the large number of students interviewed and the large difference in their evaluation of the case presentation effect, which was reflected in the fact that more respondents chose low scores, thus leading to a decrease in the average score.

4.3. Attitudes toward the Expression of Computer Vision-Based Multimodal Interactive Design

As shown in Table 4 and Figure 12, the most attractive features of computer vision-based multimodal interactive design for plantscapes are the richness of content (37%) and the impact of viewing (42%), probably because working professionals pay more attention to the role of CVT as an aid to their plant LD work, and it just so happens that the richness of information and novelty of computer vision expressions are very suitable for them. Therefore, they choose "richness of content" and "impactfulness of viewing" the most.

Table 4. Analysis of attraction points of MID expressions based on computer vision (%).

	Professionals Already Working	Landscape Architecture Students	Non-Landscape Gardening Professionals
Authenticity of the scene	12	30	28
Richness of content	37	12	9
Impactfulness of viewing	42	18	36
Interactivity of the experience	5	33	17
Nothing particularly impressive	4	7	10

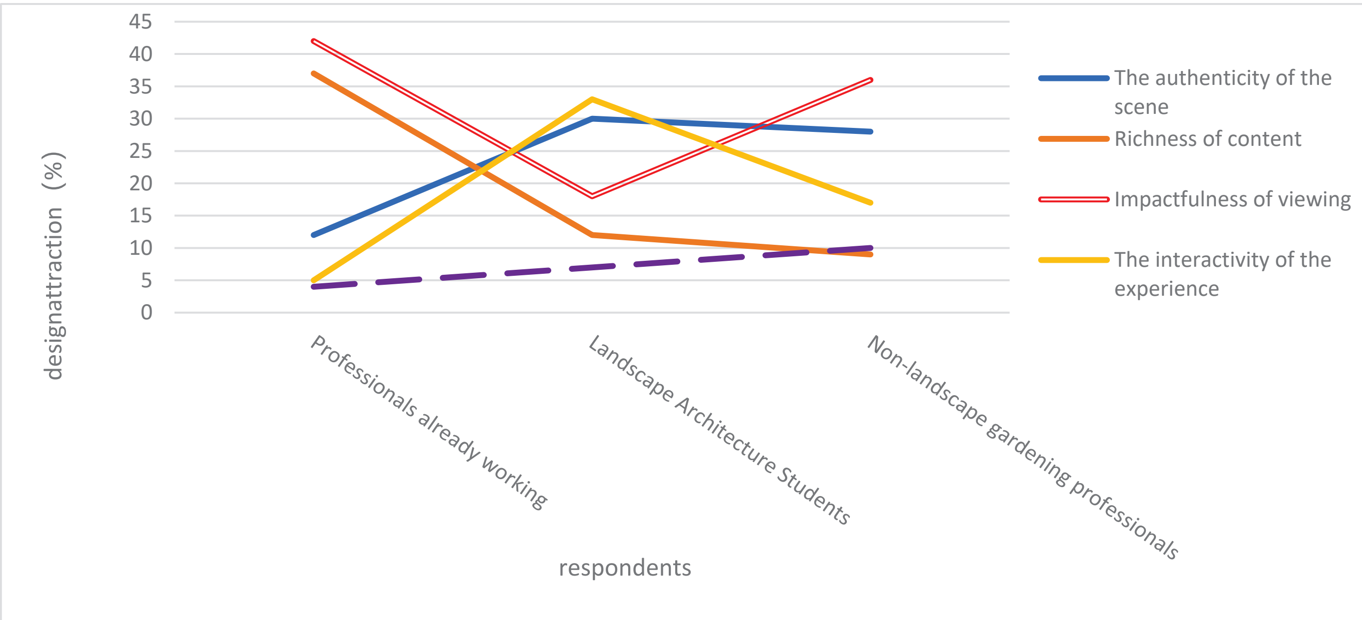


Figure 12. Design attraction points.

For landscape architecture students, their concerns were more dispersed, with slightly more people choosing "realism of the scene" and "interactivity of the experience", at 30% and 33%, respectively. Among the three categories, landscape architecture students preferred "interactivity of experience" much more than the other two categories, probably because the interactive points in the display case contain plant information, which is helpful for students to understand and learn plant characteristics, so the interactivity in the multimodal design display is more attractive to them.

For non-landscape professionals, "impact of viewing" (36%) and "realism of the scene" (28%) were the most attractive features of computer vision and multimodal interactive design displays, i.e., 64% of non-landscape professionals were attracted to computer vision displays. The reason for this is probably because non-professionals lack the appropriate professional knowledge and rely more on visual images to understand the designer's intention, and are more interested in the outcome of the design than the rationality of the design, so they are more impressed by the visual experience brought to them by computer vision displays.

4.4. Interactivity throughout the Design Process

The multimodal interactive design of MU planting based on CVT can be divided into three processes: pre-design, design process, and post-design [29]. As shown in Figure 13, in the pre-design stage, extensive and detailed information collection is required, including landscape general style cases, user research and analysis, and information collection on the current situation of the plot. This process involves the first interactive design, which strengthens the communication with tourists in the research process, and derives the general or special needs of tourists from the psychological analysis of the researchers, indirectly making tourists participate in the LD. In the middle of the design, with full consideration of user experience and interaction, a detailed design of various parts of the landscape such as plants, paving, landscape facilities, etc., increases the direct interaction between visitors and the landscape, which is the second interaction process between landscape and people. In the late design stage, in the property customer service department, through the visitors' information feedback on the landscape, the landscape will be modified for quality improvement, which is the third interaction process. Therefore, the mutuality design of the landscape in the study area should follow this principle, so that interactivity occurs throughout the design process.

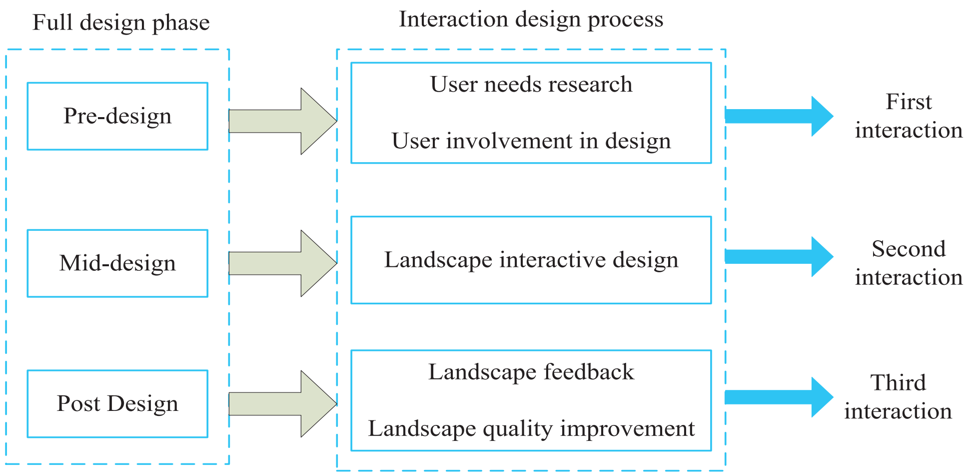


Figure 13. Three processes involved in interaction design.

4.5. Data Result Analysis

(1) Using willingness analysis

According to Figure 14, although people working or studying in the field of landscape architecture have a general understanding of multimodal interaction technology, most of them (87%) still prefer to use interactive technology for design when possible. This also indirectly indicates the professionals' liking and affirmation of VR multimodal interaction expression methods. As shown in Figure 15, for non-professionals who are not familiar with landscape design, most people (80%) are still willing to try interactive technology to experience the plant landscape space in the ocean city.

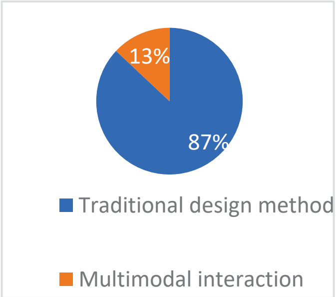


Figure 14. Analysis of preference for design means.

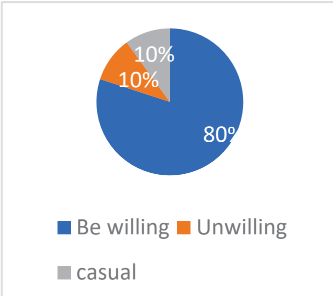


Figure 15. Analysis of willingness to use interactive technology.

(2) Expectations for the future application of VR multimodal interaction technology

According to Figure 16, as many as 97% of the respondents expressed their expectations for the future combination of multimodal interaction technology and the field of landscape architecture, indicating that interactive technology is highly popular among different groups of people.

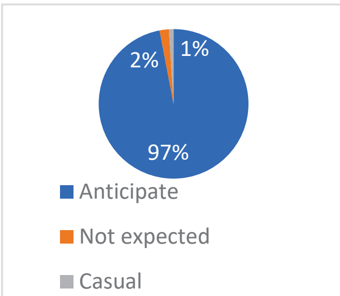
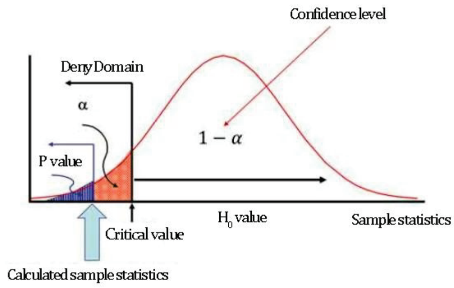


Figure 16. Interviewees' expectations for the application of multimodal interactive technology in plant landscape in the future.

(3) Statistical Differences in Respondents' Willingness

The basic formula of the χ^2 test, according to the respondents, is $\chi^2 = \sum(1 - \alpha)^2/\alpha$; the χ^2 value reflects the degree of agreement between the actual frequency and the theoretical frequency. If H0 holds, the difference between 1 and α should not be huge; the χ^2 statistic should not be extensive. The more significant the difference between 1 and α, the larger the χ^2 value and the smaller the corresponding p value. According to the p value obtained by the significance test method, generally, $p < 0.05$ is considered to have a statistical difference, $p < 0.01$ is deemed to have a significant statistical difference, and $p < 0.001$ is regarded as a highly significant statistical difference. These values mean that the probability of the difference between samples being caused by sampling error is less than 0.05, 0.01, and 0.001, respectively [30]. According to the specific analysis of the chart, it is concluded that, as shown in Table 5, there is the most significant statistical difference in the statistics of non-landscape professional groups. The reasons are that the groups have different occupations and considerable age differences, and are influenced by their living environment. Secondly, students majoring in landscape architecture have apparent differences in applying technical means due to other individual concepts. Finally, there are working groups in this profession to develop more and better design methods, and there is a slight difference in willingness.

Table 5. Statistical differences in respondents' willingness.

Target Statistics	p Value	Professionals Already Working	Landscape Architecture Students	Non-Landscape Gardening Professionals
Acceptance of interaction concept	$p \leq 0.001$			•
	$p \leq 0.01$	•		
	$p \leq 0.05$		•	
Diagram schematic analysis				

5. Discussion

5.1. Comparison of Relevant Literature Results

A Literature Research Results

There are few studies abroad on the multi-modal interaction and landscaping of garden plants, and most are biased towards the protection, utilization, and ecological research of wild plants. The book *Landscape Plant Configuration* by British scholar Brian Clouston discussed the design of trees, shrubs, ground cover plants, herbaceous plants, aquatic plants, and forest planting from the perspective of ecology and aesthetics [31]. The maintenance and management of gardens combines garden design, construction, and maintenance management, and puts forward the viewpoint of a four-dimensional management scale, systematically organized in the book *About Face: The Essentials of Interaction Design* by American scholar Alan Cooper [32]. Regarding some design concepts of digital product interaction design, a more detailed introduction to the application of computer vision technology, and elaboration on plant landscape design, plant planting and maintenance, especially the close relationship between landscape and environment, is provided [33]. The scientific and artistic importance of design has been analyzed in detail; the discussion on the functions of plant materials and planting design in the book Elements of Landscape Architecture Design written by American scholar Norman K. Booth in 1983 has become the basis of plant landscape construction, especially in the classic basic theory of plant space construction [34].

The research and attention on multi-modal interaction design technology in landscape architecture are gradually increasing. Zeng Junfeng and Qiu Cuiju discussed the application of interactive technology in garden design earlier in the *Chinese Garden* magazine. Li Guosong et al. used the Analytic Hierarchy Process (AHP) to evaluate the interactive realization method of plant construction under the five sensory modes [35]. Thus, the sense of touch is the best way to realize the interactive form of landscape garden plants. In terms of theoretical research, there are mainly the following essential papers: "Interactive Design and Visualization of 3D Plant Models", "Interactive Plant Modeling System", and "Forward

Interaction: From Voice, Gesture Design to Multi-modal Fusion", "Chinese Garden Plant Landscape Art" by Professor Zhu Junzhen, and "Garden Plant Landscape Design and Construction" edited by Zhao Shiwei, etc. all have high academic value [36]. These studies systematically summarize the development process, design principles, and theoretical basis of multi-modal interaction, guiding people to explore new interactive experiences. They also analyze the characteristics and limitations of each modality and outline the design model of multi-modal interaction, from voice and gesture design to multi-mode fusion, building a graphical voice interface fusion model with growth capabilities. Although corresponding progress has been made in theory, many problems remain. In theoretical research, there is no systematic theory to guide practice: the practice is too limited and stays in the local environment, and the city as a whole is not considered uniformly.

B Research results of this article

This paper integrates design cases with interactive technologies, highlighting the immersive, interactive, and imaginative advantages of multimodal interaction design in plant landscaping through the exchange of people's "five senses"(Table 6). This is significantly different from the traditional focus on plant adaptability and environmental protection in landscape planting.

Table 6. The embodiment of multimodal interaction characteristics in plant landscape design of marine cities.

Characteristic	Basic Content	Embodiment in Plant Landscaping of Marine Cities Based on Multimodal Interaction
Immersive	Multi-dimensional perception: observe the scene personally	Assisting in scheme deliberation and feeling plant landscape artistic conception: increasing the dimension of space exploration between designers and the public
Interactivity	Manipulate virtual reality scene: interact with the scene	Changes and contrast schemes that are conducive to designers' feelings: save and verify the fleeting design inspiration in time.
Conceptual	Deepen concepts or sprout new ideas in the observation and manipulation of objects	Inspire the production of new design ideas or concepts

(1) Immersive scenario experience. Compared with traditional plant landscape creation, computer vision technology immerses people directly in a multimodal three-dimensional space, achieving the effect of being on the scene in person [37]. The immersive scenario provides a new visual and sensory experience for both professionals and the general public, adding to the dimension of the designer's exploration space. The information received by the brain in daily life is caused by multiple senses, so it is impossible for people to have an immersive experience if it is just visual immersion. With the aid of necessary computer vision and interactive devices, it is possible to achieve sensory immersion beyond visual cues by incorporating auditory and olfactory cues, allowing visitors to experience the ambiance of different botanical landscapes. It adds a weather conversion function to the system to simulate natural landscapes such as rain, snow, and fog. In cooperation with spatial audio technology, the unique plant landscapes of the ocean city can be felt even while sitting at home.

(2) Unobstructed view space. In addition to the immersive visual experience, computer visual interaction technology also provides people with the opportunity to view space freely. Renowned British urban planner Gordon Cullen, in his book *Cityscape*, mentions that understanding space is not only about looking at it but also about moving through it [38]. With the help of computer vision and interactive technology, users can simulate a coastal visit, observing the form and texture of plants up close. In the past, designers typically used hand-drawn plans, perspectives, and even physical models to aid in the exploration of plant landscape spatial structure design. However,

the creation of landscape spatial sequences stems from the continuity of human behavior, which reflects the "human-centered" design concept.

(3) Real-time feedback on modifications. The lack of computer precise positioning design will lead to a lack of judgment on the on-the-spot environment, which leads to a lack of aesthetics in plant landscaping, and even the inability of plant interspersed design to interact with people [39]. Aided by computer vision, the plant scene is designed to see effects at any time scale. This ensures that landscape designers can make timely modifications and compare effects when design errors are discovered, ultimately resulting in the most suitable plan. Since plants are different from buildings that possess a vital nature, plants of the same species with different sizes can have an important impact on the landscape space and the effectiveness of the landscape [40]. The advantage of setting and modifying scene elements in real time is that the inspiration experienced by the designer during interactive editing is saved to ensure the continuity of design thinking.

5.2. Research Innovation and Significance

The case design analysis above validates the credibility of previous research and the results of multimodal interaction [41]. The use of multimodal interaction technology will enable close integration of the relationship between plants in ocean cities and tourists, resulting in that when people walk into the landscape, plants are not only the landscape through which people travel; rather, they experience a new type of landscape. The multimodal interaction study of computer vision technology in plant landscaping in ocean cities is not only of practical significance for the design of plant landscapes, but also has multi-aspect research significance for future interaction research fields [42]. After using computer visual interaction technology, plant landscape design reinforces the communication and interaction among people, and between people and scenery, and its innovative value is mainly reflected in three aspects: the expansion of design expression tools and display methods, the gradual innovation of traditional thinking, and the realization of multiple landscaping effects.

(1) Expand the design performance tools and display means. The visual interactive technology craze has broken the shackles of two-dimensional expression, placing the design process in a multi-dimensional computer scenario, with the application of new technology signifying the intervention of new tools [43].
(2) Traditional ways of thinking are gradually reforming. Existing examples show that the emergence of new software can not only break through the limitations of past design expressions, but can also change design thinking, such as the introduction of parametric software that has increased landscape plant design from perceptual art creation to a combination of perceptual knowledge and logical thinking [44].
(3) Diversified landscape effects. The five senses of plant characteristics are brought into the plant landscape design, which adds more design principles and sensory experience to the original single-plant layout to achieve conservation and aesthetic improvement of the plant environment in the ocean city.

5.3. Research Limitations and Future Research Routes

This case study attempts to integrate people's multi-sensory experience with plant design through the introduction of computer vision technology, achieving a visually modernized plant landscaping performance. The creative plant configuration method tailored to different visitor experiences was explored through a questionnaire survey. However, there are still some limitations to the research that need to be further strengthened in the future.

(1) There is currently insufficient in-depth research on the literature of computer visual interaction technology related to plant landscaping, which is still a field that scholars should continue to explore more deeply.

(2) Plant landscapes in different ocean cities may be influenced by climate and geographical location according to different regional characteristics, which will lead to differences in plant matching designs according to different ocean cities.
(3) Since multimodal interactive plant design is mostly determined by people's sensory consciousness, this does not represent the most appropriate design method for the whole case, and there are inevitable limitations based on the analysis of the results of different people's design experiences.

In light of the limitations of the above research, the effect presented by multi-modal interactive technology is not enough to satisfy people. There is still a distinct difference from the ideal state, which objectively hinders the combination with its landscape environment [45]. The emergence of tools is necessary to meet people's needs. If the interactive technology software cannot provide enough support for garden plant landscaping, it may be as short-lived as the once-popular 3D TV and eventually disappear in the landscape industry. Therefore, in the future, designers will play a more significant role in promoting than programmers in the development process of the combination of the two. Designers should explore and consider the application potential of multi-modal interaction and provide more constructive suggestions for software development with their professional sensitivity [46]. In the future, the VR virtual interaction software used in garden plant landscaping should integrate scene modeling, design deliberation, and post-production performance. The model does not need to be converted between various software. The software should be intuitive and easy to operate, allowing designers to focus on the design and express their thoughts and ideas through VR virtual interactive software without hindrance [47].

6. Conclusions

A perfect plant landscape needs to meet the unified combination of scientific and artistic principles, i.e., it should meet the survival habits of plants in the regional environment and the embodiment of the plants in terms of morphological appearance [48]. It is necessary to start from the principle of artistic matching, to show the visual effect of plants alone or combined with other plants, and most importantly, to make people appreciate a wonderful sense of immersion. This paper introduces CVT and MID theory into the design of MU planting, adding a new design tool to the construction of marine cities. The use of computer vision technology brings three major characteristics to plant landscape design: immersion, interactivity, and creativity, providing a multi-sensory, multi-environment, and cross-temporal immersive experience based on the original two-dimensional plant configuration design. Computer vision interaction technology has not only become a new way to showcase urban plant landscape display solutions, but also a tool to assist designers in thinking and inspiring new design ideas or concepts, ultimately improving the quality of the design. By analyzing and discussing the various types of MU botanical landscapes, it shows the artistic effect of CVT and MID in botanical landscapes. The study shows that as a design worker, one should know how to analyze and solve the problems in the landscape from the audience's point of view, and be able to meet people's needs for ornamental, interactive, and botanical landscape content enrichment and physical and mental pleasure of MU botanical landscapes, so as to better realize the communication between humans and nature [49]. It is hoped that the research in this paper can add some constructive ideas and strategies to the construction of marine cities in the future. Through this process, people can live in a more perfect urban space, so that the art or technology of plant landscaping in the whole MC can be gradually enhanced and continued.

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plants

Article

Space Compositional Aspects Regarding the Importance of Trees in the Urban Landscape

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Abstract: Individual trees and tree compositions provide a wide range of cultural ecosystem services, including playing a key role in defining urban character. In Hungary, urban landscape protection tools have recently been expanded, bringing the topic into the spotlight. However, the significance of natural elements (and particularly trees) in relation to the urban landscape is still under-researched. In this paper, using a novel methodology, the character-forming significance of trees and tree-compositional elements of historic gardens in Hungary that define the urban character is analysed and evaluated. The urban landscape protection tools that establish the current recognition of green elements within the urban landscape are also analysed. In addition, the spatial situations and characteristics making certain trees in historic gardens defining character elements within Hungarian settlements are studied. Reasons behind the lack of significant tree features in certain historic gardens, as well as the external and internal characteristics of tree elements that determine their visual impact have been categorised. The results reveal that visually important trees, while diverse, show distinct trends in terms of visibility and are subject to constant change. The results imply that a paradigm shift is necessary to maintain, design and regulate green infrastructure in relation to visually important trees.

Keywords: heritage protection; historic gardens; visibility; tree compositions

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1. Introduction

Ecosystem services provide necessary and beneficial services for human well-being [1,2]. Several types of classification exist, however, with the most common being: provisioning services, supporting services, regulating services and cultural services [1,3]. Cultural ecosystem services (CES) can be interpreted as those non-material benefits obtained from ecosystems through recreation, aesthetic experiences, spiritual enrichment, cognitive development and reflection [1]. They have a significant effect on human well-being and life quality. In addition to other ecosystem services, they are also important in every society, and public awareness of them urgently needs to be raised [4].

Thanks to the many disciplines dealing with CES, their meaning and interpretation differ according to geographical location, as well as socio-cultural and professional background [3,5,6]. Following the same line, several classifications exist, but the most commonly used are the following categories: spiritual and religious, recreation and ecotourism, aesthetic, inspirational, educational, a sense of place, and cultural heritage. In this research, the effect of urban trees, particularly trees located in historic gardens within the urban landscape and character, is part of the aesthetic-perceptual and also cultural heritage categories [1]. The Millennium Ecosystem Assessment also emphasised the lack of recognition of CES in landscape and urban planning as well as in heritage protection.

Certain ecosystem services provided by trees are well-known and have been documented. However, cultural ecosystem services and the role trees play in building local character and the urban landscape in particular, have been a relatively under-researched topic, especially compared with regulating and supporting ecosystem services. To combat the relative lack of knowledge regarding cultural ecosystem services provided by trees in historic settings, this study focuses on their visual importance and value to the urban landscape.

Trees, especially trees in historic settings, can become objects of attachment and pride for locals, as well as being easily identifiable features for visitors. Individual trees can have myths and legends attached to them, and they may be prominent features in people's memories and mental maps. In many ancient cultures, mature trees were treated as gods. They were personalised, they continue to play a role within legends and may have religious significance. Legendary species were admired and protected. In some cases, trees could obtain attention because they were planted in an important place in history or they have connections with important people [7]. These kinds of trees can be located outside of settlements (such as General Sherman, the largest tree in the world, or the Linden of Zsennye in Hungary), or within them.

This research is focused on trees and compositional elements consisting of trees in Hungarian historic gardens and their urban context, especially their impact on the urban landscape as an ecosystem service. The definition of "*historic garden*" was formulated by the ICOMOS-IFLA International Committee for Historic Gardens in 1982 [8]. The Charter makes clear historic gardens' significance in terms of heritage and the primary role of vegetation as a "*living monument*" feature in the spatial composition of these gardens. Historic gardens are not only of value in and of themselves but also in terms of the garden architectural elements they contain. When historic gardens are located within an urban environment, their tree species may also be recorded in people's mental maps as a characteristic element of a settlement or part of a settlement; hence, an individual tree, group of trees or row of trees cannot only be part of a historic garden but also contribute to the character of the whole urban landscape, providing (cultural) ecosystem services. In this paper, the focus of analysis is how trees located in historic parks and gardens impact the local landscape and how they can become central elements of the urban character.

This paper focuses on trees within Hungarian historic parks and gardens and the effect of such trees on the settlement's landscape. Therefore, selected gardens and parks with notable individual trees that are located within or very close to the urban environment were selected—gardens and parks with no visual connection to settlements (such as the gardens of Rum and Alcsútdoboz) are not included in this current research. The factors enabling and increasing the effect of individual trees on the urban landscape, including location and contrast, are studied, as well as reasons that can cause otherwise notable trees (large solitary trees in a suitable situation) to lose their importance and cultural ecosystem service.

In the last decade, Hungary has introduced new regulatory and planning tools for the protection of the urban character and landscape—the system of Urban Landscape Handbooks (*Településképi Arculati Kézikönyv*) and municipal decrees for the protection of the urban landscape (*településkép védelméről szóló rendelet*) has been in force since 2017. As every municipality had to create one of each document, the framework for the protection of local visual character and heritage can be considered complete. However, the handbooks and decrees effectively created and accepted by local municipalities almost exclusively focus on built heritage and architectural character, and rarely mentions the elements of green infrastructure, trees and other plants, even though the official framework allows their inclusion as protected visual elements [9].

In this research, the effect of trees located in gardens and parks of historical value on the urban environment and townscape is analysed. As the focus is on the public visual perception of these plants and the mental connections, the attachment people feel towards them, only trees that are located in publicly accessible open spaces or are visible from public areas (streets, parks) at eye level were taken into consideration.

There are numerous international examples of manuals, handbooks and other documents created to help protect the local urban landscape, especially in Latin America (Buenos Aires, Colima, Estado de México, Zapotlán el Grande) [10–13]. However, the topic of trees as valuable and important elements of the urban landscape is barely mentioned in any existing manuals. In cities that have a category for locally important protected or "heritage trees" (Quito, Portland, Cuenca, Budapest), their visibility or impact on the urban landscape is not considered a primary factor in selecting such trees [14–17]. This means that even though the framework for researching and protecting trees with a profound impact on the urban landscape already exists in several places worldwide, there are no examples of it being used in this way.

Based on the above, the following research questions were formulated:

- What are the properties of trees located within historic gardens as compositional elements that make them attract and hold attention, and thereby make them significant elements of the urban environment?
- How big is the area of impact these trees have in terms of visual importance?
- What is the role of seasonality and how much does it determine trees' visual significance?
- How can trees, as important elements of the urban landscape, be integrated into the existing legal framework and how can their appearance be protected?

2. Materials and Methods

There are around 1500 historic gardens and parks in Hungary, according to certain sources [18]. However, the number of gardens with considerable value is much smaller. Therefore, to select and analyse gardens, a database including a more manageable number of such parks was chosen—specifically the list of gardens from a piece of research conducted previously (Dendrological gardens in 19th-century garden architecture in Hungary) concerning a more limited selection of Hungarian landscape-style gardens [19]. Most still existing Hungarian garden heritage elements were constructed or transformed in the late 18th century and the 19th century in the landscape garden style, in part due to their popularity amongst trend-following owners; however, some were demolished for political ends in the second half of the 20th century, but fortunately, a large number of such gardens survived from this period. This research focuses on parks situated in or directly adjacent to the urban fabric, as trees located within these areas can be reasonably expected to have an effect on the local urban landscape.

As established in the Introduction, trees as urban landscape elements are rarely included in existing urban landscape protection tools (handbooks and regulations). Similarly, the impact of trees on the character of the local settlement is a relatively new direction in research. While the perception of trees and attachment towards them have been studied by an increasing number of researchers [20–22], these typically ignore their urban context. Recent studies [23,24] have focused on individual trees in residential and heavily urbanised environments. The novel research methodology (Figure 1) presented here uses the results of these studies, especially the factors identified as major influences in the visual importance of individual trees (location and spatial context, unique or unusual appearance, contrast) in the analysis.

In this paper, the impact tree elements located in gardens of historic value have on the urban landscape is studied. Therefore, parks and gardens located outside of the urban fabric or only loosely attached to their settlements have been excluded from the analysis. Examples of such gardens include Rum (Bezerédj-Széchenyi chateau garden) and Alcsútdoboz (the park of the summer residence of Palatine Joseph and Archduke Joseph) and several other locations [25–27]. Historic gardens with a strong connection to the urban fabric, however, not only have a positive effect on urban ecology, urban climate and the livability of the surrounding settlement but also act as an important element of the local urban character (cultural ecosystem service), even becoming important local landmarks (e.g., Schönbrunn (Austria); Derby (UK); Versailles (France); Fertőd (Hungary)) [28–30]. Based on the list of gardens of the source material mentioned previously [19] and adjusting it to present a more representative look into existing Hungarian historic gardens, a total of 98 locations were included on the preliminary list.

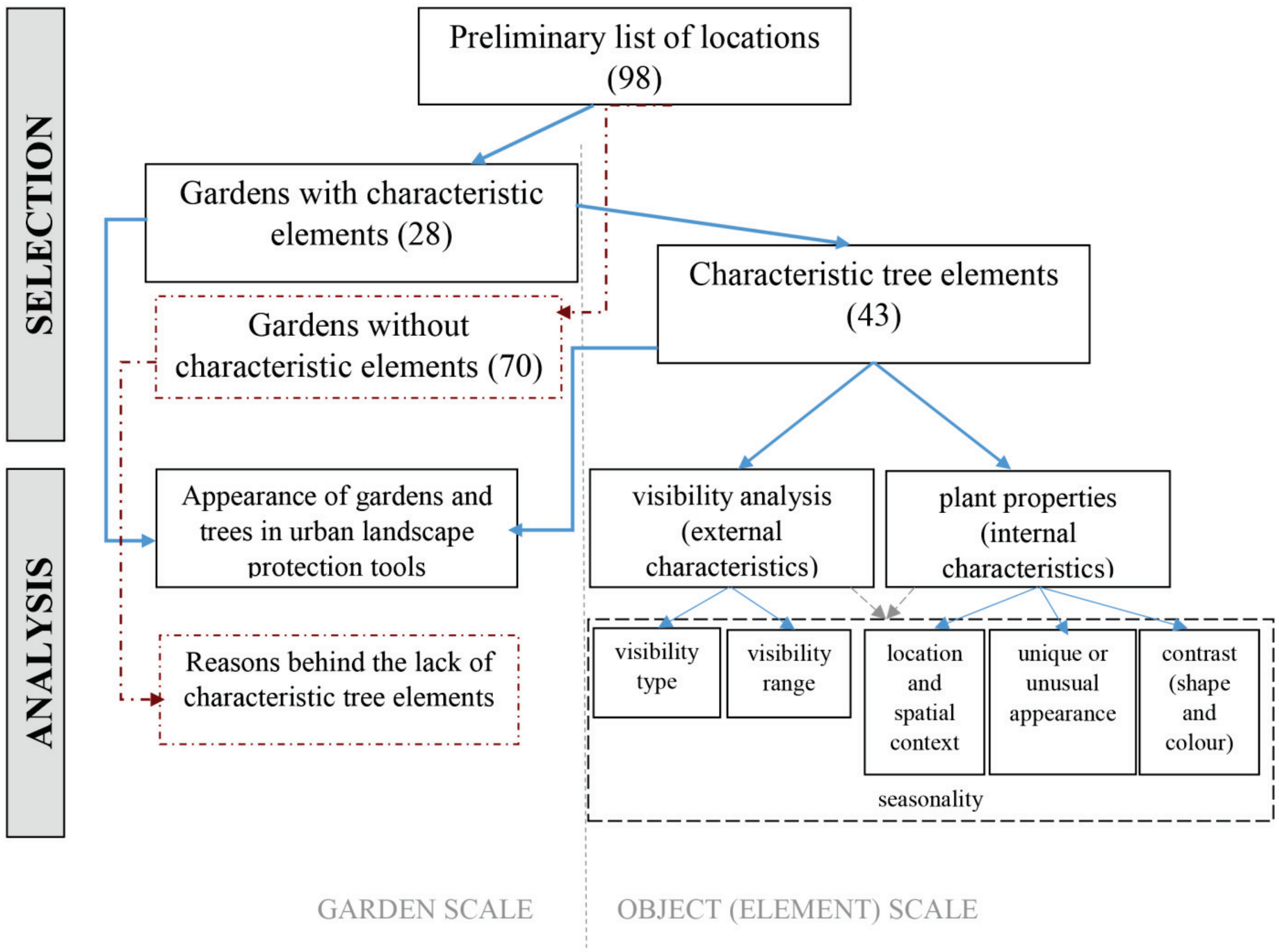


Figure 1. Flowchart of research methods. Blue arrows represent research regarding gardens with characteristic tree elements. Red dotted arrows represent research regarding gardens without such elements. Grey dotted arrows represent research on seasonality.

The primary criterion was that compositional tree elements situated in parks must be clearly visible and perceptible from public spaces outside the garden itself, in order for them to be considered elements of the urban landscape. Those characteristic compositional elements in historic parks that can only be seen by walking within the park itself can also contribute to the local character and mental image. However, in this research compositional elements with a visual impact restricted to the park itself were not taken into consideration.

The research method (Figure 1) consists of two main parts: selection and analysis. In the selection phase, using the preliminary list of gardens with historic value, a decision was made on whether they include characteristic tree elements (solitary trees, homogenous tree groups or rows of trees) with a significant impact on the settlement's urban landscape (See Figure 1: Gardens with characteristic elements (28)). All individual tree elements were also listed separately, as a single garden can include multiple characteristic elements. For the selection phase, pictures from field surveys of the past 16 years (since 2007) were used, as well as Google Street View [31]. Ultimately, the final selection reflects the perception and visibility of the study period. The 28 selected sites represent the distribution of historic parks in Hungary well, as there are significantly fewer historic gardens in the Central-Eastern region of the country (Figure 2), for historical reasons. The gardens were created between the 1790s and the 1910s, and the majority of them were constructed in the 19th century.

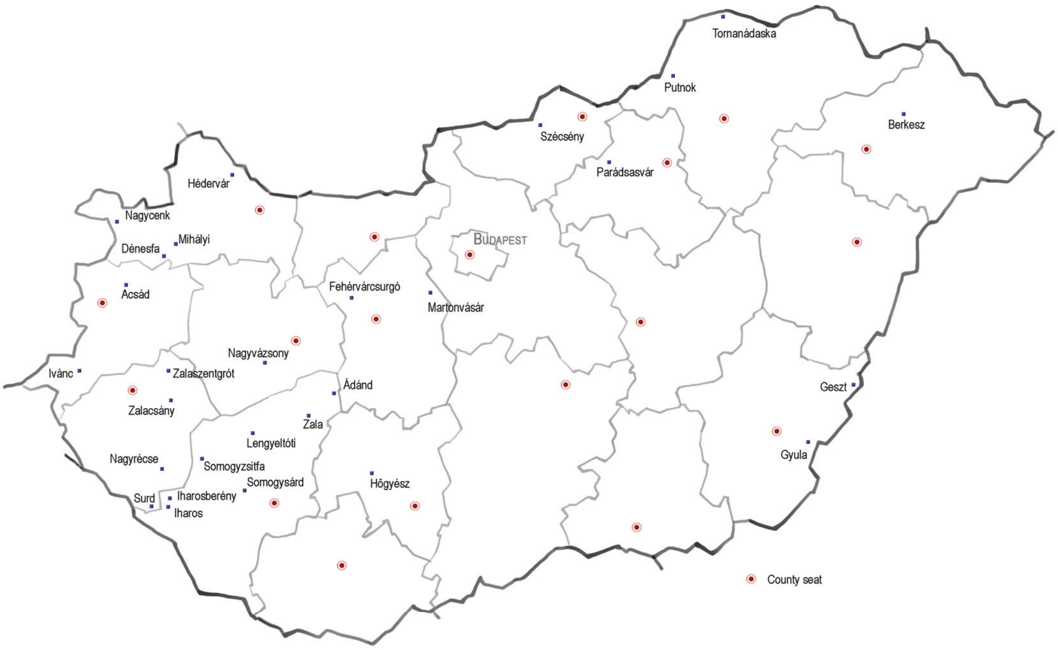


Figure 2. Map of Hungary with selected 28 gardens; map edited by the authors.

Within each historic garden, characteristic living compositional elements consisting of trees (solitary tree, tree group, rows of trees) that visually stand out within their environments, and therefore draw attention to themselves with their characteristic appearance, were identified and analysed. Tree elements can be divided into three categories (Figure 3) based on their composition: (1) solitary appearance (standalone individual), which may not only mean a tree located in the centre of a large "empty" (paved or lawn) area but also being a standalone, unique individual amongst a mass of trees of a different species; (2) tree group (of the same species or cultivar), with a visually well-defined, compact form; (3) homogenous rows of trees (of the same species or cultivar).

(a) (b) (c)

Figure 3. Analysed compositional element types: (**a**) solitary tree—Gyula (2012), (**b**) tree group—Nagyvázsony (2017), (**c**) row of trees—Acsád (2007). Source: M.S.

In the analysis phase, on the garden scale, the inclusion of gardens or their individual tree elements in current municipal urban landscape protection tools as protected or valuable urban elements was studied. In the case of gardens excluded from the selection (those without any tree elements with significant impact), the reasons behind their lack of such elements were studied. In particular, the existence of large, potentially impactful tree elements was evaluated, and in gardens including such trees, the factors behind their lack of visual importance were studied.

On the object scale, the characteristics of selected tree elements (solitary trees, tree groups and rows of trees) that might contribute to their importance were surveyed—their visibility and visual context (external, situational characteristics) and their individual properties (internal characteristics) were analysed separately. In the visibility analysis, elements were categorised based on visibility type (answering the question “How does the tree element appear within the urban landscape?”) and visibility range (answering the question “From what distance is the tree element visible and impactful?”).

Based on field research, the following methodology was developed and applied to describe and categorise the external characteristics. The following three different *visibility types* (Figure 4) can be described:

1. Perpendicular visibility: the character element (tree, tree group or row of trees) is visible at a right angle from the viewer’s path. This type of visibility usually occurs when the element is located close to streets or typical routes of viewers, only becoming visible from a short distance, at a narrow-angle.
2. Parallel visibility: this also occurs when the viewer is on a path close to the character element, but due to the visibility angle being wider, the object is visible from a much greater distance.
3. Multi-angle visibility: the character element is visible and visually impactful from several different viewpoints and directions: each visibility axis is at an angle to all other visibility angles from public spaces, squares, and streets.

In addition to the type of visibility for tree elements, the *distance* within which each of the analysed objects have a significant influence on the urban landscape was also studied. Based on this, visibility range categories of each element within (or even beyond) its urban context were created. Three categories were identified:

A. The characteristic tree element is only visible from a short distance (<50 m)
B. Characteristic elements with a visibility range of an entire neighbourhood or settlement part (>100 m or at least 50 m in several different directions)
C. Elements with visual connections (being perceptible and identifiable) from almost the entire settlement or even beyond the urban borders.

In the case of individual properties (internal characteristics), three plant properties identified by Nádasy (2022) as particularly important contributors to trees’ importance in the urban landscape were analysed: prominent location and unique spatial context (trees located on corners, intersections, in the centre of open spaces, elevated or otherwise focal locations, or those that are much taller than surrounding elements); unique or unusual appearance (compared to the “typical”, single-trunked, symmetrical tree shape) and contrast with nearby elements (including colour and shape contrast, both in terms of foliage and habit). Seasonality (leaf coloration, deciduousness, seasonal features such as flowers or fruits) was also taken into account as a factor in all object-scale analyses.

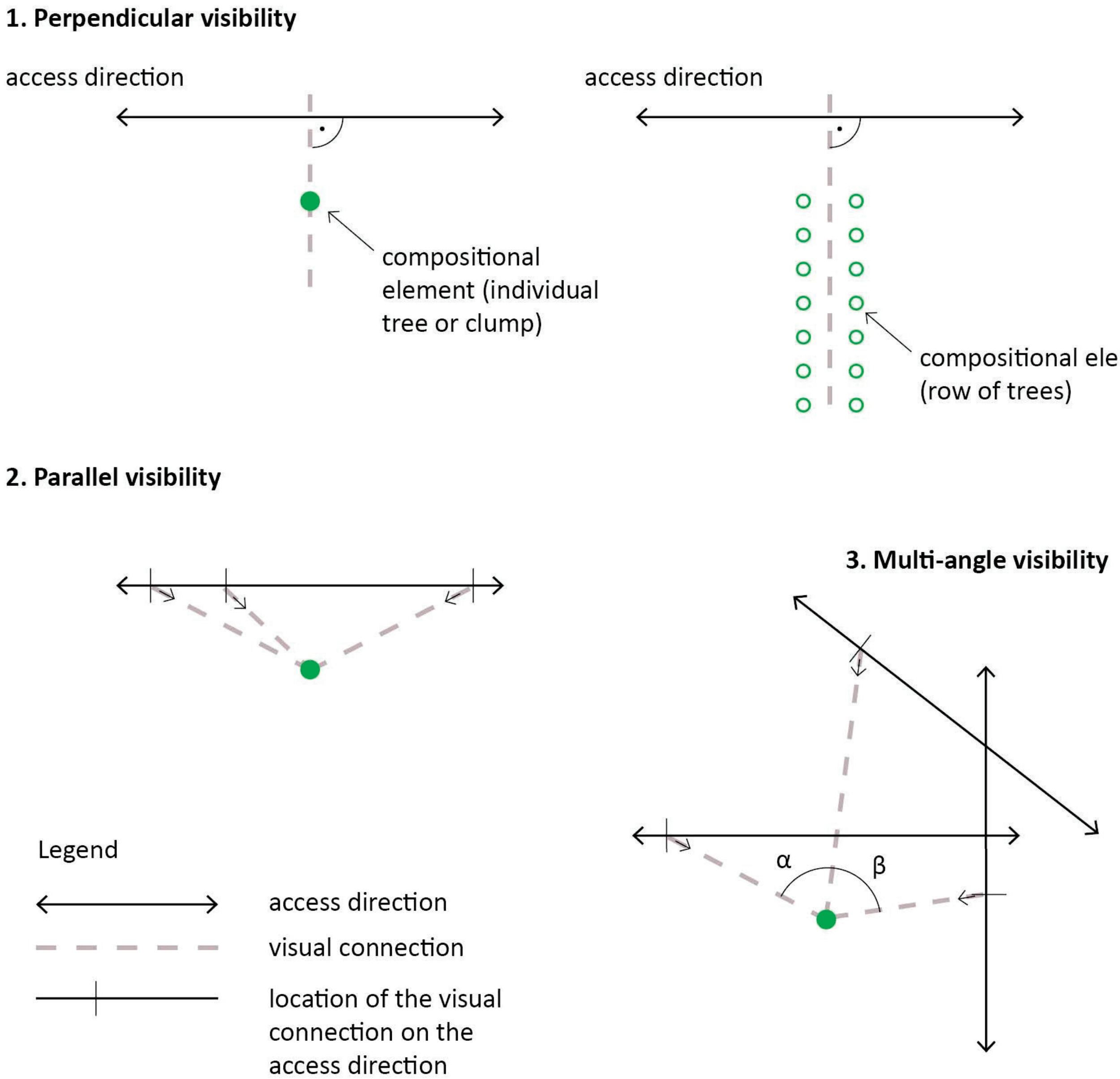


Figure 4. Schematic figures of visibility types (perpendicular, parallel, multi-angle). Source: authors.

3. Results

3.1. Results of the Selection Phase

The preliminary list of gardens, containing 98 historic gardens, was narrowed down to a list of 28 parks (Table A1) with at least one characteristic compositional element (individual tree, tree group or row of trees). Ten locations include more than one such element, with the total number of characteristic compositional tree features being 43. As an exception, the ancient *Sequiadendron giganteum* in Zalacsány has been included on the list, despite its death in the drought year of 2012, as it was an exceptionally important feature of the settlement's image and a major landmark (Figure 5), even though it is not physically present anymore. In the selection phase, any gardens located separately from the settlement that are not included in the urban fabric itself (e.g., the well-known Alcsútdoboz arboretum) were removed, as these gardens do not have enough urban context to be included in the detailed analysis.

(a) (b)

Figure 5. Characteristic compositional elements that once existed in Zalacsány. Source: Google Street View [32]: (**a**) 2011, (**b**) 2021; pictures edited by the authors.

3.2. Results of the Analysis Phase

The analysis phase involved two different scales, the garden and object scale, as mentioned in the Section 2. Results will therefore be presented following the same scale-based categorisation.

3.2.1. Results of the Garden Scale Analysis

The reasons why gardens included in the preliminary list do not have characteristic tree elements with a marked impact on the urban landscape were analysed. The reason for excluding gardens from the second phase that are directly connected with the neighbouring settlement was that there is no characteristic, unique tree elements that have a significant impact on the urban landscape. Several factors were identified that may result in a lack of characteristic tree elements in historic parks.

Several gardens currently do not include trees that could potentially be important landmarks. This is mostly due to the homogenous tree cover or a large, uniform mass of trees that does not allow any individual trees or compositional elements to stand out and become notable, unique visual features. Featureless plant mass falls into the same category. Examples include Vép, Doboz, Nádasdladány, Názsa, and Bicske (Figure 6).

In several gardens, existing and potentially visually impactful compositional elements can be identified, but they are not visible from public spaces or their visibility is so reduced that they cannot be considered an important element of the urban landscape. These elements can be hidden from view in several different ways, by plants, built elements or topography.

- Topography can hide even the largest trees if they are located behind a hill or mound, or they stand significantly below street level or on top of a steep incline, outside the comfortable view range of the average onlooker. The garden of Szeleste is a good example of tree elements being hidden on different sides of the park by topography, buildings and homogenous green walls (rows of street trees) (Figure 7).

Figure 6. Homogenous or mass-like tree cover without conspicuous elements: (**a**) Vácrátót—2013; (**b**) Vép—2012; (**c**) Doboz—2012; (**d**) Názsa—2012. Source: **a**, **c**, **d**: M.S., **b**: Google Street View [32].

Figure 7. Buildings and green elements hiding the garden of Szeleste from view (2022). Source: Google Street View [32].

- Living elements can also block characteristic trees from view. Hedges, shrubs and trees (either deliberately planted or spontaneously grown from seed) located around the borders of the property can make anything, including the most conspicuous tree elements, invisible from the outside. An example of this is the historic garden of Körmend, where spontaneously grown vegetation hides most of the notable trees from most public viewpoints.
- Built elements are the most common features restricting the visibility of trees inside historic gardens. Buildings surrounding the garden (e.g., the former archducal park of Sárvár) and tall solid fences (e.g., the park of Batthyány Mansion in Ikervár; the garden of the former Vigyázó Mansion in Vácrátót; the Archbishop's garden of Kalocsa) can both block elements from view (Figure 8).

Figure 8. Built elements restricting the visibility of parks in Ikervár (**a**)—2010, Kalocsa (**b**)—2012 and Acsa (**c**,**d**)—2012. Source: M.S.

Several of the identified factors may also be present at the same time. A good example of this is the garden of the Prónay Mansion in Acsa, where the park's existing and visually characteristic tree elements are invisible from public areas, due to the combined hiding effect of a tall solid fence, a mass of vegetation around the garden, buildings within the park and the trees being located in an unfavourable location in terms of topography.

The urban landscape protection tools were also analysed in all 28 settlements where gardens with characteristic tree elements with a marked impact on the urban landscape are located (Table 1). Out of the 28 urban landscape handbooks, only 11 (39%) mentioned the importance of the historic garden or its trees as significant elements in the urban landscape or as valuable visual heritage. Good examples include the handbooks of Berkesz and Dénesfa, where both the garden and its trees are emphasised as important, valuable and in need of urban landscape protection, and Tornanádaska, where the giant *Sequoiadendron giganteum* itself is mentioned for its visual appeal.

Table 1. Emphasis on gardens and trees in urban landscape handbooks.

Name of Settlement	Tree Elements or Gardens Emphasised in Handbook as Valuable
Acsád	No
Ádánd	No
Berkesz	Yes
Dénesfa	Yes
Fehérvárcsurgó	No
Geszt	No
Gyula	No
Hédervár	Yes
Hőgyész	No
Iharos	Yes
Iharosberény	Yes
Iváncs	No
Lengyeltóti	No
Martonvásár	No
Mihályi	No
Nagycenk	Yes
Nagyrécse	Yes
Nagyvázsony	Yes
Parádsasvár	No
Putnok	No
Somogysárd	No
Somogyzsitfa	Yes
Surd	Yes
Szécsény	No
Tornanádaska	Yes
Zala	No
Zalacsány	No
Zalaszentgrót	No

Seventeen (61%) of the handbooks do not mention the analysed parks at all (Putnok, Lengyeltóti etc.), often only analysing the chateau or castle buildings, but not their surroundings. Others only include it in the enumeration of public green spaces (Gyula, Martonvásár, Mihályi) or as a nature protection area (Hőgyész, Ivánc, Szécsény), but not as valuable elements of the urban landscape. This is especially noteworthy as the majority of settlements included in the analysis are small towns or villages, with relatively few landmarks.

3.2.2. Results of the Object Scale Analysis

External Characteristics

The results of the object-scale analysis show that the three different visibility types are similarly common among the 43 analysed elements. Perpendicular visibility can be observed in 15 cases (35%), while 14 elements (32.5%) were visible in a parallel way. Fifteen tree elements (32.5%) are also characterised by multi-angle visibility. The proportional occurrence of all three types demonstrates that all of them can be considered widespread and typical (Figure 9).

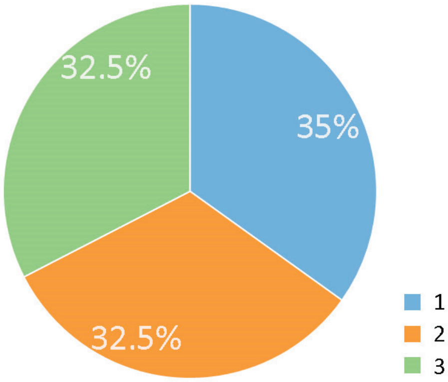


Figure 9. Proportion of visibility types (1, 2, 3). Key: 1. Perpendicular visibility; 2. Parallel visibility; 3. Multi-angle visibility. Source: authors.

In terms of visibility range, there are much larger differences than in the case of visibility types (Figure 10). 18 studied objects (42%) are only visible from a short distance (category A), 23 (53.5%) can be viewed from different parts of the settlement (category B), and only two (4.5%) are visually impactful from beyond their close urban environment (category C).

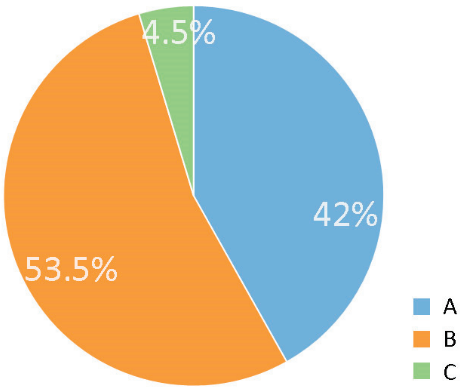


Figure 10. Proportion of the different visibility range types (A, B, C). Key: (A) short distance visibility of characteristic tree elements (<50 m); (B) character element that can be perceived from several directions in the settlement (>100 m or at least 50 m in several different directions); (C) a character element that can be perceived from almost the entire settlement or even beyond the urban borders. Source: authors.

Seven different combinations of visibility type and visibility range categories have been recorded (Table 2). The visibility range category C does not have any combinations with visibility types 1 and 2, as these mean there are more localised visual connections, while category C implies a much wider area of visual impact. The most common combination—32.5%, 14 occurrences—was between the perpendicular (narrow) visibility type and small visibility range (1/A). This means that the majority of analysed gardens—and settlements—do not typically have large-scale visual connections, and visibility is often blocked. One of the second most common combinations (2/B), with 25.6% of all cases (11 examples), is also logical from a visual design standpoint: a linear visibility axis can often extend over 100 m. The combination 3/B, which also occurs in 25.6% of examples (11 occurrences) included in the analysis, is similar to 2/B, but with multiple angles of visibility.

Table 2. Combinations of visibility types and visibility ranges. Key: 1. Perpendicular visibility; 2. Parallel visibility; 3. Multi-angle visibility; (A) short distance visibility of characteristic tree elements (<50 m); (B) character element that can be perceived from several directions in the settlement (>100 m or at least 50 m in several different directions); (C) a character element that can be perceived from almost the entire settlement or even beyond the urban borders.

Visibility Type	Visibility Range	Combination	Number of Examples	% of Examples
1	A	1/A	14	32.5%
1	B	1/B	1	2.3%
1	C	1/C	-	0%
2	A	2/A	3	7.0%
2	B	2/B	11	25.6%
2	C	2/C	-	0%
3	A	3/A	1	2.3%
3	B	3/B	11	25.6%
3	C	3/C	2	4.7%

The combination 1/B was identified in a single case (Szécsény), where a solitary *Sophora japonica* 'Pendula' is visible from a much larger distance than 50 m, even though the angle of visibility is quite narrow. Three examples (7%) have been found for the combination 2/A (parallel visibility type with a mid-sized range): Iharosberény (*Ginkgo biloba*), Fehérvárcsurgó (*Aesculus hippocastanum*) and Somogysárd (*Sequoiadendron giganteum*). In each of these gardens, the characteristic trees are visible from a path running nearby them, but due to an object (vegetation or buildings) blocking them from view, they only reveal themselves when the visitor is already closer than 50 m.

Characteristic elements visible from a wide angle or multiple directions (category 3) include a single example of *Platanus* trees located in the front garden of the Hédervár Castle that are visually dominant in their surroundings, but due to the dense vegetation bordering the garden, they only appear when visitors are already in front of the castle (3/A). This effect is unchanging all year, even in the winter, when there are no leaves. Category 3 also includes tree elements that are visible from an exceptionally large range. The giant sequoia (*Sequoiadendron giganteum*) in Tornanádaska is easily visible from outside the village, making it an important local landmark (Figure 11). Another *Sequoiadendron* specimen in Zalacsány was visible from over 600 m before 2012 (Figure 5). In both examples of the 3/C combination, advantageous topography helped to create a wide visibility range for trees.

Figure 11. Visual connection beyond the settlement borders. Characteristic giant sequoia in the park of Hadick mansion in Tornanádaska—2012. Source: M.S.

Internal Characteristics

After categorising the visibility of compositional elements, an analysis was made regarding which inherent properties of trees and tree compositions are the most important factors behind their impact on the urban landscape, as previously explained in the Section 2.

According to the analysis results, unique or unusual appearance is the most common factor, with 36 (83%) of studied elements having significantly different shapes or habits from "typical" trees. Contrast with neighbouring living elements, in colour or shape, or even both in some cases, can be observed in 22 (51%) of trees and tree compositions. Trees standing in a prominent, special location (e.g., on corners or in the centre of large open spaces) were the least common, with only 12 (28%) such elements occurring in the analysis (Figure 12).

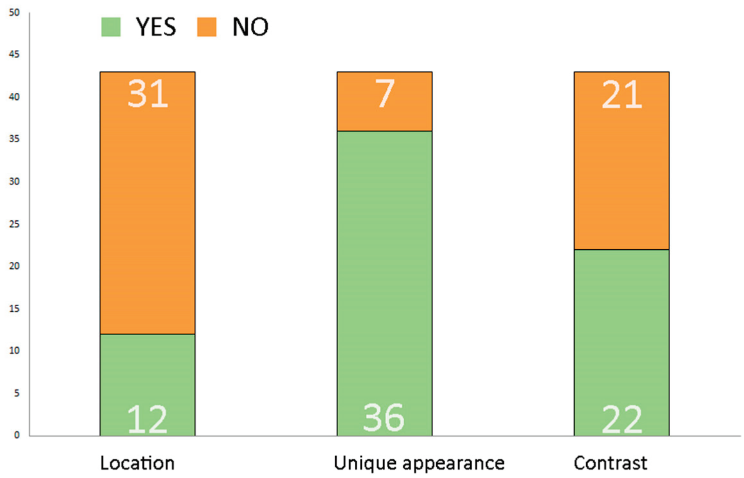


Figure 12. The presence or absence of internal characteristics (location, unique appearance, contrast) of the elements. Source: authors.

The occurrence of different combinations also led to interesting results. The most common combination was between unique appearance and contrast, in 19 cases. Nine tree elements with a unique or unusual appearance and a prominent, special location were observed, while five trees standing in a special location and with a significant contrast to their surroundings were identified (Figure 13).

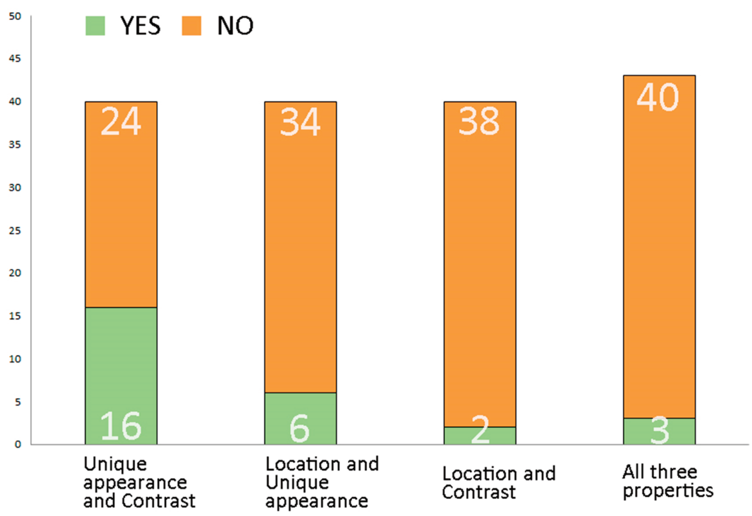


Figure 13. The number of elements with more than one internal characteristic. Source: authors.

In three cases, all three analysed factors were present: the poplar (*Populus alba*) of Gyula that stands in a prominent open area next to a road provides visual interest with its multi-stemmed habit, the light-coloured trunks and silver-backed leaves providing contrast with surrounding plants. The same garden includes a group of sycamores (*Platanus* × *hybrida*) that also show all three analysed properties. The third such example is the sycamore (*Platanus* × *hybrida*) in Ádánd, which has a tilted trunk (unique shape) bending over a road (prominent location), with differently coloured trees in its vicinity (contrast).

In a separate analysis, the way seasonality affects the prominence of trees in the urban landscape was studied. Several trees were especially noticeable during certain seasons: evergreen plants stand out from a mass of deciduous trees during the winter, while they may not even be visible in summer. The trunks, bark colouration, branch structure and unique habits of certain trees (*Platanus* species and *Aesculus hippocastanum* in particular) are also more prominent in leafless periods than during the warmer months. Taxa with spectacular leaf colouration in the autumn (*Ginkgo biloba*, *Larix decidua*) or in spring and early summer (*Fagus sylvatica* 'Atropunicea' and other purple-leaved cultivars) are also highly seasonal in appearance, and even though their location, size or habit can also help them become local landmarks, seasonal colouration certainly strengthens the effect.

4. Discussion and Conclusions

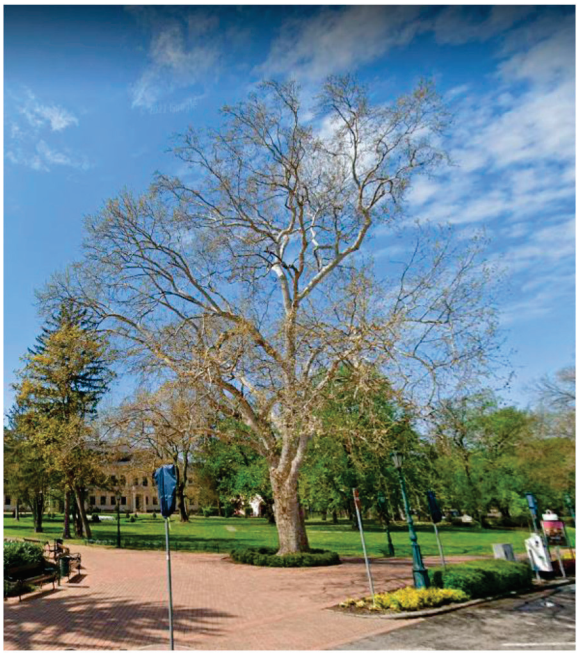
The results described above have several practical implications for several fields of study, including landscape architecture, green surface maintenance, tree assessment and the study of ecosystem services. Results show that the contribution to the urban landscape is a major component of the cultural ecosystem services of trees, which as a factor is rarely included in currently-used tree evaluation methods [33,34]. Results concerning tree visibility types can be particularly helpful in furthering research on the perception-based value of trees [20,21] and visibility-based research on urban areas [35]. The impact of trees and tree compositions on the urban landscape and therefore the perception and attachment of people to historic gardens within the urban fabric can be a meaningful new approach to research into cultural ecosystem services [3,32,36,37].

When also taking the contribution of trees and tree compositions to the urban landscape into account as a cultural ecosystem service, priorities for maintenance and the design of green areas and vegetation may be somewhat different. In historic gardens and green areas with existing elements that have a major impact on the surrounding urban landscape, retaining—and if possible, improving—visibility must be the most important aspect of maintenance. In other cases, where potentially impactful trees and tree elements are currently hidden from view, the removal of existing features (living or built) that block their visibility from public areas may be an overall positive decision, especially if these features do not have any inherent historic or cultural value. Research results suggest that even the removal of surrounding, less characteristic or valuable trees might be necessary to improve the visibility and visual impact of tree elements. Similarly, the design and execution of green infrastructure development must take into consideration existing trees and tree compositions of value to the urban landscape. Newly-planted street trees, hedges or shrubs may block the visibility of these valuable elements, overall reducing the cultural ecosystem services of their surroundings. This is especially true of tall and dense shrubs and evergreens in particular, as these create an unchanging spatial wall, completely severing visual connections.

The unique appearance of certain individual trees can be attributed to properties that are generally seen as undesirable in tree assessment and maintenance. Asymmetrical growth, twisted branches and visible scars can all contribute to the uniqueness—and therefore the visual importance—of these plants. While most existing tree assessment methods consider these properties negative and the goal of traditional maintenance is usually to change or "rectify" them, the results of this research imply that there is an inherent value in the unusual and bizarre appearance of certain trees. However, this does not mean that these characteristics must be maintained at all costs: any factors endangering the survival or overall attractiveness of trees, and especially visitor safety, can and should be prioritised over visual interest.

The results suggest that time is a significant factor in the visual importance of trees. The analysed elements are dynamic, living components of the urban landscape, and their characteristics can change drastically on several different time scales, which can be due to changes in the seasons or even death because of extreme weather conditions, diseases or senescence (Figures 5 and 14). However, due to time restraints, this research could not analyse this complex topic in detail. Still, the results show that the role of trees in the urban landscape may decline or completely cease to be due to many factors, and trees can also become important features over time. Further studies are necessary to fully understand the impact of seasonal changes and long-term processes on the system of visually important tree elements.

(a)



(b)

Figure 14. A sycamore tree in changing environment (Gyula). Source: (**a**) M.S.–2012, (**b**) Google Street View [32]—2021.

Hungary provides a good case study for this research because there is a large number of towns where historic parks account for a significant proportion of their greenery. The European network of connections between members of ruling houses, nobility and the clergy, as well as in scientific and artistic circles, is well known. Through marriage, travel, due to the role of the Church as an intermediary, as well as the invitation and employment of various professionals and craftsmen (stonemasons, botanists, and garden artists), a similar cultural foundation formed throughout the continent, which also allowed the evolution of local, vernacular specialities in garden history, unique to the local landscape [38–41]. Because of this, the results can potentially be applied to various other European countries. Furthermore, the existence of a fully implemented urban landscape protection system in Hungary provides the necessary framework to successfully study the topic in all its complex contexts. While the methods and results are not specific to the country and can be considered to be widely applicable and globally relevant, further research in different geographical locations and different types of green areas can establish a wider recognition of the importance of trees and tree compositions in the urban landscape.

Research on the inclusion of trees associated with historic gardens and parks in urban landscape protection tools in Hungary suggests that even with an existing framework, the recognition of trees as visually significant elements are lacking. While regulation on the protection of the urban landscape is implemented to a variable degree around the world, professional recognition of features as valuable is key to ensuring their survival and maintenance. Furthermore, results suggest that the visibility and visual connections of trees can also be extremely important. This implies that in addition to ensuring the protection of trees and tree compositions themselves, integrating them into the wider urban and green infrastructure planning system is vital to maintaining the impact of these valuable living elements in their wider context.

In conclusion, the results show that trees associated with historic gardens have a diverse and dynamically changing impact on the urban landscape, which has recently come to play an increasingly important role in protecting local cultural heritage. Factors behind the visual impact on tree elements were identified, as well as different visibility types, which can help categorise and preserve the cultural services provided by these living pieces of cultural heritage.

Author Contributions: Conceptualisation, L.Z.N., I.V. and M.S.; methodology, L.Z.N. and M.S.; investigation, M.S.; data curation, L.Z.N. and M.S.; writing—original draft preparation, L.Z.N.; writing—review and editing, I.V. and M.S.; visualisation, M.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data is contained within the article. The data presented in this study are available in Appendix A.

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

Appendix A

Table A1. Data table of analysed tree elements. Legend: 1. Perpendicular visibility; 2. Parallel visibility; 3. Multi-angle visibility; (A) short distance visibility of characteristic tree elements (<50 m); (B) character element that can be perceived from several directions in the settlement (>100 m or at least 50 m in several different directions); (C) a character element that can be perceived from almost the entire settlement or even beyond the urban borders.

Nr. of Location	Nr. of Element	Settlement	Name of the Mansion and the Park	Scientific Name of the Trees	Garden Architecture Element	Visibility Type	Visibility Range	Location	Unique Appear-ance	Contrast
1	1	Iváncz	Park of Sigray mansion	*Sequoiadendron giganteum*	Individual (element)	2	B		x	
2	2	Zalacsány	Park of Malatinszky-Batthyány country house	*Sequoiadendron giganteum* *	Individual	3	C		x	x
3	3	Nagycenk	Park of Széchenyi mansion	*Tilia cordata*	Linear element (row of trees)	1	A		x	
	4	Nagycenk	Park of Széchenyi mansion	*Platanus* × *hybrida*	Linear element (row of trees)	2	B		x	
4	5	Nagyvázsony	Park of Zichy mansion	*Pinus nigra*	Clump (group of trees)	1	A			x
5	6	Tornanádaska	Park of Hadick mansion	*Sequoiadendron giganteum*	Individual	3	C		x	x
6	7	Surd	Zichy Park	*Platanus* × *hybrida*	Linear element (row of trees)	3	B		x	
	8	Surd	Zichy Park	*Quercus robur f. fastigiata*	Individual	3	B		x	x
7	9	Acsád	Park Szegedy mansion	*Platanus* × *hybrida*	Linear element (row of trees)	3	B		x	
	10	Acsád	Park Szegedy mansion	*Sequoiadendron giganteum*	Individual	3	B		x	

Table A1. *Cont.*

Nr. of Location	Nr. of Element	Settlement	Name of the Mansion and the Park	Scientific Name of the Trees	Garden Architecture Element	Visibility Type	Visibility Range	Location	Unique Appearance	Contrast
8	11	Martonvásár	Park of the Brunszvik mansion	*Sophora japonica* 'Pendula'	Individual	1	A		x	x
9	12	Iharos	Park of Inkey mansion	*Platanus* × *hybrida*	Individual	2	B		x	
	13	Iharos	Park of Inkey mansion	*Ginkgo biloba*	Individual	1	A		x	x
10	14	Iharosberény	Park of Inkey mansion	*Platanus* × *hybrida*	Mass-like appearance	3	B	x	x	
	15	Iharosberény	Park of Inkey mansion	*Ginkgo biloba*	Individual	2	A			x
	16	Iharosberény	Park of Inkey mansion	*Cedrus deodara*	Individual	2	B		x	x
	17	Iharosberény	Park of Inkey mansion	*Fagus sylvatica* 'Atropunicea' (group of 3)	Clump	2	B		x	x
11	18	Nagyrécse	Park of Inkey mansion	*Sequoiadendron giganteum*	Individual	2	B		x	x
12	19	Somogyzsitfa	Park of Véssey-Somssich mansion	*Quercus robur f. fastigiata*	Individual	1	A	x		x
13	20	Fehérvárcsurgó	Park of Károlyi mansion	*Aesculus hippocastanum*	Individual	2	A			x

Table A1. *Cont.*

Nr. of Location	Nr. of Element	Settlement	Name of the Mansion and the Park	Scientific Name of the Trees	Garden Architecture Element	Visibility Type	Visibility Range	Location	Unique Appear-ance	Contrast
14	21	Zalaszentgrót	Park of Batthyány mansion	*Platanus* × *hybrida*	Individual	1	A		x	
	22	Zalaszentgrót	Park of Batthyány mansion	*Platanus* × *hybrida*	Individual	2	B		x	
	23	Zalaszentgrót	Park of Batthyány mansion	*Sophora japonica* 'Pendula'	Individual	3	B		x	x
15	24	Lengyeltóti	Park of Inkey-Zichy mansion	*Platanus* × *hybrida*	Individual	3	B		x	x
16	25	Somogysárd	Park of Somssich mansion	*Seauoiadendron giganteum* (2)	Clump	2	A		x	
17	26	Szécsény	Park of Forgách mansion	*Sophora japonica* 'Pendula' *(2)*	Individual elements	1	B	x	x	
18	27	Parádsasvár	Park of Károlyi mansion	*Pinus nigra (2)*	Individual	2	B		x	x
19	28	Geszt	Park of Tisza mansion	*Platanus* × *hybrida (2)*	Individual	1	A	x	x	
20	29	Gyula	Park of Harruckern-Almássy-Wenckheim mansion	*Platanus* × *hybrida*	Individual	3	B	x	x	x
	30	Gyula	Csigakert public park	*Populus alba*	Individual	3	B	x	x	x
21	31	Ádánd	Park of Csapody mansion	*Platanus* × *hybrida*	Individual	2	B	x	x	x

Table A1. *Cont.*

Nr. of Location	Nr. of Element	Settlement	Name of the Mansion and the Park	Scientific Name of the Trees	Garden Architecture Element	Visibility Type	Visibility Range	Location	Unique Appear-ance	Contrast
22	32	Hőgyész	Park of Apponyi mansion	*Platanus × hybrida*	Individual	2	B	x	x	
23	33	Zala	Park of Zichy mansion	*Aesculus hippocastanum*	Linear element (row of trees)	1	A		x	
24	34	Hédervár	Park of Khuen-Hédervár mansion	*Platanus × hybrida* (inside the garden)	Individual (in winter), mass-like appearance (summer)	3	A		x	
	35	Hédervár	Park of Khuen-Hédervár mansion	*Platanus × hybrida* (front of the garden)	Individual elements	3	B	x	x	
25	36	Berkesz	Park of Vay mansion	*Aesculus hippocastanum*	Linear element (row of trees)	1	A	x	x	
26	37	Putnok	Park of Serényi mansion	*Fraxinus excelsior*	Individual	1	A	x		
27	38	Mihályi	Park of Dőry mansion	*Aesculus hippocastanum* (2)	Individual	1	A		x	x
	39	Mihályi	Park of Dőry mansion	*Pinus nigra*	Individual	2	B			x
28	40	Dénesfa	Park of Cziráky mansion	*Seauoiadendron giganteum*	Individual	3	B	x		x
	41	Dénesfa	Park of Cziráky mansion	*Fraxinus angustifolia*	Individual	1	A		x	
	42	Dénesfa	Park of Cziráky mansion	*Tilia cordata*	Individual	1	A		x	
	43	Dénesfa	Park of Cziráky mansion	*Larix decidua*	Individual	1	A		x	x

* Dead at the time of writing.

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Article

Assessing the Spontaneous Spread of Climate-Adapted Woody Plants in an Extensively Maintained Collection Garden

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Abstract: Climate change may strongly modify the habitat conditions for many woody plant species. Some species could disappear from their natural habitats and become endangered, while others could adapt well to the changed environmental conditions and continue to survive successfully or even proliferate more easily. A similar process can occur within the artificial urban environment as the hitherto popularly planted urban trees may suffer from the extremities of the urban climate. However, among the planted taxa, there are species that spread spontaneously and appear as weeds in extensively managed gardens. In our study, we evaluated the native and non-native species involved in spontaneous spreading in the institutional garden of Buda Arboretum (Budapest) during the COVID-19 period in 2020–2021 when entry was prohibited, and maintenance went on in a restricted, minimal level. We investigated the correlation between spontaneously settling and planted individuals, and then performed multivariate analyses for native and non-native spreading plants for spatial and quantitative data. During our studies, we observed the spontaneous spreading of 114 woody species, of which 38 are native and 76 are non-native. Taking the total number of individuals into account, we found that, in addition to the 2653 woody species planted, a further 7087 spontaneously emerged weeds developed, which creates an additional task in the maintenance.

Keywords: woody plants; spontaneous spread; weed; invasive species; native plants; climate change; garden maintenance

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1. Introduction

The priority tasks for the maintenance of urban green spaces include the removal of spontaneous weeds or invasive species. Plants appearing in undesirable places and conditions may cause problems for residents and maintainers with their constant pressure on the existing vegetation. They can limit the growth, reduce the habitat, and result in amorphous, asymmetrical growth due to fight for light or reduced water or nutrient uptake in a divided root zone. Botanical and collection gardens are often leaders in the introduction of new plant species for public green or garden use; their recommendation, introduction, and commercialization require scientific soundness and professional responsibility [1–4].

Botanical gardens play an essential role in the observation and study of plants. Their role is unquestionable in research projects on climate change, phenological monitoring of plant adaptation strategies, and physiological processes [5–7]. These experiences can help with the planting design of public green spaces. When working on plant selection, we must know which species are acceptable and which plants should be avoided from an ecological aspect. Gardens often push the limits of species' distribution [8]. Taxa with questionable survivorship may be problematic to maintain in public green spaces; still, others are easy to care for because they are stable and they thrive and reproduce, as reported in several studies [1–4]. A suitable planting design may significantly reduce the maintenance tasks.

Spontaneously occurring tree species in urban environments include native species such as *Acer campestre*, *A. platanoides*, and *Ulmus* spp., which have a spreading ability similar to invasive plants. These are referred to as 'spreading native species' [9,10]. In this case, the relevant literature [11,12] agrees that the term 'invasion' is not appropriate to describe the spread of native plant species, even when their population increases. Some non-native species belonging to the invasive lists are ready to 'escape' and spread from their original plantation and can pose significant ecological and economic challenges.

Several definitions of invasive species exist in the literature. According to Richardson et al. [11], an invasive species is defined as any non-native species introduced directly or indirectly into a region with an increasing population. Hilton-Taylor and Brackett's definition takes the habitat consequences of a species into consideration, i.e., the damage it causes to semi-natural and natural habitats [13]. The spread of invasive species and the habitat conversion impacts due to human activities could result in habitat fragmentation and significant transformation [14]; the process may end in a severe loss of biodiversity, ecosystem degradation, and reduced resilience to the disturbance in both natural floras [15,16] and planned green spaces. Moreover, according to Pimentel et.al. (2005) [17], social attitudes and public perceptions often attribute, for example, damage to roads and building foundations to invasive plants, in addition to causing public health problems. However, the term weed can refer to native and non-native taxa, species that settle in valuable green areas and thus cause a high maintenance challenge.

In landscape architecture and horticultural practice, the adaptability and applicability of plant species with different conservation statuses (protected, highly protected, and invasive) are common issues [18]. Invasive species, which often start their careers in botanical gardens, have the opposite effect on conservation. Plants, once released from gardens, can infest large areas due to their high reproductive patterns and aggressive spread, causing severe ecological and economic damage. Control is often a problem, even in intensively managed plantations.

The 100 most dangerously invasive organisms (ISSG 2017) [19,20] include 21 woody species on a global scale. Some of these tree taxa (e.g., *Acacia mearnsii* De Wild, *Lantana camara* L., *Pinus pinaster* Aiton, *Rubus ellipticus* Sm., *Schinus terebinthifolius* Raddi., *Tamarix ramosissima* Ledeb., and *Ulex europaeus* L.) often occur in Europe, causing severe ecological problems. The same list compiled for Europe (on a continental scale) contains 16 woody species; 2 of them (*Ailanthus altissima* Mill. and *Robinia pseudoacacia* L.) belong to the invasive classification in Hungary [21–23].

Fortunately, most introduced species have spread only on a local scale, and they are under control. However, an insignificant minority of species have become self-sufficient and have spread beyond all imagination [18]. The spread of Indian and American poke (*Phytolacca acinose* Roxb. and *P. americana* L.) may cause severe ecological problems in the sandy habitats of Hungary (Transdanubia and the southwestern region); the false indigo (*Amorpha fruticosa* L.) and boxelder maple (*Acer negundo* L.) have spread all over in the floodplains. In drier areas and, unfortunately, even in the mountains, the black locust (*Robinia pseudoacacia* L.) and their peers are appearing ever-increasingly.

Botanical gardens have regularly collected information on alien species from the beginning [7,19]. According to many publications, botanical gardens and the horticultural trade seem to be the first steps for invasive species [1]. In 2013 the association of European Botanical Gardens adopted a standard code of conduct for the management of invasive species in gardens [24], which, for example, manifested itself in a decrease in the seed exchange of invasive species [25].

The university in the southeast region of Hungary (The University of Szeged, Department of Geoinformatics, Physical and Environmental Geography) has created a GIS database for the territorial distribution of the most common invasive plant species in Hungary [26]. The database shows the occupation of several invasive species in different years. For example, the first Hungarian Black List (invasive tree and shrub species) appeared in 2002 and based on observations, the latest one was published in 2020 [27]. This comprehensive technical publication discusses a collection of invasive species, the so-called Black List and the Grey List, which describe the potentially invasive species.

This research investigates the quantitative proportions and species composition of invasive (non-native species) (IAS) [28] and all other spontaneously spreading species and the relationships between their distribution and sustainability in an extensively maintained garden such as the Buda Arboretum. This study draws attention to the taxa that may have the potential to spread in public areas due to the changing climate. The field survey occurred during a special period in 2020–2021 when garden management had to remove the regular garden workers' and the horticultural and landscape architect students' participation in garden maintenance due to the strict COVID-19 closures and restriction.

Our research questions are as follows:

What are the relationships between the abundance and composition of spontaneously occurring species and individuals and the size of patches and green patches? For which species are there correlations between the number of individuals established and spontaneous occurrence? Are patterns and regularities of spreading observed for species? What is the proportion of invasive and aggressively spreading native species among the spontaneously occurring species? Which taxa may threaten the maintenance of green areas in public spaces? Are there any taxa that should be monitored for their potential to spread?

2. Results

2.1. Spontaneously Settled Species in the Study Area

During the Buda Arboretum site survey, we encountered a lot of weeds. The total plant collection consisted of 2108 taxa (basal species, varieties, forms, and variants). We found 114 taxa that can self-sustain and spontaneously appear in many parts of the garden, weeding out the intended concept and causing maintenance difficulties. The proportion of native and non-native plants was approximately one-third (38 taxa) to two-thirds (76 taxa) (Table 1). The number of spontaneously dispersed specimens was 7022, which represents an additional 265% of the plants planted in the garden compared to the arboretum (2653 specimens). The total number of spontaneously spread individuals was 7022, which represents a 265% extra load on the garden compared to the plants planned and planted in the arboretum (2653 individuals). Of these, 4186 individuals are non-native, which is almost 60%. The diversity calculations for the groups/spread types (see below) are presented in the following sections.

Table 1. The context for quantifying spontaneously propagating taxa and individuals in Buda Arboretum.

Spontaneously Spreading Plants		
	Taxa	**Individuals**
Native	38	2836
Non-native	76	4186
Total	114	7022

There is a significant difference between the sample medians in both case (Figure 1a,b). According to the results of the diversity analysis, there are significantly more non-native species present in the plots; there are also significantly more intensively spreading species in the plots ('parcels').

Based on the study of Bartha (2020) [27], we focused on the black-listed and the Grey-listed (the potentially invasive) taxa detected in the Buda Arboretum (Tables 2 and 3). The invasive dendro-taxa showed a wide variety; unfortunately, some of these invasive plants are already active (directly or indirectly threatening the native species through habitat modification), while others are on the watch list but are not yet managed (Table 3).

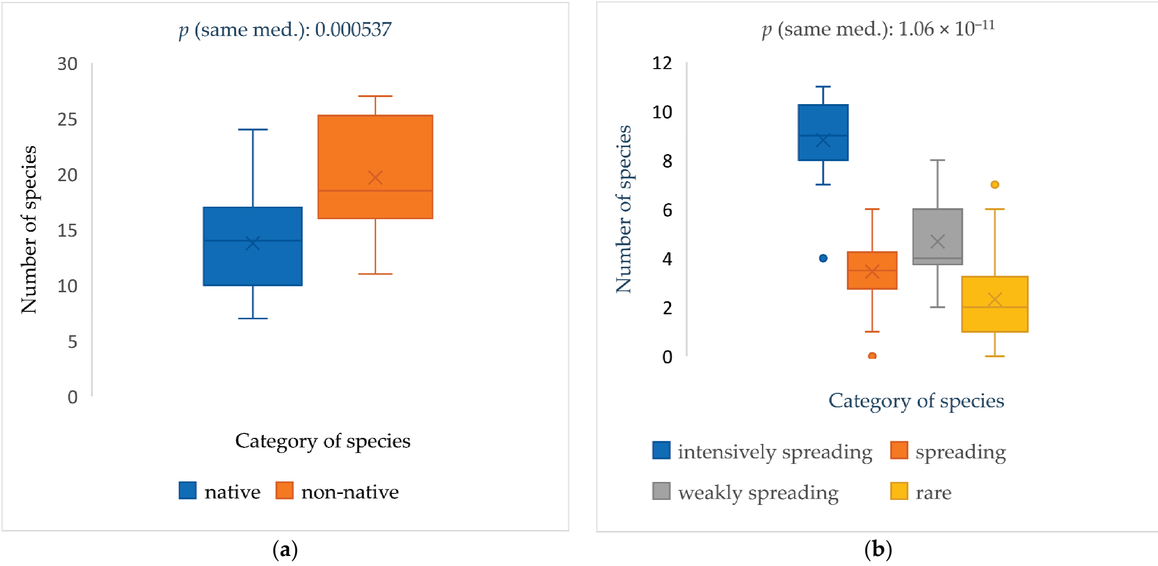


Figure 1. Boxplot of taxa number (species) in the plots ('parcels'): mean, median, 25–75% quartiles, non-outlier range, and outliers. Mann–Whitney test for "equal medians" (**a**) and Kruskal–Wallis test for "equal medians" (**b**).

2.2. The Spontaneous Emergence Categories

2.2.1. Category I

Among the alien species, the spontaneous occurrence of **intensively spreading** species was recorded for 11 species or related species. In total, the 11 species on the 22 plots of the arboretum represent 2933 individuals; the common hackberry (*Celtis occidentalis* L.) recorded the highest number of 561 individuals. In contrast, the lowest number of individuals in this category belongs to the white mulberry (*Morus alba* L.). The intensively propagating species are represented by four black-listed taxa (*Ailanthus altissima* Mill, *Celtis occidentalis* L., *Parthenocissus* spp., and *Robinia* spp.). Among the operative taxa of the Grey List, we detected three taxa in the garden (*Mahonia* spp., *Morus alba* L., and *Prunus cerasifera* Ehrh.). The species for observation are represented by four taxa (*Cotoneaster* spp., *Diospyros* spp., *Koelreuteria paniculata* Laxm., and evergreen *Lonicera* taxa). Some examples are shown in Figures 2–4. We made the numbering at the genus level for the American five-leaved creeper, holly, cotoneasters, persimmons, and evergreen honeysuckle. *Diospyros lotus* L. in 99% of persimmons, and three taxa of *Lonicera fragrantissima* Lindley & Paxton, *L. standishii* Carriére, and their hybrid, *L.* × *purpusii* Rehder are observed in evergreen honeysuckle.

Figure 2. The common hackberry (*Celtis occidentalis* L.) in the patch of evergreen shrubby veronica (*Hebe pinguifolia* Cockayne & Allan) photo by Krisztina Sz.

Table 2. The woody taxa in the Buda Arboretum according to the Black List categories * (management list in dark grey, action list in medium grey, and warning list in white) based on Bartha 2020 [27].

Species in BA	Risks of Biodiversity				Additional Criteria		Bio-Eco Criteria					
	Interspecific Competition	Hybridization	Transfer Pathogens	Negative Effect on Ecosystem	Current Distribution	Emergency Measure	Occurs in Important Habitats	Reproduction Cap.	Spread Cap.	Current Spread History	Monopolization of Resources	Facilitation of Climate Change
Acer negundo	yes	no	questionable	yes	large-scale		yes	high	high	expansive	yes	unknown
Ailanthus altissima	yes	no	no	yes	large-scale		yes	high	high	expansive	yes	yes
Amorpha fruticosa	yes	no	questionable	yes	large-scale		yes	high	high	expansive	yes	yes
Celtis occidentalis	yes	no	no	yes	large-scale		yes	high	high	expansive	yes	unknown
Elaeagus angustifolia	probable	no	no	yes	large-scale		yes	high	high	expansive	no	yes
Fraxinus pennsylvanica	yes	no	questionable	yes	large-scale		yes	high	high	expansive	yes	unknown
Lycium barbarum	yes	no	no	yes	large-scale		yes	high	low	stable	yes	unknown
Parthenocissus inserta	yes	no	no	yes	large-scale		yes	high	high	expansive	yes	unknown
Prunus serotina	yes	no	no	yes	large-scale		yes	high	high	expansive	yes	unknown
Robinia pseudoacacia	yes	no	questionable	yes	large-scale		yes	high	high	expansive	yes	yes
Syringa vulgaris	yes	no	probable	yes	large-scale		yes	high	high	expansive	yes	yes
Ulmus pumila	yes	yes	yes	probable	large-scale		no	high	high	expansive	unknown	yes
Vitis vulpina	yes	yes	yes	yes	large-scale		yes	high	high	expansive	yes	unknown
Elaeagnus commutata	questionable	no	no	yes	small-scale	available	unknown	high	high	unknown	yes	yes
Hedera crebrescens	probable	probable	questionable	yes	small-scale	available	no	high	high	expansive	yes	unknown
Ptelea trifoliata	questionable	no	no	yes	small-scale	available	yes	high	high	expansive	unknown	unknown
Akebia quinata	probable	no	no	yes	absent	available	yes	high	high	unknown	yes	yes
Baccaris halimifolia	yes	no	no	questionable	absent	available	yes	high	high	expansive	unknown	yes
Eucalyptus sp.	probable	no	no	yes	absent	available	no	high	high	expansive	yes	yes
Ligustrum sinense	probable	no	questionable	yes	absent	available	unknown	high	high	expansive	unknown	yes
Pinus pinaster	yes	no	probable	yes	absent	available	yes	high	high	expansive	yes	yes
Toona sinensis	yes	no	probable	probable	absent	unknown	unknown	high	high	unknown	yes	yes

* The species in the management list (dark grey) are already in the early stages of invasion, but the means to control them are unknown or they occur over a large area. The species in the action list (light grey) are also in the early stages of invasion but live in a small space and have the means to eradicate them. The warning list (white lines) is a collection of species considered to be flood species in areas with similar endowments, but they may not settle in the near future.

Table 3. The woody taxa in the Buda Arboretum according to the Grey List categories and their spontaneous appearance in urban environments.

Taxa in BA	Operative Group	Watch List	Spontaneous Appearance in Urban Environments
	For Natural Habitats		
Acer pseudoplatanus cv. Atropurpureum	x		x
Acer opalus		x	
Broussonetia papyrifera		x	x
Buddleja davidii	x		x
Celtis australis		x	x
Cotoneaster divaricatus		x	
Cotoneaster horizontalis		x	
Cytisus scoparius		x	
Diospyros lotus		x	
Euonymus fortunei		x	x
Fallopia baldschuanica		x	x
Gleditsia triacanthos		x	x
Juglans nigra		x	x
Koelreuteria paniculata		x	x
Lonicera fragrantissima		x	
Lonicera × *purpusii*		x	
Lonicera standishii		x	
Mahonia aquifolium	x		x
Mahonia repens	x		
Morus alba	x		x
Parthenocissus quinquefolia	x		x
Paulownia tomentosa	x		x
Phyllostachys viridiglaucescens	x		x
Pinus nigra	x		x
Populus × *euramericana*	x		x
Prunus cerasus	x		x
Prunus mahaleb	x		x
Prunus cerasifera	x		x
Pterocarya fraxinifolia		x	
Rhus typhina		x	x
Robinia viscosa		x	
Rosa rugosa		x	x
Rubus phoenicolasius		x	
Yucca filamentosa			x

Figure 3. The tree of heaven (*Ailanthus altissima* Mill.) large seedling in the shrub in front of the wall, photo by Krisztina Sz.

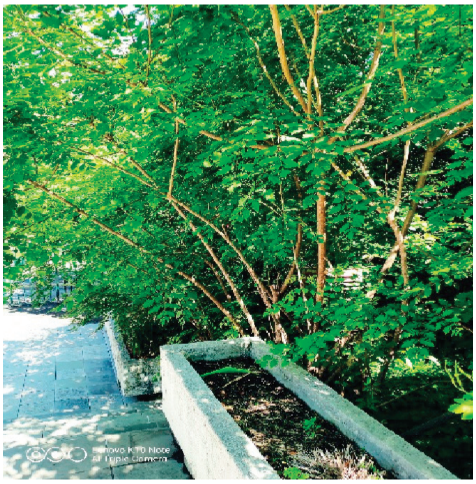


Figure 4. A weeding bug of goldenrain tree (*Koelreuteria paniculata* Laxm.), photo by Krisztina Sz.

Among the expanding native species, 38 different taxa have been recorded as spontaneous occurrences. Of the native species, the maple (Acer spp.) genus has an outstanding ability to spread. We found the maple (*Acer platanoides* L.) to be the winner. However, it is a negative victory, not only in the group of native taxa but also among all non-native invasive species in the Buda Arboretum. In addition to the native maple, even the sycamore maple (*Acer pseudoplatanus* L.) is represented among the intensively spreading (I. category) woody taxa. Two more woody taxa, the field maple (*Acer campestre* L.) and the linden (*Tilia* spp.), and five shrubs (the erect habit elderberry (*Sambucus nigra* L.), the common dogbane (*Cornus sanguinea* L.), the wild plum (*Ligustrum vulgare* L.), and roses, mainly dog rose (*Rosa canina* L.), and others such as creeping clematis (*Clematis vitalba* L.)), belong to the same category. Each of them pollutes the arboretum with more than 100 specimens, the maple with 647 specimens.

2.2.2. Category II

For the **spreading** species, 522 individuals of 8 species were weeded in the arboretum, representing an average of 19% per unit area in this category. However, two of the Black List species, bush maple (*Acer negundo* L.) and ash (*Fraxinus* spp.), were only recorded at the genus level. Among the Grey List species, the wine raspberry (*Rubus phoenicolasius* Maxim.) represented a reasonable spread. The remaining taxa in this category were cock's-foot (*Crataegus crus-galli* L.), bright holly (*Ligustrum lucidum* W.T.Aiton.), Korean holly (*Ligustrum ovalifolium* Hassk.), cat-root (*Smilax excelsa* Duhamel), and viburnum (*Viburnum* spp.). Perhaps the surprise species among these was the evergreen-leaved glossy privet from (Latin) East Asia. No specimens of this category were found in plot 21.

Among the expanding native species in the spreading category, there are four taxa, from which we examined the manna ash (*Fraxinus ornus* L.) as exact species, while the others are listed as a genus, oaks (*Quercus* spp.), viburnums (*Viburnum* spp.), and elms (*Ulmus* spp.).

2.2.3. Category III

In the category of **weakly spreading**, 23 different taxa with a total of 587 individuals were observed with the spontaneous appearance of 15%/m^2 on average: horse chestnut (*Aesculus hippocastanum* L.), Chinese barberry (*Berberis julianae* C.K.Schneid.), trumpet creeper (*Campsis* spp.), Judas tree (*Cercis siliquastrum* L.), American yellowwood (*Cladrastis kentukea* (Dum. Cours) Rudd.), fontanesia (*Fontanesia phillyreoides* Labill.), Kentucky coffeetree (*Gymnocladus dioicus* (L.) K.Koch.), Japanese honeysuckle (*Lonicera japonica* Thunb.), Tatarian honeysuckle (*Lonicera tatarica* L.), wolfberry (*Lycium barbarum* L.), Persian ironwood (*Parrotia persica* C.A. Mey.), poplars (*Populus* spp.), prunus (*Prunus* spp.), pagoda tree (*Styphnolobium japonicum* syn. *Sophora japonica* L.), common lilac (*Syringa vulgaris* L.), bee-

bee tree (*Tetradium daniellii* (Benn.) T.G.Hartley), Chinese cedar (*Toona sinensis* M.Roem.), grapes (*Vitis* spp.), and Chinese wisteria (*Wisteria sinensis* (Sims) DC.). Three black-listed species from the categories wolfberry, common lilac, and Chinese cedar, as well as operational Grey-listed taxa poplars and prunus. Of the others, more attention should be paid to the maintenance of Chinese barberry, trumpet creeper, Judas tree, poplars, and Chinese wisteria, which are more common in urban applications.

Among those indigenous taxa, appearing with less than 50 individuals, includes species such as Tatarian maple (*Acer tataricum* L.), common hawthorn (*Crataegus monogyna* Jacq.), common ash (*Fraxinus excelsior* L.), Tatarian honeysuckle (*Lonicera tatarica* L.), poplars (*Populus* spp.), sweet and bird cherry (*Prunus avium* L., *Prunus padus* L.), buckthorn (*Rhamnus cathartica* L.), silver linden (*Tilia tomentosa* Moench), and common hazel (*Corylus avellana* L.).

2.2.4. Category IV

To the infrequent, **just emerging** category belong 30 taxa and 107 individuals representing an average of $4\%/m^2$ load, including black-listed chocolate vine (*Akebia quinata* (Thunb. ex Houtt.) Decne.), together with the evergreen taxa of the genus level silverberry (*Elaeagnus* spp.) and common hoptree (*Ptelea trifoliata* L.). Grey-listed species include paper mulberry (*Broussonetia papyrifera* L), summer lilac (*Buddleja davidii* Franch.), Mediterranean hackberry (*Celtis australis* L.), honey locust (*Gleditsia triacanthos* L.), and sumac (*Rhus* spp.). The spontaneous appearance of some warm-demanding species, Jerusalem thorn (*Paliurus spina-christi* Mill.), holly oak (*Quercus ilex* L.), English holly (*Ilex aquifolium* L.), and Chinese-pepper (*Zanthoxylum simulans* Hance), has been surprising; in some cases, the evergreen oaks grow hundreds of meters away from the mother plant.

Interestingly, among the expanding native species, the spontaneous spreading of smoke trees (*Cotinus coggygria* Scop.) is not significant from the emerging category; however, much of the garden is non-irrigated, and sunny places on a southern slope would be suitable. Among other species, the edible fruits are worth interest, such as snowy mespilus (*Amelanchier ovalis* Medik.), simple barberry (*Berberis vulgaris* L.), wild pear (*Pyrus pyraster* L. Burgsd.), and Turkish hazel (*Corylus colurna* L.). Interestingly, we found European beech (*Fagus sylvatica* L.) seedlings in the sunny and warm part of the garden.

2.2.5. Category V

Among the vegetative propagating and **colonies forming**, some taxa may cause significant maintenance surplus, such as, e.g., Caucasian spurge (*Andranchne colchica* Fisch & C.A. Mey. ex Boiss.), Japanese knotweed (*Fallopia japonica* Houtt.), eastern tree (*Forsythia* spp.), sumac (*Rhus*), alpine currant (*Ribes alpinum* L.), and bamboos, of which the rapidly spreading, oppressive colonies of Japanese knotweed and bamboos should be given priority in the future.

The number of native plants prone to colony formation is only two. One is the Russian almond (*Prunus tenella* Batsch.), planted in two places in the lower garden. The plant propagates by root suckers, hence the current patch size is several times larger than the original planting. The spreading colony thus threatens the survival of the surrounding plantation and reduces their ornamental value. The other is the common ivy (*Hedera helix* L.), which also has several adult individuals and can spread by vegetative creeping and rooting shoots or generatively too. In many cases, the vigorous shoots of ivy climb up into the crown and create a separate 'crown of ivy', which can be harmful and even dangerous to the supporting parent plants in a short future.

Figure 5 shows the results of our analysis on the connection between the spontaneously spreading species groups. In terms of the four groups (Cat. I–IV) in the binary data, the results show that there are two relatively distinct groups: intensively spreading (Cat. I) and spreading (Cat. II), but the others are very similar. For all these quantitative data, the objects (species groups) are "similar" to each other, and the groups are overlapping, apart from the two "outlying" species (*Robinia* spp. and *Rubus phoenicolasius*).

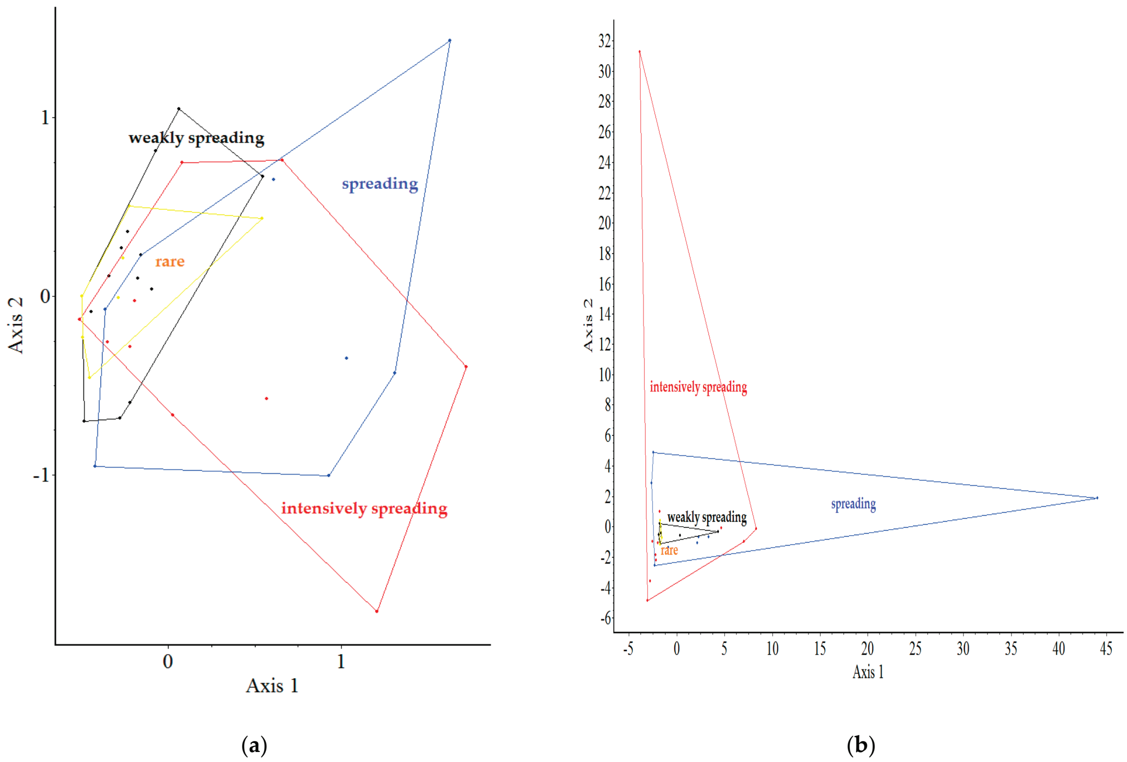


Figure 5. Partition (groups of spreading types) superimposed on ordination (PCoA) for spontaneously spreading species occurrences as object data. In case (**a**) binary, the eigenvalues of the 1st and 2nd axes were 14% and 13%, respectively, and in case (**b**) quantitative, the eigenvalues of the 1st and 2nd axes were 33% and 16%, respectively. Legends: red—intensively spreading (Cat. I); blue—spreading (Cat. II); black—weakly spreading (Cat. III); yellow—rare/just emerging (Cat. IV).

2.3. Correlation between Spontaneously Emerging and Established Individuals Per Plot

Almost all the correlations gave positive results, and some species are strongly correlated. Among the non-indigenous *Disopyros* species, *Prunus cerasifera* are in the group of intensive spreaders in Cat. I, *Fraxinus* species in Cat. II, and *Fontanesia phillyreoides*, *Gymnocladus dioicus*, and *Lonicera japonica* in Cat. III. *Toona sinensis* and *Wisteria sinensis* show a strong positive correlation. Among the native species, *Acer pseudoplatanus*, *A. tataricum* and *Ulmus* species show a strong positive correlation (Table 4). In terms of correlation, only some creeping, vine-like, and strongly rooted species showed a negative correlation, for example, *Rubus* spp., *Campsis* spp., *Clematis vitalba*, and *Lycium barbarum*.

Table 4. Correlation coefficients (r [−1, 1]) between spontaneously emerging/spreading and established individuals per plot (I–XXII) (bold: strong positive correlation r ≥ 0.7; species list is in alphabetical order).

Non-Native/Non-Indigenous Intensively spreading taxa (> 100) Category I	*Ailanthus altissima*	0.24
	Celtis occidentalis	0.16
	Cotoneaster spp.	0.59
	***Diospyros* spp.**	**0.75**
	Koelreuteria paniculata	0.40
	Mahonia spp.	0.11
	Morus alba	0.02
	Parthenocissus spp.	0.13
	Prunus cerasifera	**0.76**
	Robinia spp.	0.34

Table 4. *Cont.*

Non-Native/Non-Indigenous Intensively spreading taxa (> 100) Category I	*Ailanthus altissima*	0.24
Non-Native/Non-Indigenous Spreading taxa (number of individuals (50–99) Category II	*Acer negundo*	0.56
	Crataegus spp.	0.48
	***Fraxinus* spp.**	**0.80**
	Ligustrum spp. (evergreen)	0.17
	Ligustrum ovalifolium	0.43
	Smilax spp.	0.39
	Viburnum spp.	0.18
Non-Native/Non-Indigenous Weakly spreading, taxa with a low distribution (10–49) Category III	*Aesculus hippocastanum*	0.12
	Berberis julianae	0.14
	Cercis siliquastrum	0.31
	Cladrastris kentukea	0.58
	Cotoneaster multiflorus	0.01
	Fontanesia phillyreoides	**0.99**
	Gymnocladus dioicus	**1.00**
	Lonicera japonica	**0.83**
	Parrotia persica	0.52
	Populus spp.	0.40
	Prunus spp. (mahaleb)	0.28
	Sophora japonica	0.01
	Symphoricarpos spp.	0.24
	Tetradium daniellii	0.44
	Toona sinensis	**1.00**
	Vitis spp.	0.46
	***Wisteria* spp.**	**0.92**
Native/Indigenous Category I–III	*Acer campestre*	0.44
	Acer platanoides	0.55
	Acer pseudoplatanus	**0.75**
	Acer tataricum	**0.73**
	Corylus avellana	0.28
	Crataegus spp.	0.48
	Fraxinus excelsior	0.27
	Fraxinus ornus	0.16
	Ligustrum vulgare	0.07
	Lonicera tatarica	0.12
	Prunus avium	0.50
	Prunus padus	0.15
	Quercus ssp. (deciduous)	0.31
	Sambucus nigra	0.03
	Taxus baccata	0.33
	Tilia spp.	0.52
	Tilia tomentosa	0.42
	***Ulmus* spp.**	**0.72**
	Viburnum spp.	0.18

2.4. Effect of the Area on the Number of Individuals

In the regression analysis for the plot-by-plot assessment of the relationship between green space (area) and spontaneous species (total number of individuals), the regression coefficient is R^2 = 0.5865, i.e., the size of the green space explains 59% of the variation (abundance) of individual species in each plot (Figure 6).

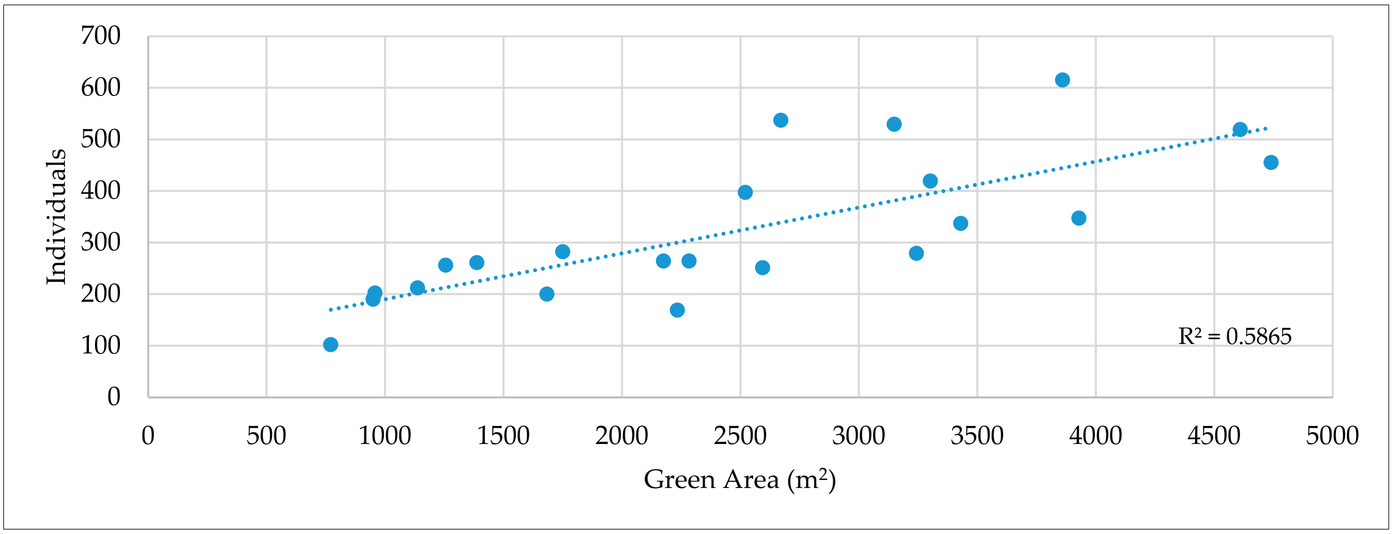
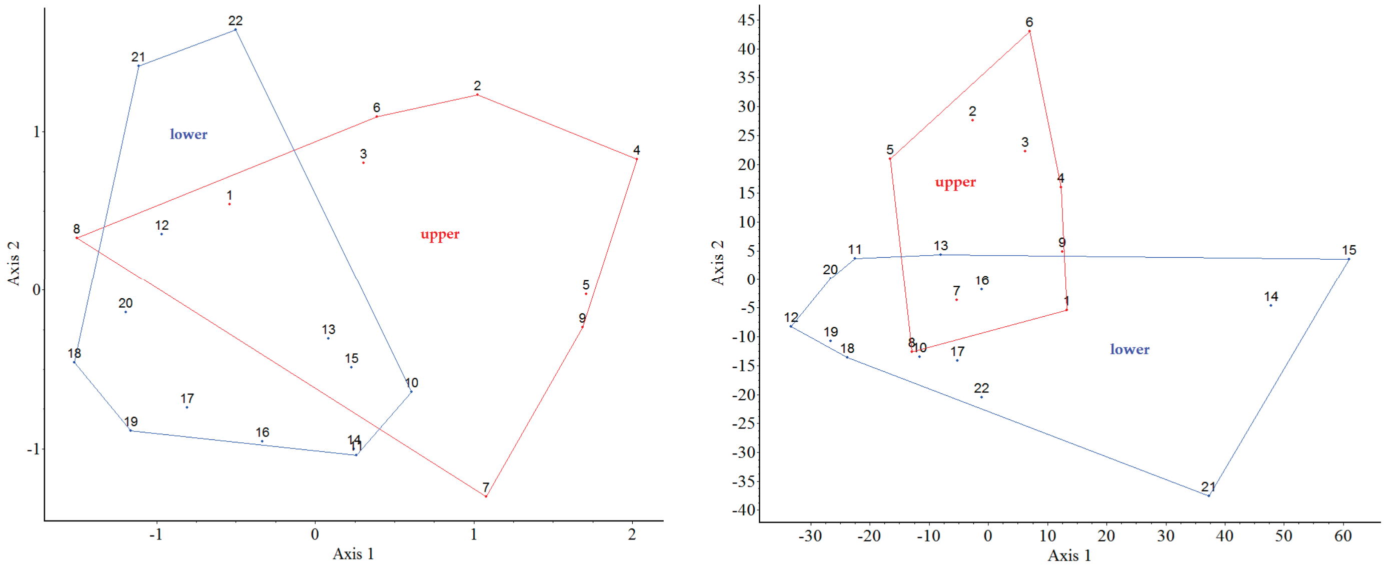


Figure 6. Linear regression of spontaneous spreading species in plots (I–XXII parcels).

2.5. Comparison of Plots Using a Multivariate Analysis

Figure 7 shows the results of our analysis on the connection between the native species and plots. There are no distinct plots based on the presence of native species (38 species), but there are very similar plots (clusters), e.g., 11-14, 5-9, which are not adjacent. However, for the binary data (species presence or absence) the lower and upper gardens are observed to be distinct (Figure 7a). In terms of the quantitative data (individuals of species in plots), distinct (similar) plots can be observed: 14-15-21 and six are self-contained. The other plots are "similar" to each other; they are in a cluster (Figure 7b).



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

Figure 7. Partition (groups of the plots of upper and lower garden) superimposed on ordination (PCoA) for the native species occurrences as object data. In case (**a**) binary, where eigenvalues of the 1st and 2nd axes were 19% and 13%, respectively. In case (**b**) quantitative, where eigenvalues of the 1st and 2nd axes were 36% and 20%, respectively. In both cases, the red cluster indicates the upper garden, and the blue one indicates the lower.

Figure 8 shows the results of our analysis on the connection between the non-native species and plots. In terms of the presence of non-native taxa (76 species) in the binary data, the results show that there are no distinct groups (plots), but there are very similar ones, e.g., 8-13, 11-16 (Figure 8a). For all these quantitative data, the non-native invasive taxa have distinct plots (clusters), e.g., 4, 5-6-7 and 9-10-16. The other plots are "similar" to each other; they are in the same big cluster (Figure 8b).

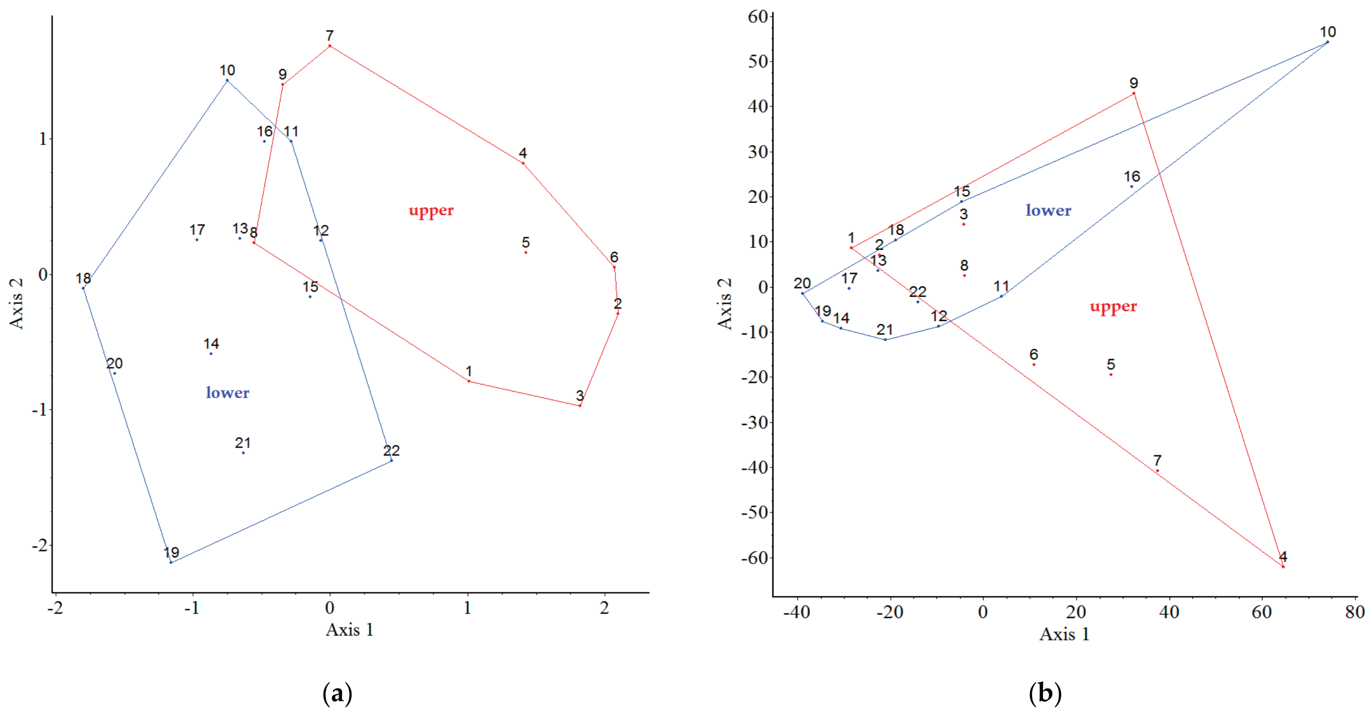
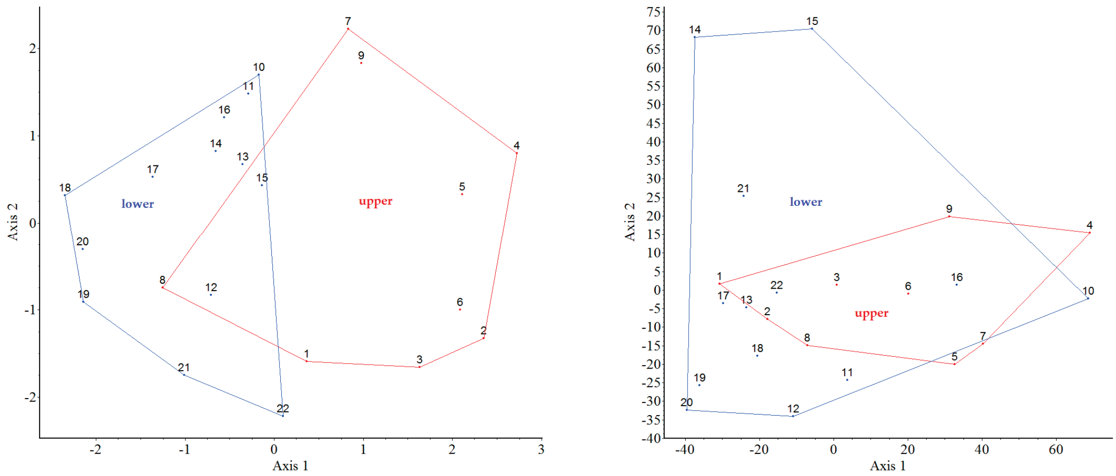


Figure 8. Partition (groups of the plots of upper and lower garden) superimposed on ordination (PCoA) for the non-native species occurrences as object data. In case (**a**) binary, where eigenvalues of the 1st and 2nd axes were 14% and 10%, respectively. In case (**b**) quantitative, where eigenvalues of the 1st and 2nd axes were 31% and 19%, respectively. In both cases, the red cluster indicates the upper garden, and the blue indicates one the lower.

Figure 9 shows the results of our analysis of the connection between all spontaneously emerging/spreading species (native species and non-native together) and plots. If we compare the native and non-native species together, i.e., the species assessed by the spontaneous occurrence, then, when applied to the binary data (presence or absence), we find that the lower garden is distinct from the upper garden, within which the adjacent ones are similar (Figure 9a). If we compare the native and non-native species together, i.e., the species assessed by the spontaneous occurrence, then, when applied to the quantitative data (individuals), we find that the lower garden is not distinct from the upper garden, but some adjacent plots (parcels) are very similar (clusters): 2-3-6, 4-5, 7-9, and 10-11-13-14-15-16 (Figure 9b).

Our results—the partition superimposed on the PCoA ordinations shows clear differences between the upper and lower garden—confirm that the position of the plots (parcels) has an impact on both native and non-native woody plants.



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

Figure 9. Partition (groups of the plots of upper and lower garden) superimposed on ordination (PCoA) for the native and non-native species together occurrences as object data. In case (**a**) binary, where eigenvalues of the 1st and 2nd axes were 14% and 11%, respectively. In case (**b**) quantitative, where eigenvalues of the 1st and 2nd axes were 23% and 15%, respectively. In both cases, the red cluster indicates the upper garden, and the blue one indicates the lower.

3. Discussion

3.1. Woody Weeds in the Garden and Other Habitats

In addition to the well-known woody weeds, especially in extensive areas, such as *Ailanthus altissima* Mill, *Acer negundo* L., which is very widespread in Hungary, *Celtis occidentalis* L., *Koelreuteria paniculata* Laxm., *Ulmus pumila* L., and *Prunus cerasifera* Ehrh. Our arboretum research could not confirm the increasing weeding ability of *Celtis australis* L., though the invasion problem seems relevant in the southern regions of Hungary [29,30]. We have measured many specimens not only in the arboretum but in other extensively managed areas, such as the *Acer platanoides* L. seedlings in these unfavorable urban open spaces. Similar problems occur with *Acer campestre* L. and *Fraxinus excelsior* L. species. The spontaneous occurrence of *Cornus sanguinea* L. was very high in the botanical garden, though, as this species is rarely used in public spaces, we did not encounter its firm weed control. Due to its high environmental tolerance, its vast and expanding patches are often in nature with species from the same environmental conditions as, for example, *Prunus spinosa* L. on the southern slope of Bükk mountain (in the northeast region of Hungary) and other natural areas [31]. High numbers of *Sambucus nigra* L. were recorded in the garden, a weed in public areas, especially in neglected areas. [31]. High numbers of *Sambucus nigra* L. were also recorded in the garden, a weed in public areas, especially in neglected areas. Spontaneously emerging individuals of *Ailanthus altissima* Mill, *Celtis occidentalis* L., *Acer platanoides* L., *Acer pseudoplatanus* L., *Cornus sanguinea* L., *Clematis vitalba* L., *Koelreuteria paniculata* Laxm., *Ligustrum vulgare* L., *Mahonia aquifolium* (Pursh) Nutt., *Morus alba* L., *Parthenocissus* spp., *Prunus cerasifera* Ehrh., *Robinia* spp., *Rosa* spp., and *Sambucus nigra* L. species occurred in almost all sites (plots), regardless of where they were planted; hence, they are invasive plants because their seeds can cover large areas and cause weed infestation in remote areas for kilometers from the parent plant. Their dominance is a huge problem among the individuals presented. In semi-natural, extensively maintained public areas, ineradicable colonies of *Poligonum japonicum* (Houtt.) Ronse Decr. may threaten habitat planting.

3.2. Potential Weeds in Public Open Spaces

The results of the arboretum survey draw attention to the spread or potential proliferation of several species that are still not listed in the conservation protocols. In most cases, these potentially weeding plants grow in private gardens and, though rarely, in public open spaces. It seems that their capacity for rapid acclimatization and high tolerance will cause maintenance difficulties in the future, even in extensively managed areas. The first to be discussed here are the evergreen honeysuckles, which belong to the taxa *Lonicera fragrantissima* Lindl. & Paxton, *L. standishii* Carriére and their hybrid *Lonicera* × *purpusii* Rehder, already mentioned. All three taxa are decorative plants with showy morphological features all year round. They are true winter garden plants, growing quickly and with a rich and fragrant flowering in early spring; furthermore, they often bloom in winter and are prone to second flowering (remontage). Their tasty, sweet, fleshy, and red-ripening fruits are suitable for bird feeding, though birds can be responsible for the seeds' distribution. In the planting design, these plants are suitable for space forming, as they can form groups, patches, and appear solitary too.

Of the genus *Diospyros*, the *Diospyros lotus* L. is able to spontaneously emerge. The fruits ripen well in our region, and their seeds germinate and strengthen far from the mother plant. There is a spontaneous sprouting specimen in the Buda botanical garden that has grown into a solitary tree over the past few decades. Since it was a plant rarity about 30–50 years ago, gardeners left it. Some *Diospyros kaki* L. seedlings also live in the arboretum, though their numbers are not significant as their fruits are difficult to ripen in the garden.

Another unique species is *Ligustrum lucidum* W.T.Aiton, which is present in the Buda Arboretum in significant numbers. It can be an excellent solitary large shrub or tree with its evergreen, large, and spectacular leaves. With its fragrant flowers and long-lasting bluish and black fruits, it could be a popular ornamental plant, but its potential 'release' needs attention. Nevertheless, according to our phenological observations, it well-tolerated the extremely dry weather in 2021 (the driest year in an 80 years' period).

3.3. Proposal for Reclassification: A Prelude to Change

Based on our research, some potentially invasive species [27] need more attention in the future; so we propose to move them from the watch list to the operational list. Examples include *Cotoneaster* spp., *Diospyros lotus* L., *Koelreuteria paniculata* Laxm., and evergreen *Lonicera* taxa. We have recorded more than 250 individuals of *Koelreuteria paniculata* Laxm., and our observations show that it causes weed infestations and maintenance problems, not only in the arboretum but also in public spaces. It is one of the most common plants in residential green areas, along with *Acer platanoides* L., *Acer negundo* L., *Ulmus* spp., and *Ailanthus altissima* Mill. The spontaneous spread of *Gleditsia* ub the observation category is not significant in the arboretum because there are thornless (f. *inermis* L.), rather cultured species without fruits. However, our previous site analyses found that the basic species are all along roadsides, in old castle gardens, historic gardens [32], and even in urban green spaces. The *Celtis australis* L. is likely to cause problems in public areas in the future, similarly to its relative, the *Celtis occidentalis* L. However, the 2021 surveys did not confirm this.

The local distribution observed in *Pterocarya fraxinifolia* (Poir.) Spach., *Rhus* spp., *Fallopia baldshuanica* (Regel) Holub., *Rubus phoenicolasius* Maxim., *Juglans regia* L., *Rosa* spp., and *Robinia* spp. taxa occurred in 80–90% of the plots with variable individuals. The evergreen *Lonicera* spp. and *Diospyros lotus* L. are present in the arboretum in high numbers, though they are not common yet in public use.

Of the operational Grey List taxa found in the arboretum, *Buddleja davidii* Franch., *Paulownia tomentosa* (Thunb.) Steud., *Populus* spp., and *Prunus mahaleb* L. are rare, while *Mahonia* spp., *Morus alba* L., *Parthenocissus* spp., and *Prunus cerasifera* Ehrh. are common. *Phyllostachys viridiglaucescens* (Carriére) Riviére & C. Riviére shows a local spread, but presents a relevant biotope problem for the neighboring plants.

3.4. Spontaneous Spreading Abilities of Several Planted Individuals

The survey may help the garden management plan with the timing and sequencing of maintenance works and defining the urgent interventions. The number of spreading specimens detected in the survey clearly shows the most neglected parts of the Buda Arboretum (Figure 10).

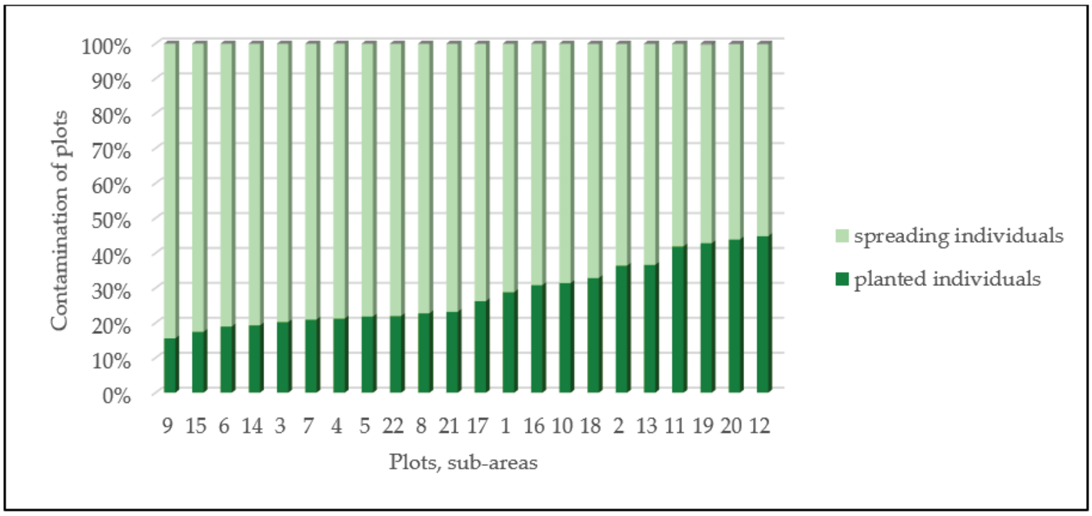


Figure 10. Contamination of garden plots: spontaneously spreading and invasive individuals in the Buda Arboretum.

Recommendations for public open spaces should also consider how spontaneous emergence evolves concerning the numbers planted. A few examples highlighted within the survey results prove (Table 5) that the number of planted specimens seems to be the determining factor in spontaneous spreading, and hence, the number of invaded specimens. The table shows that the ratio of spontaneous and planted individuals is a preferable indication of plants' spreading or their spontaneous emergence capacity, even in public application practices. According to these rates, there is no relevant difference between the native taxa *Acer platanoides* and *Acer pseudoplatanus*. The most problematic non-native species are *Celtis occidentalis*, *Ailanthus altissima*, *Koelreuteria paniculate,* and *Diospyros lotus*.

Table 5. Rate of spontaneously appearing and planted individuals in Buda Arboretum.

Ranking	Species	Spontaneous Number of Individuals	Planted Number of Individuals	Rate
1	*Celtis occidentalis*	561	3	187
2	*Ailanthus altissima*	432	3	144
3	*Koelreuteria paniculata*	258	5	52
4	*Acer campestre*	216	5	43
5	*Diospyrus lotus*	157	4	39
6	*Acer platanoides*	647	18	36
7	*Morus alba*	108	3	36
8	*Acer pseudoplatanus*	193	6	32
9	*Prunus cerasifera*	337	20	17
10	*Acer negundo*	52	4	13

There is only a partial agreement between the results in Tables 4 and 5. According to the correlation per quadrat (per plot) among the highly correlated ($r \geq 0.7$) ones, only *Prunus cerasifera* and *Diospyros* spp. belong to the individuals planted and spontaneously spread in the total green area. This may suggest that the taxa of the highly correlated assemblages (Table 4), except for the *Diospyros* and *Prunus* taxa, are typical in their spontaneous occurrence in the vicinity of the planted parent plant, especially in the case of the weakly spreading (Cat. III) species (e.g., *Wisteria* spp., *Fontanesia phillyreoides*, *Gymnocladus dioicus*, *Lonicera japonica*, and *Acer tataricum*).

3.5. Diversity Analysis and Other Additional Correlations

According to the results of the diversity analysis, the plots have significantly more intensively spreading alien species due to their successful dispersal, lack of pests, and the reduced competition that they face in their new habitats [10].

The PCoA assignments based on the data collected show clear differences between the upper and lower gardens—confirming that the location of the garden plots has an impact on both native and non-native woody plants. The relationship between the groups of spontaneously dispersing species, based on the four binary data sets (Cat. I–IV) forms two relatively distinct groups: intensively dispersing (Cat. I) and dispersing (Cat. II), while the others are similar. For all these quantitative data, the objects (species groups) are "similar" to each other, with the groups overlapping except for the two "outliers".

Our results confirm that the size of a green space has a moderate effect on the total number of native and non-native woody plants' individuals.

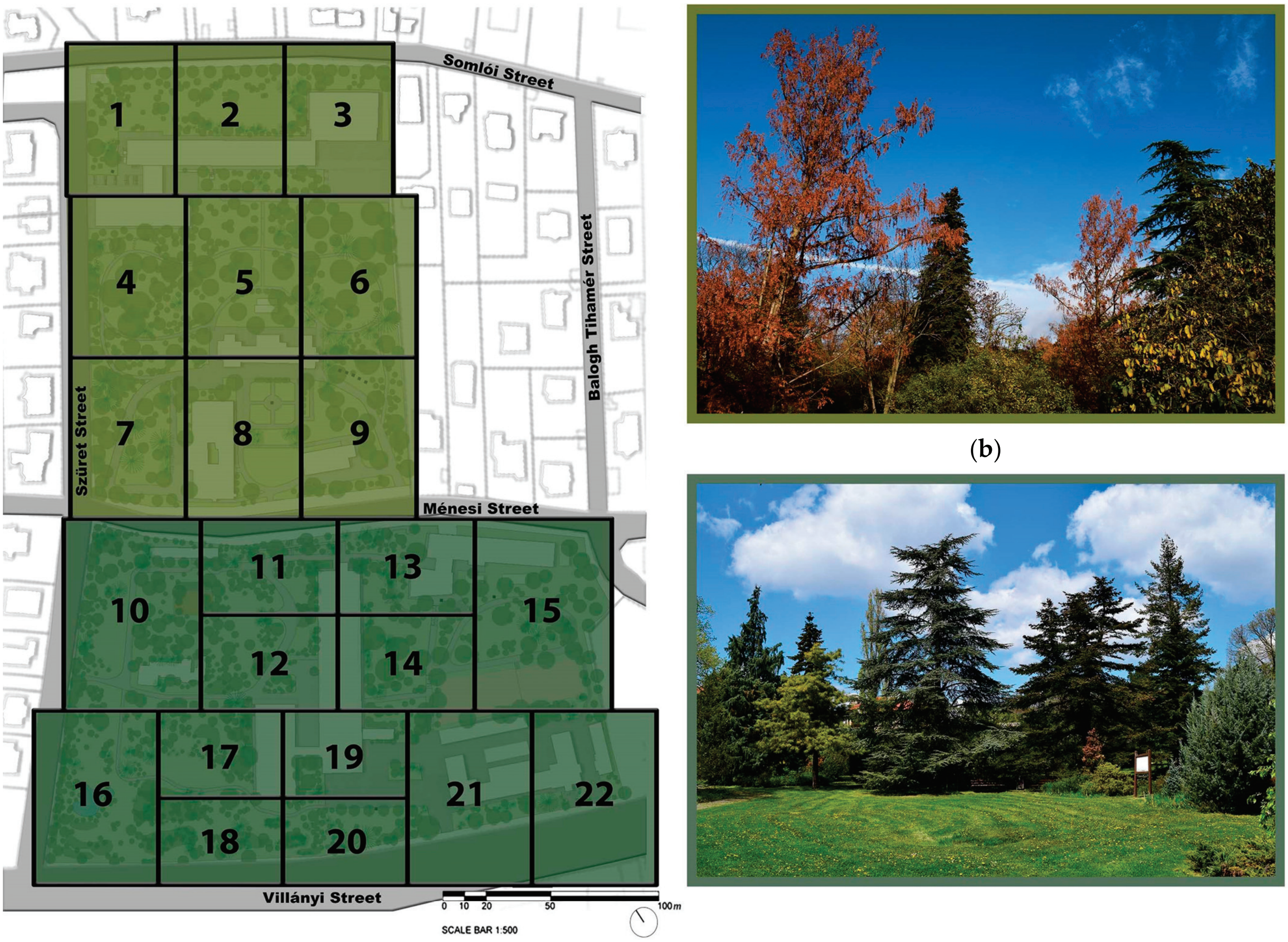
4. Materials and Methods

4.1. Research Area—Buda Arboretum

"Green island or green oasis in the heart of the bustling city"—that is what you can read about the Buda Arboretum in Budapest (Figure 11) [33]. The Buda Arboretum, one of the richest ones in Hungary, was officially founded in 1894 [34,35], and it is a nature conservation area of metropolitan status (1975). It plays a vital role in the life of the district and the green space system of Budapest as a valuable ecological, conditioning, and cultural–educational area.

Figure 11. Location of the Buda Arboretum (illustrations by Barnabás Tóth).

The 7.5 hectares-large arboretum is situated on the southern slope of Gellért Hill and is divided by the Ménesi Street into two parts, the so-called lower and upper garden. The upper garden part is divided into the university library, the dormitory, and the sports hall, which, like the Ménesi Street, create a significant ecological barrier between the two gardens [36–38]. The entire garden area consists of 22 plots, with a varied green space and planted stock shown in a geometric pattern of Figure 12.



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

Figure 12. (**a**) The upper (in light green) and the lower gardens (dark green) with their 22 sub-areas; two characteristic photos of the Buda Arboretum; (**b**) upper garden and (**c**) lower garden (illustrations and photos by Barnabás Tóth).

The planting of ornamental plants in the upper garden began in 1893, designed by Károly Räde, the chief gardener of the Horticultural Academy, who was responsible for garden development [36,37,39,40]. The plant population has been constantly developing and changing [41]. Our database shows precisely that the garden contains 2108 different tree taxa with 2653 planted specimens. There is an ex situ plant conservation program too (currently including 43 protected plant species, of which 17 are woody) [42,43].

The arid, continental environment is characterized by an annual rainfall of only 600–620 mm, although in recent years it has been much lower at 450 mm. The garden is a so-called heat trap, as the surrounding urban fabric on the rapidly warming southern slope adds extra heating. The dry, less ventilated, and urban 'smoke cloud' over the university garden poses a long-term challenge in sustaining sensitive plants in wetter habitats. The poor to good water balance refers to previous local climate and ecological studies and observations (Figure 13) [35,39,42,44]. This heat-trap situation and the overall climate change, together with urban heat pollution, increase the environmental stress on the garden. Hence, the water-demanding species planted in the 20th century slowly died out; many other individuals became extinct, while drought-tolerant taxa from less water-sensitive or Mediterranean areas took over the dominance.

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

Figure 13. (**a**) The landscape characteristics and spatial structure; (**b**) the water retention capacity of the green area in the upper and lower gardens, Buda Arboretum (illustrations by Barnabás Tóth).

The arboretum is generally maintained on an extensive or semi-intensive level. Only three permanent gardeners work at the campus, while horticulture and landscape architecture students, and even external contractors, take part in the maintenance. During the COVID-19 pandemic, the students' maintenance practices were prohibited due to the required exclusionary rules [45]. The arboretum was closed to visitors and residents looking for recreation and peace within the natural landscape character. On the other hand, there is no irrigation in most parts of the garden. Regular irrigation is only possible in certain priority areas, mostly in areas planted with intensive herbaceous vegetation.

4.2. Field Sampling and Data Collection

The study and its site analysis focus on the spontaneously reproducing species, including invasive and native taxa in the institutional green area, the Buda Arboretum. For the site analysis, directed in the summer of 2021, we divided the 7.5 hectare-large area into 22 sub-areas. Prior to the study, we verified the whole planting and all species in the maps, plans, plant lists, and other documents of previous field surveys [39]. The site analysis focused on fast and easy spreading species published in plant lists adapted to the local conditions and the national invasive species lists [22,27]. Adult specimens of all the species included in the study are present in the garden. Because of previous maintenance, there were no reference data for seedlings (spontaneously spreading specimens), only the COVID-19 pandemic restrictions and the lack of regular maintenance provided the unique situation in the almost abandoned arboretum worth this detailed study.

During the field survey, we recorded all spontaneously occurring woody species with a height of 20 cm. Species with vegetative reproducing, such as spreading rhizomes, stems, or root systems, received special concern to define their total occupied area; we separately checked the species threatened by adjacent, proposed, and established invasive plants to monitor the occupancy and the impact on the threatened species. The results were recorded in the arboretum map to define the 'infested' areas and identify taxa that may be of concern for maintenance in urban applications. Based on the number of individuals recorded, five categories of spontaneously occurring species were identified:

Category I—Intensively spreading taxa (> 100);
Category II—Spreading taxa (number of individuals 50–99);
Category III—Weakly spreading, and taxa with a low distribution (10–49);
Category IV—Just emerging (rare) (number of individuals 1–9);
Category V—Colonization species (species that reproduce only vegetatively and form large colonies)—not included in statistical evaluations.

4.3. Data Analysis

To reveal the possible differences or similarities in the data structure, a PCoA (Principal Coordinates Analysis) helped organizing the collected data along the properties of individuals/specimens (native or non-native spontaneously spreading trees). We used binary (presence–absence) and quantitative (number of individuals) data in the analysis. In PCoA, the distance matrix of objects was searched for a coordinate system where the original distances could be preserved, so the first few axes usually gave a reasonably good representation of the distances [46]. For data processing, the Euclidean distance resemblance matrix offered the proper way. For computation, we used the SYN-TAX 2000 program package [47]. Several statistical analyses performed in the survey used the MS Excel 2016 software: we made a regression analysis for the plot-by-plot assessment to define the relationship between green space and spontaneously spreading individuals and the correlation between spontaneously spreading and established individuals per plot. The diversity of the samples ('parcels') appeared in the number of taxa (species). The metrics used the PAST 4.12 software package [48]. Non-parametric tests (Mann–Whitney U test and the Kruskal–Wallis test) helped to compare the diversities. The dependent variable was the species number, and the independent variable was plots (1 to 22).

5. Conclusions

Botanical gardens and arboretums are unique plant societies of taxa from various remote countries, regions, and geographical areas; however, these plant collections can adapt to different climate circumstances and the separation from the original ecosystem and associations or the artificial plantation according to various compositional situations. Even the power balance among the newly assembled plant groups can be challenging for many species. Observing, evaluating, and predicting all these aspects of arboretums is a fundamental professional task within horticultural science [49–51].

The Buda Arboretum has a diverse, species-rich collection, with numerous artificial plant compositions that are, in many cases, based on taxonomic or plant geographical presentation ideas. There are many species in the garden that required more effort to conserve a few decades ago. These species had been planted in sheltered areas, for example, in front of retaining walls, to create a favorable microclimate. One example is the wax-leaved Privilege (*Ligustrum lucidum* W.T. Aiton), which has already reached a height of more than 10 m in its original planting site, and has spontaneously appeared in several parts of the garden due to climate change. Even though it spreads in this garden, we have the reports of Vera Csapody (an amateur botanist and famous illustrator for her plant drawings) of the Plant-friendly Company [52], stating that it froze in several other gardens. Primark and his colleague came to a similar conclusion: changes in global and local urban climates make it easier for previously sensitive species to survive the cold winters, and they can even become invasive [8]. Metropolitan heat islands may provide shelter and incubation opportunities for many warmth-loving, drought-tolerant newcomers [50,51], which, in the worst case scenario, escape from the city and expand in natural habitats.

Among the species in the garden, some are ideal for urban planting. These include the groundhog (*Baccharis halimifolia* Moench), which could be an excellent salt-tolerant plant, and so it may enrich a poor urban plant community; however, it is a potential invasive taxon in disturbed and saline areas [8,53–55]. We did not detect the groundhog spreading in the Buda Arboretum; however, it has produced viable seeds in other gardens, so an invasive behavior in our country cannot be excluded [56].

A potentially large number of species can ‘escape’ as a relevant consequence of a diverse collection garden with low maintenance; among the potential escapers, we can find a large number of native taxa. For example, the native maple (*Acer platanoides* L.) causes spreading problems in the Buda Arboretum or other collection gardens and urban open spaces in Hungary.

The land use variety and the fragmented space structure of the arboretum (Ménesi Street and various institutional buildings) affect the ecological conditions of the garden in terms of spontaneous species. On the one hand, buildings and built infrastructure create a barrier for dispersal, and this is the case of Ménesi Street. However, the buildings, as the hostel/school complex, have a light fragmentation effect; in this case, the different intensities of management of the two garden parts are responsible for taxa invasion problems.

Based on the experiences observed and collected in the garden, non-native species introduced into the urban environment as built-in elements can increase the aesthetic and recreational benefits [15] and have a positive ecological impact on urban green spaces [57]. However, ‘escaped’ species present significant ecologic and economic challenges [58,59]. Invasive plants can cause a decrease in biodiversity [15], a decline in the resilience of the ecosystem to disturbance, and degradation of the ecosystem [11]. In a world without borders, few, if any, areas remain sheltered from these immigrations [60]. The manifestation of invasive behavior depends not only on the species’ biological characteristics but also on random processes [61], while conscious human dispersal and selection activities contribute to the process [60]. The introduction of invasive or potentially invasive taxa by botanical gardens or the cultivation in nurseries can also trigger an intentional invasion [62], so collection gardens have a massive responsibility for plant use proposals in the future.

These research findings raise awareness of maintenance quality, and the justification of plants to avoid the spread of species listed as potentially invasive species; furthermore, this research draws attention to native species that require high maintenance efforts in gardens and large urban green spaces.

It is very important for botanical gardens to broaden their plant monitoring to respond to climate change issues, not only for the purposes of ornamental horticulture, but also for improving the maintenance of green spaces, and species conservation together with genetic resource communities [7]. The cooperation with economic actors such as nurseries should be improved to arrive at safe and sustainable horticultural production. Closer cooperation is essential for creating a sustainable environment in the long term. Priority should be given to the proper evaluation and testing of plant introductions for commercialization; recognition that the introduction of new plants into the country is not the most important part of the program but only the first step; full consideration of invasive species control policies and due diligence in assessing the potential risks posed by new introductions; and cooperation and exchange of experience between gardens.

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Article

The Role of Urban Cemeteries in Ecosystem Services and Habitat Protection

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Abstract: Cemeteries, like urban public parks, are an important part of the urban ecosystem, providing semi-natural habitats for many plant and animal species as well as a wide range of ecosystem services: they improve air quality, reduce the urban heat island phenomenon and provide aesthetic and recreational value. This paper explores the role of the cemeteries in the green infrastructure network beyond their sacred and memorial role and their importance as a habitat for urban flora and fauna. In our study, we compared two large public cemeteries of Budapest (Nemzeti Sírkert/National Graveyard and Új Köztemető/New Public Cemetery) with the Zentralfriedhof Wien (Central Cemetery of Vienna), the latter of which has been forward-looking in terms of green infrastructure development and habitat creation in the past years. Our goal was to determine which maintenance technologies and green space development methods are most beneficial in terms of sustainable habitat creation and the use of appropriate plant species in public cemeteries.

Keywords: cemetery; urban cemeteries; green space; urban green infrastructure; cemetery tourism; ecosystem services

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1. Introduction

The expansion and densification of cities impose significant challenges for the urban environment: these are, amongst others, the loss of quality and quantity of green spaces, the decline of biodiversity, the degradation of ecosystems and the disconnection of human beings from nature, which affects their mental and physical health, including their well-being. When we talk about urban green spaces, we usually think of urban forests, tree alleys, urban parks and gardens, while cemeteries are frequently ignored. However, in the works of Sallay et al., 2022 [1]; Straka et al., 2022 [2]; Dlugoński et al., 2022 [3]; McClymont et al., 2021 [4]; and Nordh et al., 2018 [5], the topic of cemeteries as urban green infrastructure and recreational space has been unfolded (Figure 1). Going beyond, in this paper, we aim to analyze the role of urban cemeteries in biodiversity conservation and nature protection and the ecosystem services and habitat potentials they provide.

Cemeteries and burial grounds are primarily considered sacred places, closely linked to the history of a local community, but also custodians of natural and cultural values [6]. According to Skår (2018) and Maddrell (2016) [7,8], cemetery as a term refers mainly to the process of grieving and the dignified remembrance, but also to the management and maintenance of cemeteries [9]. However, cemeteries are an integral part of our neighborhoods, cities and society [10].

Over the past two centuries, land-use changes, rapid and accelerating urbanization, and population growth have led to a significant loss of natural habitats worldwide [11]. Due to this, the role of urban green spaces in providing semi-natural habitats has increased. In the changing metropolitan landscape burial grounds, cemeteries and churchyards might become islands of biodiversity conservation. Due to their size, habitat heterogeneity and continuity, cemeteries play an important role in urban biodiversity conservation [12]. Previous research has highlighted the important conservation functions and benefits of cemeteries in non-urban settings [4], which contribute to the preservation of natural habitats and rare species worldwide. Old cemeteries can provide "islands of habitat" for native species gradually squeezed out of intensively used rural landscapes, such as special endemic orchids in Turkey [13]. As stated by Löki and colleagues after reviewing 97 studies from five continents, cemeteries and churchyards have a significant conservation role. Even in highly modified environments, they often provide refuge for populations of rare and endangered species.

Figure 1. Word cloud: the diversity of purposes for visiting a cemetery, based on [1] (by authors).

Cemeteries can provide important ecosystem services (ESs) such as support services (e.g., soil formation, photosynthesis, primary plant mass production, nutrient and water cycles), regulatory services (e.g., regulation of microclimate, of stormwater issues, of air and water quality) and cultural ecosystem services related to recreation, well-being and health [3,4,6,14]. ESs are the goods provided by living systems, and the human quality of life is determined by the sum of them. ESs can be classified into three groups [15]:

- Provisioning services: tangible goods provided by ecosystems that can be traded and consumed directly or indirectly, such as plant and animal food, raw materials and fibers, biomass and animal energy;
- Regulating and sustaining services: including how ecosystems regulate or modify biotic and abiotic environmental factors; they are not directly consumable or consumable goods, for example, bioremediation, flood control, erosion control, pollination, pest and disease control; soil formation and soil structure; climate regulation;
- Cultural service: intangible (non-tangible) assets that have symbolic, cultural or intellectual significance, such as tradition, heritage, aesthetics, recreation, leisure; educational–research activities [2]. Based on the ESTIMAP: Ecosystem services mapping at European scale methodology, urban green spaces contribute significantly to recreational opportunities [15].

A meta-analysis of 87 studies in 75 cities by Beninde and colleagues in 2015 revealed that the connectivity of habitats in cities is more important than the distance between green spaces. For contiguous habitats, an average minimum size of 50 hectares is required to conserve the rare species that live there [16]. The same study found that the level of damage caused by visitors, pets or road traffic and the level of disturbance caused by enclosure are lower than expected.

While there have been a number of studies on the contribution of urban parks to biodiversity conservation according to their size and land coverage [17–20], little is known about the similar role of cemeteries. Though urban parks and cemeteries share some common characteristics (e.g., existing woody and grassland habitat mosaics), there are significant differences in terms of the way they are used, the intensity of their maintenance and the specific "built elements" they include (e.g., high proportion of artificial surfaces in cemeteries due to paved surfaces and graveyard features). The role of cemeteries in relation to biodiversity is different from that of public parks, and this needs to be examined. The green spaces of cemeteries have a varying, but certainly measurable, impact on the local climate of their surroundings, mitigating the urban heat island effect. On a sunny, warm summer day, a cemetery can be several degrees cooler than its surroundings: the two largest cemeteries of Budapest (i.e., Nemzeti Sírkert and Új Köztemető) were respectively 1.7 °C and 7 °C colder than the neighboring urban areas, measured in August 2016, based on satellite and field surveys by Szent István University [21].

Cemeteries are dynamically changing landscapes; due to the continuous burials, their transformation might be more dynamic than that of public parks. However, cemeteries and especially their ecological or "green" conditions change gradually with each new burial. Their biodiversity largely depends on the character and size of the given cemeteries, their structural heterogeneity and, above all, the type and intensity of management [4,6]. If some areas of cemeteries are less intensively used or maintained, or even abandoned, this can lead to the development of a "novel", more natural-like environment, allowing visitors to experience natural processes [2]. The management of cemeteries as living habitats has become increasingly popular in recent years; in the recent publication entitled "Der Friedhof lebt! Orte für Artenvielfalt, Naturschutz und Begegnung." (The cemetery is alive! Places for Biodiversity, Nature Conservation and Social Exchange.), the author describes cemeteries as a paradise for flora and fauna [22]. The habitat characteristics of cemeteries are likely to be determined by the interaction between natural processes, management and design issues. The maintenance technologies and their intensity in the different areas of a cemetery have a strong influence on its ability to function as a habitat: the less intervention needed for maintenance, the more native plant and animal species can be found in the area [23].

This paper aims to fill the gap we have identified in this topic area by examining the potential of urban cemeteries for ecosystem services and environmental–biological values (Figure 2). We therefore address the following research questions:

- What role does a cemetery play in urban green infrastructure?
- What habitat functions may cemeteries perform?
- Do cemeteries have specific ecological functions that differ from the potential of other urban green spaces?
- What ecosystem services do urban cemeteries provide? Do they differ in each case study?
- How do the three main functions of cemeteries (i.e., memorial, cultural/touristic and ecological) relate to each other? Do they reinforce or weaken each other? How can they be harmonized?
- How can the full potential of cemeteries be improved or exploited?

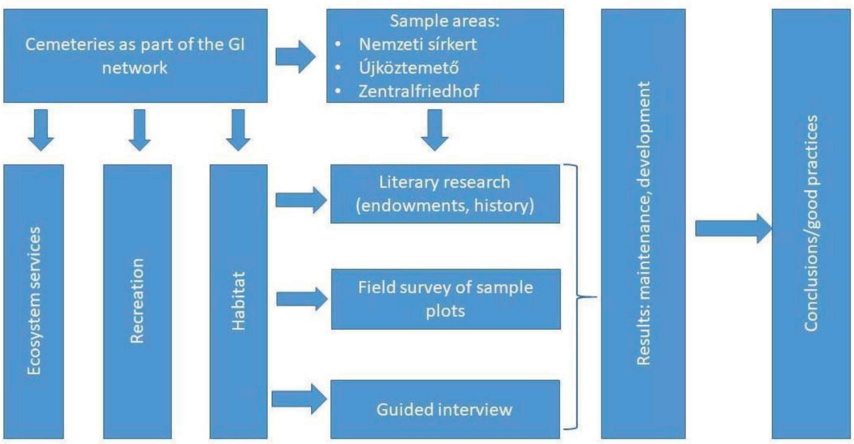


Figure 2. The structure of the study (by authors).

Many of the problems we have identified as research questions are not quantifiable and can only be measured at a normative level. Thus, we have chosen our research methods and materials accordingly.

2. Study Areas

Under the Austro-Hungarian Monarchy in the 19th century, the two cities of Vienna and Budapest experienced a similar development in the centralization of cemeteries. After the end of the Monarchy and especially after the Second World War, their development has taken different directions. By the 21st century, the use and development of central, large-scale cemeteries became significantly divergent.

2.1. Historical Context

A major change in the location of cemeteries in Hungary was brought about by the decree of Maria Theresa in 1775, in which the Empress prohibited burials around churches, which had been common practice since the Middle Ages, for public health reasons. Cemeteries were thus moved to the outskirts of the city. At the same time, the Hungarian capital was also undergoing enormous development, and Pest cemeteries moved further and further out over the next century. Yet the city caught up and overtook them: today, our largest cemeteries are integrated into its fabric, surrounded by houses. One of the oldest cemeteries in Budapest, still in operation today, is the Nemzeti Sírkert, a green space comparable in size to Városliget or Népliget, and only the Új Köztemető is larger. How these sites are viewed has also changed. Much larger areas than before were designated for the cemeteries, with plots, roads and junctions within them modeled on the urban spatial structure. Thus, the cemetery became a public pedestrian space, requiring a tree line and noble vegetation.

In the Middle Ages, Vienna, like Budapest, had several Christian and Jewish cemeteries. The cemeteries were subordinate to the parishes and were located around the parish churches within the city walls. From the 16th century to the 18th century, the monarch and the city administration sought to move the public cemeteries from the walled city to the suburban area, but this was only gradually achieved due to opposition from the ecclesiastical authorities. Spacious crypts (catacombs) were built under parish and monastery churches for the burials of wealthier people. The Josephine Toleration Decree (1781) meant that there was nothing to prevent Protestants from being buried in public cemeteries; in 1858, a separate Protestant cemetery was opened in front of the Matzleinsdorf line (Evangelischer Friedhof). These Josephite cemeteries were called municipal cemeteries after the takeover of the Vienna municipality in 1869. As the suburbs grew, space for the dead again became too limited. Hernals and Döbling, as well as the western suburbs, were given their cemeteries, of which the cemetery at Hietzing was particularly prestigious. The cholera epidemic of 1873 greatly intensified the debate on the relocation of cemeteries for health reasons. The five municipal cemeteries were no longer located on the outskirts of the town, as they had originally been, but in the center of the town. The most important innovation was the creation of the Zentralfriedhof, which was opened on 1 November 1874, next to the village of Simmering [24].

The Zentralfriedhof was not particularly popular at the beginning because of its distance from the city and its large size. To compensate for this, famous dead were moved there from other cemeteries, creating an attractive attraction with decorative plots.

In the Austro-Hungarian Monarchy, there was a rivalry with Vienna, Austria, German culture and the West on the part of the Nemzeti Sírkert. The Zentralfriedhof in Vienna was declared to be the nation’s cemetery, and its status was given immediately after its opening by secondary burials [25]. Although it was only opened in 1874, it developed much more dynamically, and by the 1930s it was much more orderly and impressive than the Nemzeti Sírkert. The generous design of its ornamental parcels is still almost unique in Europe.

2.2. Nemzeti Sírkert (National Graveyard), Budapest, Hungary (Figure 3)

Creation: The cemetery was opened in 1847 as a public cemetery in Pest, and by the end of the 19th century it had become the most prestigious memorial site in Hungary. When it was opened, the cemetery had a simple rectangular layout, and by the 1870s the main roads had been planted with trees, earlier than its grounds were designed and executed in its present architectural layout at the beginning of the 20th century. In 1885, it was already registered as an ornamental graveyard, before that as a public cemetery, so it was not originally founded as a memorial site of the nation. In 1952, the cemetery was closed and the liquidation of the cemetery began, and in 1956, the Metropolitan Council declared the cemetery a National Pantheon. In the 1970s, the cemetery was landscaped, with many graves being removed and replaced by landscaped green areas. In December 2013, the entire cemetery was declared a national monument and listed as a historical monument. In 2016, the National Heritage Institute was appointed as the cemetery's administrator and trustee. It is one of the capital's most important attractions, its splendor and richness reminiscent of the cemeteries of the world's cities, both a beautiful park and a major pilgrimage site [25–27].

Environment, location and green space connections: The cemetery garden, known for its rich flora and fauna, covers 56 hectares, one of the largest contiguous green spaces in the capital. It is one of the largest cemeteries in Europe, with a large number of natural and architectural features, and is as important as green space as it is as a cultural space. As a green space, it is an important link in the "green arch" between the Városliget and the Népliget [25]. The condition of the park is also important for the city, and special attention is paid to the woody plants living there, including several veteran trees over a hundred years old [26]. The Jewish cemetery on Salgótarjáni Road, which was opened in 1874 and covered 4.8 hectares, is directly connected to the cemetery area and has a significant plant population and mature tree trunks.

Current state, flora and fauna: The National Heritage Institute considers the cemetery's trees, planted in the 19th century, to be of outstanding historical value. The quadrangular and diagonal paths are flanked by rows of old sycamore (*Platanus* × *hispanica*), chestnut (*Aesculus hippocastanum*), hackberry (*Celtis occidentalis*), linden (*Tilia* sp.), acacia (*Robinia pseudoacacia*) and cigar tree (*Catalpa bignonioides*). The total number of plant groups in the tree-lined parcels exceeds 3500. Among the trees of unique value are the oak trees (*Quercus robur*) next to the tomb of János Arany. The back plots of the cemetery, which are richly vegetated, provide important habitat for fauna. The Hungarian Society for Ornithology and Nature Conservation has observed more than 100 species of birds living and 40 species breeding there (e.g., thrushes, barn owls, woodpeckers, wood sparrows, sparrows, wood owls). The flowers attract insects and insectivorous bats in large numbers. There are numerous species of small rodents in the undergrowth of the cemetery (including various species of mice, some of which are rarer, and also pelicans, the eastern hedgehog and woodland or red squirrels in the trees). Due to their increasingly scarce natural habitat, wild animals have recently been moving into the inner areas of towns and cities, and several fox families have moved into the cemetery. Red foxes hunt mainly at night, their main prey being mice and voles, but they also threaten ground-nesting birds [25,26,28].

Planning/development context: In 2021, the National Heritage Institute commissioned the preparation of a management plan for the Nemzeti Sírkert. Following a general green space assessment of the cemetery (vegetation, tree lines, spatial structure, road network, small architectures), the authors have formulated maintenance and development proposals. The ecological development strategy also aims to increase biodiversity and preserve and expand habitats:

- Low-impact conservation technologies, limiting the use of pesticides;
- Extensive "wildflower" grassland management, creation of flower meadows (planned expansion of extensively maintained grassland areas, which, in addition to increasing biodiversity, also serves to reduce the costs of operating green spaces);
- Management of bird and insect species;

- Ecological use of plant waste and straw, with on-site composting (shredding, mulching);
- In terms of flowering areas (in priority, super-intensive areas), the role and surface area of more ecologically and economically maintained perennial beds should be increased in preference to annuals;
- Awareness raising and information are a priority when introducing ecological green space management models [29].

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

Figure 3. Nemzeti Sírkert, Budapest: (**a**) the sycamore alley leading to the Deák Mausoleum, (**b**) chestnut alley, (**c**) landscaped plot (authors' photos, 2022).

2.3. Új Köztemető (New Public Cemetery), Budapest, Hungary (Figure 4)

Foundation: The cemetery, which has grown to 207,000 square meters, is one of the largest cemeteries in Europe. A significant part of it was designated as a military cemetery: this is where the present Heroes' Cemetery was created [25]. The regular, geometric layout and the rectangular plot system formed by the rectangular road network were based on plans by the architect Győző Czigler in 1903, but some of the plots still have no graves. To date, some 3 million people have found a final resting place here. The victims of the conceptual trials of the 1950s and the 1956 revolution were buried in plots 298, 300 and 301 of the cemetery. In recent decades, this part of the cemetery has been tidied up, a visitor center has been built and it has been declared a national memorial site [30].

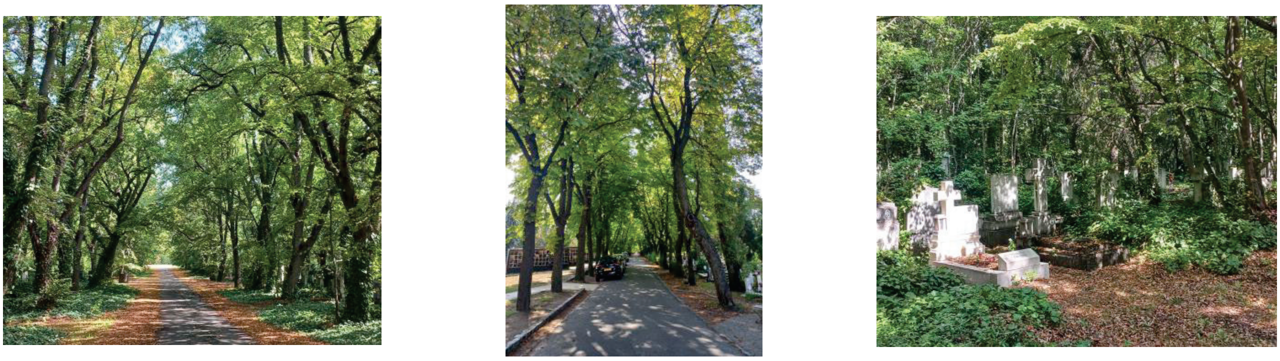
Environment, location + green space connections: The cemetery is located on the outskirts of Budapest, on the border of Kőbánya and Rákoskeresztúr. The Jewish cemetery of Kozma Street and the Orthodox Jewish cemetery of Gránátos Street are located next to the cemetery and also have significant vegetation cover. The Új Köztemető is bordered to the east by the Keresztúr Forest, which, in addition to its importance as green space, also serves the recreational needs of the residents of the area.

Current state, flora and fauna: Only about a quarter of the green areas in the vast cemetery are regularly maintained, leaving a large number of unmaintained, overgrown plots. Forest animals feel at home in the cemetery: there is a deer population of 50, and larger mammals such as foxes and hares are often seen. The cemetery is an undisturbed habitat for many species of birds (e.g., owls, ravens) and bats. In 2019, a nature trail, a jogging track and a cross-country skiing track were created in the Crossroads Forest next to the cemetery.

Planning/development context: no information available at present.

2.4. Zentralfriedhof (Central Cemetery) of Vienna, Austria (Figure 5)

The Zentralfriedhof was established in 1870 by two architects, Karl Jonas Mylius and Alfred Friedrich Bluntschli. The cemetery was inaugurated in 1874. Mylius and Bluntschli's neo-baroque design is based on the shape of a Greek cross. Each of the three arms of the cross culminates in a circular square from which eight streets are radiating, similar to a baroque etoile square. The church was projected at the intersection of the main axes but was only constructed in 1908–1910 following the design of Max Hegele. The cemetery was extended seven times until 1921. Today it covers an area of about 2.5 km^2, making it the second-largest cemetery in Europe after Hamburg Ohlsdorf. It contains 33,000 gravestones. Over the years, some 3 million people have been buried here. Some 1000 of them are famous personalities, including all the Austrian presidents since 1945, buried in the presidential crypt in front of the Art Nouveau church. There are also sections for Catholic and Lutheran cemeteries, old and new Jewish cemeteries and Russian Orthodox cemeteries [31]. Most of the Zentralfriedhof is currently managed by Friedhöfe Wien GmbH. The Protestant and Jewish cemetery sections are exceptions. The Jewish cemetery is run by the Jewish Community of Vienna IKG, and the Protestant cemetery is run by the Protestant Church. Since April 2021, the University of Vienna, in cooperation with Friedhöfe Wien GmbH, has been conducting research under the project "BaF—Biodiversity in cemeteries" under the direction of project leader Thomas Filek. The aim is to study biodiversity and anthropogenic impacts on cemeteries as habitats [32].



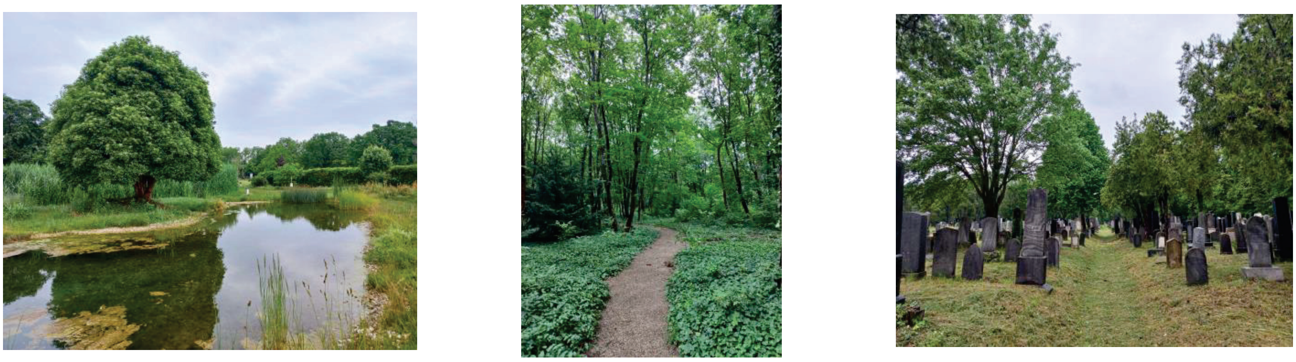
(**a**) (**b**) (**c**)

Figure 4. Új Köztemető, Budapest: (**a**) lime tree alley along one of the main roads in the cemetery, (**b**) chestnut tree alley, (**c**) wooded plot (authors' photos, 2022).

Environment, location + green space connections: Contrary to its name, the Zentralfriedhof is located on the southeastern outskirts of the city, in Simmering, which was annexed to Vienna in 1892 and was not part of the city when the cemetery was built. The Zentralfriedhof is part of the eastern part of Vienna's Green Belt, which was established in 1905. The Vienna Green Belt encompasses the city's entire area and covers a total area of about 21,500 hectares. The Green Belt's eastern part includes the Zentralfriedhof and the Prater and the Simmeringer Haide. Opposite the cemetery, near the Feuerhalle Simmering, is a historic oak forest, a natural monument already mentioned in a document from 1649 [33].

Current state, flora and fauna: The cemetery contains nearly 15,000 trees, a significant proportion of which is made up of alleys, trees along paths and the dense tree population in the area of the old Jewish cemetery. In 2009 and 2016, plots were transformed into forest cemeteries. The so-called Naturgarten was created in 2011 next to Gate 9, with a large elder tree (*Sambucus nigra*) as its centerpiece. This area covers 40,000 square meters. The area also includes a biotope and two butterfly fields to increase biodiversity. In the large open green areas where taller grass grows, signs indicate this is a "natural meadow for insects and their mates". Due to its size, its location on the outskirts of the city and its diversity, the Vienna Zentralfriedhof is also of special importance as a refuge and habitat for many animal species, such as field cricket (*Gryllus campestris*), Viennese night peacock (*Saturnia pyri*), blue butterfly (*Polyommatus icarus*), little eider (*Coenonympha pamphilus*), green toad (*Bufo viridis*), sand lizard (*Lacerta agilis*), middle-spotted woodpecker (*Picoides medius*), field hamster (*Cricetus cricetus*), various species of bats [34], storks, badgers and martens. There are also many squirrels, which are often fed by visitors to the cemetery, despite the many signs warning visitors not to feed the animals, as inappropriate feeding can endanger their lives. The cemetery's largest "animal residents" are the 20 or so roe deer, a favorite in the old Jewish cemetery, not least because of the evergreen plants growing around the old gravestones, which provide a reliable source of food, especially in the colder seasons. Field observations show that the biodiversity differs between parts of the cemetery; e.g., the old Jewish cemetery has become overgrown and is more species-rich, while the new Jewish cemetery, founded in 1911, is more regulated and in its character comparable with the non-religious part of the Zentralfriedhof [35]. Until the mid-1980s, the rich population of roe deer and other wildlife was officially controlled by hunting and a hunter appointed by the Forestry Directorate. Today, the City of Vienna's environmental department, Network Nature, with its species and habitat conservation program, ensures that, in addition to the well-maintained walkways and graves, the overgrown, semi-natural areas are preserved [32,36] (p. 87).

Planning/development context: The management of the Vienna Zentralfriedhof has not published any strategic plans yet. However, the Urban Development Plan of the City of Vienna STEP 2025 highlights the significant impact of the Zentralfriedhof in classifying it as "large urban green space" of regional importance which serves as a fresh air corridor and shall be linked to neighboring green spaces [37].



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

Figure 5. Zentralfriedhof Wien: (**a**) biotope in the Naturgarten, (**b**) path in the forest cemetery, (**c**) the old Jewish cemetery (authors' photos, 2022).

3. Materials and Methods

Our study is the first step of long-term research, and our aim is now to gain a deeper understanding of the problems, processes and interrelationships. Therefore, the research focuses on a qualitative understanding of the baseline situation and on collecting and analyzing opinions and attitudes. In our studies, we have carried out a detailed exploration of the research area on a small sample; our aim is not yet to be representative. Interactivity and an inductive approach were the main features of this phase of the study, which was carried out using a qualitative technique, and one of the main tasks was to highlight individual characteristics. Typical qualitative research methods were used, such as observation, expert interviews and case studies.

To address the aforementioned questions, we reviewed the historical development and changes of the study areas of Budapest and Vienna, mainly in terms of spatial extent, subdivision and vegetation cover. A literature review showed that the role of urban cemeteries in biodiversity conservation is an under-explored and under-researched topic. For rural cemeteries, there is a much larger national and international resource base (Appendix A). Secondary sources in the literature were supplemented by field visits and personal visits to the cemeteries in all three sample areas.

3.1. Literature Review

The theoretical basis was determined by reviewing literature sources on the following topics: ethnobotanical research in Hungary; botanical and habitat research in cemeteries, by reviewing international sources; green space development concepts and studies related to cemeteries in Budapest.

3.1.1. International Literature

In addition to reviewing the literature on the environmental values [4,6,38] and conservation functions [4] of cemeteries, considerable attention has been paid to sources that process and describe the special fauna and especially the flora of cemeteries [13,39–41]. In Austria, the Österreichischen Gesellschaft für Entomofaunistik (Austrian Society for Entomofaunistics) has several documents dealing with the assessment of the insect fauna of cemeteries [33].

We also addressed the use of cemeteries and newer burial methods with higher ecological benefits [42]. The works of Kowarik et al. (2016) [6] and Dlugoński et al. (2022) [3] served as a starting point for research on ecosystem services of cemeteries, while for urban habitats, we took the work presented in [43]. The role of urban parks in biodiversity conservation was based on the work presented in [19,20].

3.1.2. Budapest Cemetery Development Concepts

Chapter II.7 of the Green Space Management of the Environmental Assessment of Budapest 2021 [44] shows the distribution of burials in Budapest, which is increasingly shifting towards cremation: 86% of burials are cremations (burial, scattering, urns) and 14% are traditional funeral services. The number of alternative burial services, such as biodegradable urns or the natural disposal of ashes (e.g., boat scattering, air scattering), has also increased significantly in recent years. There is also a growing demand for eco-friendly burial sites, such as forestry burials and memorial forests. In light of changing burial patterns, the document argues that it would be advisable to provide as many alternative burial methods as possible in the capital's public cemeteries, involving the use of existing cemetery areas while at the same time meeting specific needs. One possible form of this could be the introduction of "forestry or natural burial", with site areas that are currently part of the service. Plots with more than 65% of expired graves could be suitable. By clearing the wooded plots, areas that currently appear neglected could be brought back into service or, following their park-like restoration, the recreational role of the green space could be enhanced as a kind of memorial garden. In the case of cemeteries with expansion areas, it is intended to provide for the possibility of burial with wood instead of grave markers when new plots are opened. The document also envisages the creation of memorial forests in the near future, using existing woodland within the capital. Both wood burials and forest cemeteries and memorial forests provide a high proportion of green space, which can increase cemeteries' biodiversity and habitat function. The Metropolitan Cemetery Development Study, which incorporates the above principles, was completed in 2019 and is expected to be adopted and implemented in the near future.

The Action Area X of the Radó Dezső Plan [45], approved in 2021, concerns the cemeteries of Budapest, with the following objectives: The main tasks related to the achievement of the objectives, which are also relevant to the present research, are "Better use of the recreational potential of existing cemeteries; public use of closed cemeteries; temporary green infrastructure use of disused cemeteries" and "Promotion of alternative burial methods; designation of urban areas suitable for forest burial" [45] (p. 62). The Capital intends to complete the planned improvements to the cemeteries by 2027.

3.1.3. Vienna Cemetery Development Concepts

The strategic concept on the development of Vienna's green infrastructure system, published in 2014 by the Vienna City Administration, aims at increasing the livability of the city by protecting and improving the connection between existing elements and by creating new green infrastructure units. The distance between each green space element shall be reduced to 250 m. The concept classifies the Zentralfriedhof as a semi-public green space responsible for the following:

- Everyday recreation;
- Structurizing the urban fabric;
- Providing ecological services;

- Providing pedestrian and cyclist passage;
- Potentially creating habitat [37].

3.2. Interviewing Cemetery Managers

There are many efforts or activities that are not visible or visible to the visitor and have not been published but are essential for habitat function and to provide constant ecosystem services to the surrounding urban structures. These hidden activities have been unfolded through a series of structured interviews with cemetery managers on the subject.

For all three cemeteries, the same questions were asked in writing to the cemetery managers and maintainers. The method was open-ended, with the interviewees answering the questions freely, in their own words, and at any length. Because of the written nature of the interviews, we employed two types of questions: short, factual questions and longer, more elaborative questions:

1. How compatible do you see the memorial function of cemeteries with the development of the cemetery as a habitat?
2. Are there, or have there been, any surveys of the cemetery's wildlife (plants, animals)?
3. Is the cemetery's development taking into account, and seeking to create, habitats? If so, which developments are concerned with this?
4. When maintaining the green areas of the cemetery, is it a consideration or an effort made to create habitats? If so, how and what has been changed?
5. Is there a follow-up on the impact of the developments on wildlife? Have they looked at how the composition of flora and fauna has changed?
6. Are there any developments that did not work or did not have the intended effect?
7. How has the development been received by the public? Has the group of visitors to the cemeteries changed due to the developments? If so, how? Who, if any, newcomers have come and who, if any, have left?
8. Do you have relationships with partners who prioritize protecting and enhancing the habitats and wildlife (plants, animals)?

4. Results

We examined the conditions of the Nemzeti Sírkert and the Új Köztemető regarding habitat design and habitat protection. We compared them with the solutions found in the Vienna Zentralfriedhof. The results of the literature research, the interviews and the site visits were summarized in a table, which clearly shows the advantages and shortcomings of each cemetery.

4.1. Results of Interviews

Nemzeti Sírkert (managed by NÖRI (public body of the government), data provider: János Prutkay, Deputy Service Director): The memorial function is only one of the main features, but also the educational, touristic, cultural and sacral functions are considered important, for which an appropriate and attractive natural environment is sought. The cemetery function in the traditional sense is only present in one part of the cemetery. Some areas are now less frequented, and, consequently, the natural habitat character has been strengthened. In terms of plants, an inventory of woody plants is in place and is being updated. The Hungarian Ornithological Society carried out a survey of the cemetery's bird population, according to which 110 species were observed in the cemetery. The Hungarian Ornithological Society has installed 25 B-type bird boxes and a feeder and monitors the bird species present in the cemetery, occasionally carrying out ringing. Feeding of the birds is carried out by the maintainer. A distinction is made between intensively and extensively maintained areas. Extensively maintained plots are disturbed only to the extent necessary, with only roadside mowing and no disturbance to habitats within the plots. There have been no recent developments of a comprehensive nature in the cemetery that would have had a significant impact on habitat design or wildlife. In NÖRI's experience, the green space improvements have been welcomed by the public, and feedback indicates that they are satisfied. Thanks to the improvements, and largely thanks to the NÖRI's Remembrance Education Programme, the visitor groups have increased, including schools and groups of Hungarians from outside the country. There is a good relationship with the Rákóczi Association, which brings many school groups to the cemetery.

Új Köztemető (maintained by BTI (public body of the metropolitan municipality), data provider: Ádám Horváth, Head of Division): In the experience of the cemetery's management, visitors to the cemetery would find it difficult to accept improvements to the habitat, and so there are currently no such developments in the Új Köztemető. They do not rule out the possibility of such improvements in the future, after careful consideration, in certain parts of the cemetery. They do not have any data on the cemetery's livestock, but a student is currently studying the deer on the cemetery's grounds as part of a thesis supported by the City of Budapest. A cadastral survey of the trees in the cemetery, especially the row trees, is available. Although there is no record of the whereabouts of the birds' nesting sites, i.e., the cemetery tree survey (tree register) does not cover nesting sites, efforts are being made to protect them. During the molting season, only urgent tree care work is carried out, which is also agreed upon with the tree care professionals working in the area.

Zentralfriedhof (managed by Friedhöfe Wien GmbH, data are based on an interview by [32]): Political and economic factors play a major role in managing the cemetery, but biological aspects are also taken into account. The cemetery management is aware that it has a big task ahead of it in terms of sustainability and biodiversity protection in one of the largest green areas of Vienna. In 2000, a tree register was established in the Zentralfriedhof, recording the trees' age, species and condition. Of the trees in the cemetery, 1200 are over 100 years old, according to the register. Several surveys of the cemetery's fauna have been carried out, with around 100 vertebrate species, a third of which are birds. A census of insects, mollusks and herbaceous plant species is planned for the coming years. Every year, many graves are removed from the cemetery and efforts are made to systematically cover the freed areas, taking care to create contiguous areas. If, for example, two rows of graves become completely empty, resting places are created there. If whole groups of graves are cleared, larger areas can be freed up. There are many green areas where there are currently only a few rows of graves along the roads, which were previously covered by graves. There is scope to create alternative grave types. New trees will be planted not far away during the replacement planting to create an extension area for the Waldfriedhof. They try to make as little intervention as possible, letting the forest grow naturally.

The cemetery has 80 km of roads; there is a lot of pavement, and the three etoile squares and the square in front of the church count for a lot of paved area. Access by car is allowed on paved routes. Maintenance involves mowing the paths at least nine times a year, considering vegetation growth. The main concern is accessibility and safety. Unmaintained graves are mowed at least three times a year, where aesthetics are the deciding factor. Between graves, mowing is carried out together with the graves. The meadows along the paths are mown nine times a year, as are the paths. Large open meadows not directly used are mown twice a year. They are also marked with signs as natural meadows. These green areas are deliberately left as habitats for various insects. The mowing schedule is based on recommendations from experts.

The trees are usually inspected once a year; if an anomaly is found, it must be rectified within a reasonable time. The watering of the plants can be a problem as the cemetery faces shortages of rainwater due to climate change. The officers will set a date for the next pruning and check that the work has been done. The health of the trees is also important for safety reasons so broken branches do not cause accidents during major windstorms. The cemetery is participating in a program to preserve dead trees. The cemetery has committed not to remove all dead trees but to retain them where possible as valuable habitats for insects.

Environmental protection has become increasingly important in cemeteries in the last few years. Visitors are reminded that much of the water provided in cemeteries is drinking water, which can contribute to more prudent use. Waste is collected separately. In addition, battery-powered devices are increasingly used in the cemetery. E-vehicles have also been used for years as small means of transport. Using battery-powered devices has also reduced noise levels in the cemetery, which is beneficial for wildlife.

To promote the conservation of the species, a hedgehog conservation project has been launched: leaf piles are left in the autumn to provide a habitat for hedgehogs. Nesting boxes have also been placed for the birds. In the cemetery, a large green area has been set aside as a "Netzwerk Natur" area. "Netzwerk Natur" is the Vienna Species and Habitat Conservation Programme, which contains standards and guidelines.

The Park of Peace and Strength (Park der Ruhe und Kraft) was the first development designed to enable visitors to interpret the cemetery as a place of encounter. Several programs are linked to the development, including the possibility of remembering artists on the graves of honor, attending a cemetery concert or visiting the funeral museum, and meditating in the park. Vienna's Zentralfriedhof is very popular as a local resting place for the city's residents. Many visitors come here not to mourn, visit or tend graves, but to relax, unwind and find peace. A cemetery is a popular place for hiking and photography. The cemetery is generally used intensively, and the dilemma of memorial and recreational uses arises again and again, and these need to be reconciled.

Permitted sports activities in the Zentralfriedhof include running, Nordic walking and cycling. Running is a tranquil sport; experts consider running a form of active meditation. It is well suited to the cemetery, which has plenty of space. In the past, many people used to run in the cemetery, but now they are actively invited to use the wider running track along the kilometer-marked paths. The cemetery tries to be as open as possible to innovation. For instance, a few years ago, the burial regulations stated that "ball games are prohibited", but this passage has since been deleted.

There is also an annual Biodiversity Day at the cemetery. Several projects are also run in the cemetery in cooperation with the City of Vienna and other organizations, e.g., "Biodiversität am Friedhof". They work together with several educational institutions to make the cemetery's wildlife as accessible as possible to the public and children [32] (Figure 6).

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

Figure 6. Zentralfriedhof Wien: (**a**) Park der Ruhe und Kraft/Park of peace and strength, (**b**) running route kilometer board, (**c**) bee pasture (authors' photos, 2022).

4.2. The Result of the Analysis of the Sample Area

Based on the interviews and literature sources, the habitat characteristics of the three cemeteries studied were summarized, verified and refined during the field visits (Table 1). All three cemeteries have exceptional fauna, flora and fauna. However, none of them is protected as a nature reserve, nor are there any individually protected values on their territory. The Nemzeti Sírkert and the entire Zentralfriedhof are protected as historical monuments. We have summarized the cemeteries' activities related to green space, habitat conservation and enhancement. It is clear that the three cemeteries have similar characteristics in many respects, so the improvements in the Zentralfriedhof can serve as a model for other cemeteries in Budapest.

Table 1. Summary of the three sample area cemeteries (authors' table).

	Nemzeti Sírkert (1847)	Új Köztemető (1886)	Zentralfriedhof (1874)
Size	56 hectares	207 hectares (largest cemetery in Hungary)	291 hectares (2nd largest in Europe)
Style	architectural cemetery	architectural cemetery	architectural cemetery
Management	National Heritage Institute	Budapest Funeral Institute	Friedhöfe Wien GmbH
Status	functioning and closed (mostly) parts	functioning (mostly) and closed parts	functioning, closed parts and reserve area
Location in the city	in the urban fabric (earlier at the time of creation, on the outskirts of the city)	at the outskirts of the city	at the outskirts of the city
Accessibility	public transport, vehicle access allowed, no separate parking	public transport, vehicle access allowed, no separate parking	public transport, vehicle access allowed, several parking zones in the cemetery
Delimitation/entrances	solid brick wall with several gates, but only the main entrance available; no representative reception area	solid brick wall with several gates, but only the main entrance available, representative reception area at the central gate	solid brick wall with several gates, representative reception area at the central gate
Special parts of the cemetery	artists' plots, academic plots, heroes' plots, labor movement plots, Soviet military plots, military plots	heroes' plots (plots 298, 300 and 301), military plots, monastic plot, Mohammedan plot, urn pantheon	children's graves, forest cemetery, Nature Garden, Garden of Serenity and Strength, military plots, religious plots
Green space elements	Significant vegetation: alleys, landscaped plots, but also overgrown plots	Significant vegetation: alleys, lot of overgrown plots	Significant vegetation: alleys, landscaped plots, overgrown plots and forest cemetery
Recreational areas	not specified	not specified	designated areas
Green surface (reserved)	ca. 67%	ca. 25%	ca. 75%
Green space intensity	ca. 83%	ca. 91%	no data
Green infrastructure connections	green area of the Jewish cemetery on Salgótarjáni road	green areas of the Jewish cemetery of Kozma Street and the Orthodox Jewish cemetery of Granatos Street; the Keresztúr forest	green area of the Protestant cemetery Simmering and new Jewish cemetery; part of the Vienna Green Belt
Animals	birds (110 resident bird species and 40 breeding bird species), insects, bats, squirrels, other rodents, hedgehogs, foxes	50-head deer herd, birds, insects, bats, squirrels, other rodents, hedgehogs, foxes, field rabbits	birds (e.g., ducks), squirrels, field hamsters, other rodents, roe deer, stags, bees, butterflies and other insects, amphibians, hedgehogs, rabbits
Habitat conservations status and potentials	bird watching and ringing, landscaped and overgrown plots	overgrown plots	landscaped and seminatural plots, forest cemetery
Habitat developments	bird holes	nature trail in the Keresztúr forest	beehives, Nature Garden (small pond and butterfly meadows, flower hedges, trees, deadwood pile, insect hotel), natural meadow for insects, bird holes, project for the protection of hedgehogs, "Biodiversität am Friedhof" program, deadwood program
Buildings	cemetery office, museum; administration building; chapel; funeral parlor; mausoleums and arcades	cemetery office; visitor center at plot 301; funeral parlors and crematorium; bell tower; arcades; operational buildings	cemetery office; museum; funeral parlors; cemetery chapel(s); arcades; operational buildings; solar park
Works of art	mausoleums, tombs, gravestones, statues	tombs, gravestones, statues	mausoleums, tombs, gravestones, statues
Significance	yes, national pantheon	yes, Hungary's largest cemetery	yes, Vienna's most important cemetery
Touristic offers	thematic guided walks and mobile application	thematic guided walks	thematic guided walks on foot, horse-drawn carriage or e-bike; mobile application

5. Discussion

We compared our results with those of other studies and examined how they can be interpreted in relation to previous studies and the sources we have used. We have endeavored to evaluate the results in the broadest possible context.

Ecological Solutions

Based on international sources [4,6,38], we have broken down the environmental value of cemeteries into the following subcategories: spatial context, burial type, built elements, plant application and habitat provision (Table 2). The authors highlight the need for greater attention to be paid to ecological solutions in cemeteries, with particular emphasis on vegetation management, which cannot be overemphasized as an element of climate change mitigation. Based on these aspects, we have summarized the ecological solutions that should be used in the design, maintenance and development processes and examined their presence in the sample sites.

Spatial context: Cemeteries are not considered in planning and strategy documents as facilities that reinforce the green space system and complement ecological corridors. Today's urban cemeteries are generally not intensively connected to their surroundings, existing as isolated objects. However, these areas are characterized by their exceptional natural value. They can serve as a link (ecological stepping stone or corridor) between other protected areas of higher natural value, allowing the migration of plant and animal species.

Burial method: The different burial methods have different spatial and maintenance requirements. In Hungarian and Austrian cemeteries, space for traditional burial still predominates, but other forms of burial are also gaining ground and opportunities. For example, cremation as a form of burial requires less space and can be used to reduce the size of the burial area within the cemetery. Scattering ashes is also a more ecological and space-saving form of burial than urns, and using a scattering cemetery can create a representative green space. In forest cemeteries, scattered or small grouped graves are placed under an existing forest stand. In the case of memorial forests, even grave markers are not used in the cemetery, where the deceased are buried in urns that decompose under individual trees.

Planting scheme: Architecturally designed cemeteries often have spectacular tree lines along the main roads, providing shade for road users and adding to the aesthetic appeal of the environment. Where different species are used, they also help orientation between similar plots. In the case of park cemeteries, planting ornamental trees and shrubs between the graves is typical of public parks. In woodland cemeteries and memorial woods, native species of associative trees predominate. Evergreen species are planted in cemeteries in many cultures because of their symbolism. However, a wide variety of herbaceous species also appear, especially on graves. The proportion of ornamental plants in the cemetery flora can be very high, so the potential for plant invasion in these habitat patches is a major risk. Most ornamental plants are not necessarily alien or invasive. Most of them are not able to influence native vegetation. Still, they may alter habitat structure, or some sensitive native species may not be able to compete with successful non-native plants. Non-native woody species, for example, often dominate the cemetery landscape for decades. For cemeteries to become a biodiversity base and enrich the urban environment, the prioritization of native species (both woody and herbaceous) should be an important consideration.

Cemeteries provide ecosystem services in the same way as traditional urban green spaces, and their ecosystem services are similar: air quality, regulation of local climate and water balance, reduction of urban heat island effects, wood fuel from tree care, habitat for pollinators, and provision of, for example, aesthetic and recreational values.

Based on our literature research, we have compiled an assessment table identifying the characteristics of cemeteries, their ecological importance and the ecosystem services they provide. The assessment was carried out in all three sample areas. As quantitative data were not uniformly available for all three sites, we used exploratory estimation to classify the data associated with each cemetery into three categories depending on the extent to which the value was specific in the case of each cemetery (Table 2).

Table 2 shows that a wide range of ecological solutions can be applied in cemeteries to enhance their habitat function. Habitat improvements also contribute to the enhancement of the ecosystem functions of cemeteries, primarily regulating and maintaining. Based on the interview responses, the sources and documents explored and the field visit, it can be concluded that most of the habitat improvements that have been implemented worldwide are already in place or planned to be implemented in the case of the Zentralfriedhof Vienna. In Budapest, their use is currently limited in the Nemzeti Sírkert, but the cemetery development concept has already proposed the introduction of a number of solutions that could help to enhance the habitat function of the cemetery in the future. In the case of the Új Köztemető, the conditions (size, amount of open space) for habitat development are in place, but no decision has yet been taken on their implementation.

Table 2. Environmental (habitat) values of cemeteries (authors' table).

Analytical Aspects and Criteria	Description	Significance by Means of Environmental/Ecological Benefits	Associated Ecosystem Service	Is It Present in the Cemeteries Surveyed?
SPATIAL INTEGRATION—INTEGRATION INTO GREEN INFRASTRUCTURE				
Location of cemeteries in the urban fabric	Distance and relationship to other green spaces, green corridors	Continuity in landscape/space. Provision of transport corridor and habitat for species	Regulator and management service	NS ⚘, ÚK fulllength ⚘⚘, Zf fulllength ⚘⚘⚘ [1]
Accessibility	Accessible by public transport/by bike/on foot, parking spaces available	Increased interest, high visitor numbers, intensive care, cemetery development, higher maintenance costs	Regulator and management service. Cultural service	NS fulllength ⚘⚘, ÚK fulllength ⚘⚘, Zf fulllength ⚘⚘
Design of the cemetery area	Design, internal layout adaptation to natural features (e.g., topography, hydrography–watercourse)	Minimal impact on topography, reduction of earthworks. Preservation of native vegetation. Increased space for green areas in the design of the cemetery	Regulator and management service	NS fulllength ⚘⚘, ÚK fulllength ⚘⚘, Zf fulllength ⚘⚘⚘
BURIAL TYPE				
Traditional coffin burial	Covered or framed graves, high proportion of paved surface	In the case of framed graves, it is possible to plant species on the graves	Regulator and management service	NS fulllength ⚘⚘, ÚK ⚘, Zf fulllength ⚘⚘
Cremation—urn burial	Urn placement solutions: urn walls, courtyards, urn graves	Smaller burial space, possible increase in planted areas covered by vegetation	Regulator and management service	NS fulllength ⚘⚘, ÚK fulllength ⚘⚘⚘, Zf ⚘
Cremation—ashing	After cremation, scattering the ashes in a spreading parcel (or in water, e.g., in the Danube)	Grassland, near-natural, native herbaceous plants can be used for landscaping	Regulator and management service	NS fulllength ⚘⚘, ÚK fulllength ⚘⚘⚘, Zf ⚘
Gravestone/"headstone" funerals (both coffins and urns)	(standardized) Gravestones or memorial plaques flush with turf and grassland areas	Maximum beneficial use of rainfall, smaller burial area. Requires intensive maintenance, but can be mechanized. Low level of biodiversity.	Regulator and management service	NS fulllength ⚘⚘⚘, ÚK fulllength ⚘⚘⚘, Zf fulllength ⚘⚘⚘
Forest cemetery, park cemetery	The graves are either scattered in small groups in the landscaped area or are planned to be located under the forest that was already there	More green space, more opportunities for recreational and ecological functions	Regulator and management service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘
Memorial forests, memorial gardens	Separate space dedicated to different solutions of burial, other than the traditional forms of it; e.g., urns placed around trees without grave signs	Higher plant coverage, use of decomposable urns, minimum presence of built elements and artificial materials	Regulator and management service	NS, ÚK, Zf fulllength ⚘⚘⚘

Table 2. *Cont.*

Analytical Aspects and Criteria	Description	Significance by Means of Environmental/Ecological Benefits	Associated Ecosystem Service	Is It Present in the Cemeteries Surveyed?
		ARCHITECTURE, BUILT ELEMENTS		
Funeral parlor, cemetery chapel, administrative buildings	Ecological architecture, sustainable buildings	Well integrated into the environment, prioritizing the protection of natural resources, lower maintenance and heating costs and emissions, raising social awareness	Regulator and management service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘
Supporting structures for creeping plants along the walls	Use of climbing plants on building facades (green walls)	Reduction of heating or cooling energy costs of buildings Pleasant view + habitat/shelter	Regulator and management service	NS, ÚK, Zf
Green roofs	Planting special species on roofs	Natural insulation, additional biologically active area	Regulator and management service	NS, ÚK, Zf
Lighting	Solar, LED lighting	Energy reduction, lower maintenance costs, lower light pollution	Regulator and management service	NS, ÚK, Zf fulllength ⚘⚘⚘
Covering of pavements and transport areas	Use of permeable technologies for paving surfaces	No run-off water, most precipitation quantity is used locally	Regulator and management service	NS ⚘, ÚK ⚘, Zf ⚘
Hydrological features	Reservoirs, rain gardens	Reduced water run-off and precipitation loss. More pleasant environment, microclimate valorization (humidification, temperature reduction). Habitat creation	Regulator and management service	NS, ÚK, Zf ⚘
Fencing, enclosure	Use of natural materials, providing passage for animals	Increase in biodiversity, passage for animals	Regulator and management service	NS ⚘, ÚK ⚘, Zf ⚘
		PLANT USE AND APPLICATION		
Lawn surfaces	Homogeneous plant application, intensive maintenance (irrigation, mowing)	Low species richness, but biologically active surface	Regulator and management service	NS fulllength ⚘⚘⚘, ÚK fulllength ⚘⚘, Zf fulllength ⚘⚘⚘
Perennials	Flowering meadows, native plants	Lower maintenance costs, reduced labor requirements	Regulator and management service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘
Shrubs and bushes	Hedges, e.g., around plots, along fences—functional and aesthetic role	Prevent monocultures, reduce erosion, increase biodiversity	Regulator and management service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘
Trees	Alleys, clumps, solitary trees, woody areas	Improved air quality, wind strength and wind erosion reduction, shading–temperature reduction	Regulator and management service	NS fulllength ⚘⚘⚘, ÚK fulllength ⚘⚘⚘, Zf fulllength ⚘⚘⚘
Creeping plants	Creeping species covering buildings, columns, supports and structures	Increased biodiversity and shading–temperature reduction	Regulator and management service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘
Plant diversity	Complex vegetation coverage, use of native species	Soil structure and permeability improved by roots, higher water supply, increase in air moisture, increase in biodiversity, habitat creation	Regulator and management service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘⚘

Table 2. *Cont.*

Analytical Aspects and Criteria	Description	Significance by Means of Environmental/Ecological Benefits	Associated Ecosystem Service	Is It Present in the Cemeteries Surveyed?
		HABITAT PROVISION		
Extensively used and reserved areas	Less frequent mowing, leaving mowed grass and meadow in peace, leaving cut-off branches in situ	Providing habitat for a range of animal and plant species. Increased biodiversity	Regulator and management service. Supply service	NS fulllength ⚘⚘, ÚK fulllength ⚘⚘, Zf fulllength ⚘⚘
Artificial habitats	Installation of an insect hotel, bird house, bat house, etc.	Creating better living conditions for certain animal species. Increased biodiversity	Regulator and management service. Supply service	NS fulllength ⚘⚘, ÚK, Zf fulllength ⚘⚘⚘
Bee pastures	Less mowing, use of flowering plants to provide nutrients for pollinators	Not only a feeding ground, but also a hiding and breeding place	Regulator and management service. Supply service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘
Water surfaces	Can be used to collect and store rainwater. In addition, it provides aesthetic and ecological benefits	Habitat, feeding and breeding ground, special microclimate, aesthetic pleasure	Regulator and management service. Supply service	NS, ÚK, Zf fulllength ⚘⚘
Beehives	Can be hosted in less visited areas, subject to local regulations	It has a positive impact on plant development and biodiversity, and also generates income through diverse products	Supply service	NS, ÚK, Zf fulllength ⚘⚘⚘
In situ decayed trees	Retention of decomposing, dying trees	Improved habitat creation, but might be less aesthetic	Regulator and management service	NS ⚘, ÚK ⚘, Zf fulllength ⚘⚘⚘
		AWARENESS RAISING AND EDUCATION		
Information boards and panels	Information and knowledge sharing in case of interesting plants and habitats	To familiarize visitors with the species, the importance of the habitats and the associated conservation practices	Cultural service	NS fulllength ⚘⚘, ÚK ⚘, Zf fulllength ⚘⚘⚘
QR code bars, dedicated applications	Provided information on specific species, habitats and developments using smart devices	Tourist attraction, awareness raising, increasing number of visitors	Cultural service	NS fulllength ⚘⚘⚘, ÚK ⚘, Zf fulllength ⚘⚘⚘

[1] NS: Nemzeti Sírkert, ÚK: Új Köztemető, Zf: Zentralfriedhof; ⚘: present but not dominant in habitat (less than 40%); fulllength ⚘⚘: present but in need of development/enhancement (40–70%); fulllength ⚘⚘⚘: dominant element in the cemetery (more than 70%).

From our assessment results (Table 3), it is clear that all three cemeteries need further improvements to strengthen their ecosystem services. The Zentralfriedhof scored highly in most categories, with the most potential for improvement in the built elements. For the two cemeteries in Budapest, their size and current use had a significant impact on the results: for both the greatest potential for improvement is also in the structural elements, while for educational functions, the Nemzeti Sírkert clearly shows the results of recent years' sensitization efforts. In terms of designing, planting and maintaining vegetation, both sites in Budapest have outstanding potential for improvement.

Table 3. Environmental (habitat) values of cemeteries—summary (authors' table).

	1. Spatial Integration—Integration into Green Infrastructure (Max. 9)		**2. Burial Type (Max. 18)**		**3. Architecture, Built Elements (Max. 21)**		**4. Plant Use and Application (Max. 18)**		**5. Habitat Provision (Max. 18)**		**6. Awareness Raising (Max. 6)**	
	⚓	%	⚓	%	⚓	%	⚓	%	⚓	%	⚓	%
NS—Nemzeti Sírkert	5	55	10	55	3	14	10	55	6	33	5	83
ÚK—Új Köztemető	6	66	11	61	3	14	9	50	4	22	2	33
Zf—Zentralfriedhof	8	88	12	66	8	38	15	83	15	83	6	100

⚓ indicates the extent of habitat value.

The majority of the ecological solutions identified can be applied to any cemetery, and can be implemented to ensure habitat function. However, the increasingly popular "natural burial" has a number of ecological benefits in itself, which (based on international experience) are already present in the design of such plots. Clayden et al. (2018) [42] investigate how natural burial transforms the traditional cemetery towards a more habitat-rich and spatially complex landscape, and also explore how natural burial increases the burial capacity of urban cemeteries. The ecological benefits of natural burial have been shown to reduce the total area of mown grassland, the frequency of mowing, and the use of herbicides and to create more complex habitats, including new woodlands. This potentially increases carbon sequestration and reduces NO2 emissions. Less-managed grasslands have a greater capacity for wildlife. Within the cemetery, marginal areas that are not suitable for traditional graves with headstones can be used. The recreational value of the cemetery is increased, encouraging people to visit. It may also have the effect of making the public more accepting of less intensively managed, aesthetically untidy and less well-maintained green spaces. Finding space for "wilder", "untidier" nature is also difficult because it can create a sense of neglect on the part of cemetery users [42].

6. Conclusions

Cemeteries integrate elements of the natural and cultural environment: burial sites/burial places, vegetation, built elements and transport systems. Because of their natural and built character, an integrated approach (spatial and landscape context) is required in planning, design and maintenance. Environmentally friendly solutions will contribute to the conservation and enhancement of the cemetery's wildlife and its recreational potential. In addition to environmental benefits, ecological approaches also bring social and economic benefits, which are summarized in the following table (Table 4).

Cemeteries can contribute to the conservation of biodiversity in cities. However, little is known about the diversity and composition of the plant and animal species that live in them, and researchers mainly focus on the prominent, easily detectable animal and plant species in cemeteries [39]. Thus, research in this area focuses mainly on woody stem plants [40] and bird species [41]. This was also observed in our sample plots. As most cemeteries have both natural and cultural heritage values, a better understanding of the biodiversity composition, the relationship and the needs of each species could facilitate conservation approaches. There are many examples, such as the Ohlsdorf cemetery, where development plans take into account both cultural and natural values. In the course of development, the cemetery is divided into intensively and extensively maintained areas in order to properly preserve their cultural and natural values [46].

Table 4. Environmental, social and economic benefits of green solutions (authors' work).

Environmental	Social	Economic
appropriate maintenance, "no intensive maintenance": • less frequent mowing • less tampering • leaving branches that may have been cut • artificial habitats, e.g., insect hotel • "unpaved" roads • near-natural improvements: unpaved footpaths, bee-keeping areas, other biotopes • lighting	• less disruption • acceptance of nature-based maintenance • interest in wildlife • education • community building	• guided nature walks • bees, apiary honey production and sale • collection and sale of medicinal plants • lower maintenance costs, • in the case of "unmanaged" areas, even solar energy recovery

The role of dead trees in habitat conservation was highlighted. Dead, standing tree trunks are generally absent from cemeteries, even though they are particularly important habitats for hundreds of species: fungi and insects, which depend on the different stages of decomposition of trees. In addition, the associated cavities provide a habitat for bats, woodpeckers and other cavity-dwelling insects. Dead wood is also a limited resource in urban parks, although it is an important tool for biodiversity conservation. However, this appearance does not necessarily correspond to the aesthetic preferences of urban residents and visitors to cemeteries. The ecologically valuable elements of green spaces and cemeteries, which are at odds with cultural norms, often create a sense of "disorderliness". While people like living, old trees for the many associated services they provide (e.g., aesthetics or shade), this does not necessarily apply to dead trees [2]. It can be argued that social needs and aesthetics do not necessarily match ecological benefits and biodiversity conservation, and this poses a new challenge for urban planners and green space designers.

From our previous study [1], we know that urban residents visit cemeteries for different reasons and that different characteristics of cemeteries, especially trees/vegetation and the level of maintenance, influence the time of visit. Rather than a "one-size-fits-all" strategy for the whole cemetery area, our study advocates an approach that addresses different needs by designing differently maintained parts of the cemetery. In this way, urban cemeteries provide an opportunity to maintain and nurture urban flora and fauna, which greatly supports biodiversity conservation.

Urban cemeteries provide important ecosystem services, but little is known about the specific factors that generate these benefits. This key topic is still relatively under-researched.

Climate change challenges [42]: We need to rethink how we manage urban green spaces to help create stronger and more resilient cities. We need to increase habitat diversity and reduce traditional maintenance by reducing the amount of land mown, the frequency of mowing and the use of herbicides and by creating more complex habitats, which could include new woodland. This has the potential to increase habitat diversity and carbon sequestration and contribute to enhancing ecosystem services.

In the future, grasslands could also become an unaffordable luxury in parks. Natural grasslands and meadows provide a more complex habitat than agricultural land or traditional cemetery lawns. Natural, less intensively maintained areas within urban cemeteries can play a role in public acceptance of less intensively managed, aesthetically less tidy and less well-maintained public parks to achieve greater ecosystem services.

The educational and cultural value/role of cemeteries would be enhanced if special plants were "labeled" and animal habitats were signposted. This would help to promote the discovery and knowledge of native and exotic plant and animal species.

Tools for cemetery values and habitat conservation, based on our research and experience, and following [47], can be summarized in the following points:

- Value assessment—identification;
- Raising public awareness about the values of the site;

- Dissemination of information;
- Diversification of burial customs and maintenance technologies;
- Avoiding chemical weed control;
- Reduction of invasive plants;
- Preference for native plants;
- Community involvement in planning and in maintenance.

The question is how to reconcile the different objectives, including the preservation of cultural heritage, the possibility of continuous use (visits, burials) and the conservation of biodiversity. The answer can be found in a planning method that has been used in international practice for many years in the case of many cultural and natural sites: conservation management plans (CMPs) might be a suitable tool to achieve these goals.

During our research, it has emerged that there is no complex database available on urban park cemeteries. A few cemeteries have basic tree inventories, and/or surveys on endemic plant and animal species, but there is no database on cemeteries as complex systems, where the aspects of heritage, conservation, tourism and ecology are managed together. We would like to use the results of our research to lay the foundations for working out what data need to be collected for complex site developments. Soon we plan to set up a pilot project involving biologists, botanists, heritage conservators and representatives of stakeholders for formulating complex development proposals that help the management and maintenance of cemeteries with regard to strengthening their ecological services.

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Abbreviations

NÖRI	Nemzeti Örökség Intézete—National Heritage Institute
BTI	Budapesti Temetkezési Intézet—Budapest Funeral Institute

Appendix A

Ethnobotanical research on cemeteries in Hungary.

Since the beginning of the 20th century, ethnographic researchers in Hungary have been researching village cemeteries, local graves, traditional burial customs and folk beliefs. In his book entitled The Folk Art of Cemeteries, published in 1983, Ernő Kunt described the plant species most commonly used in Hungarian folk cemeteries, and drew attention to the parallel between the vegetation of village gardens and cemeteries and the surviving traces of natural vegetation in old village cemeteries [48]. Iván Balassa, in his 1989 monograph The Cemeteries of Hungarian Villages, noted that the inhabitants of villages rather use in cemeteries those traditional flower species that had been excluded from small residential gardens due to new fashion trends, and thus, an earlier imprint of folk garden culture can be nowadays observed in cemeteries [49]. Ethnobotanical studies in the Carpathian Basin found that cemeteries reflect the relationship of the inhabitants of a village to the surrounding flora. In many cases, plant species of the former natural vegetation found shelter in the cemetery [50]. A similar conclusion was drawn by researchers at the University of Debrecen, who identified village cemeteries as the survival sites of the original natural vegetation communities based on a study of 2800 cemeteries in 17 countries [39].

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plants

Article

Cross-School Collaboration to Develop and Implement Self-Construction Greening Systems for Schools

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Abstract: The positive effects of green infrastructure in the urban environment are nowadays widely known and proven by research. Yet, greening, which serves to improve the indoor climate and people's well-being, is integrated very limited in public facilities such as schools. Reasons for this are seen in a lack of knowledge and financing opportunities. A focus, among others, of the MehrGrüneSchulen research project is the interdisciplinary development of cost-effective greening solutions for schools. The designs were developed in close collaboration with students of a technical college (HTL) and a horticultural school. This study describes the development process and presents the results of the first implementations of greening systems at the HTL-building complex and at nine other schools in Austria.

Keywords: urban green areas; school greening; low-cost greenery systems; construction manuals; interdisciplinary collaboration; student participation

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1. Introduction

As a measure for climate change adaptation and the improvement of urban ecology, it has already been demonstrated at various levels of national and international projects that green infrastructure in the built environment has positive effects on the microclimate. The previous school greening projects GRÜNEzukunftSCHULEN [1] and GrünPlusSchule [2] confirm the positive effects in the school sector. Due to the usually high cost of greening systems available on the market, greening in and on buildings, regardless of their use, has only been implemented on a small scale to date. However, public interest in integrating more "green" into the urban environment is increasing.

According to a survey by UNICEF [3], children and young people spend 38.5 h a week at school and doing homework. Hence, good indoor air quality is significant for the well-being and conductive to concentration. If the indoor air quality in a room is poor, well-being can be affected and the performance of the people in it can decrease. Especially in schools as places where children learn and develop, it is of great importance to provide a healthy learning environment and a high indoor air quality. Extensive greening at schools can make an essential contribution to this.

The research project MehrGrüneSchulen, funded by the Climate and Energy Fund and carried out as part of the program "Smart Cities Demo-Living Urban Innovation 2019", aims to enable more greening solutions at schools in Austria. Simple greening systems that can be implemented with low financial resources are to be developed and made available free of charge in the form of do-it-yourself (DIY) construction manuals. Schools are thus supported in their role as experimental spaces in the city. Throughout the development, an increased independent, practical implementation of green infrastructure at schools will be promoted, based on scientific findings from preliminary projects.

The goal of this study is to reveal the process of developing greening systems within an interdisciplinary teaching format and to present the results of student work and construction and greening workshops. Finally, previous research on school greening is cited and related to the results of this study in order to provide guidance for teachers and advance the integration of greening into regular school operations.

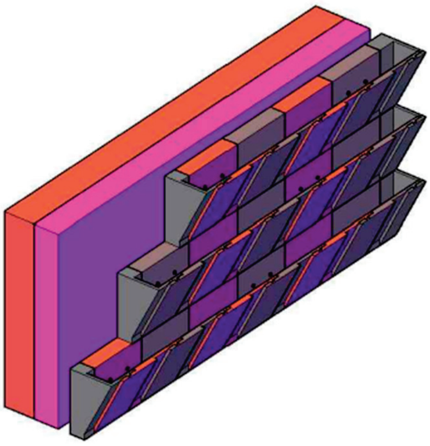
2. Results

An important output of the MehrGrüneSchulen research project includes four construction manuals for indoor greening systems and five construction manuals for outdoor greening systems. The systems can be built as described or adapted and further developed as desired. In ten schools, distributed throughout Austria, innovative greening systems were created, which contribute to an improvement of the learning environment and thus offer a sustainable added value for the schools and consequently for society.

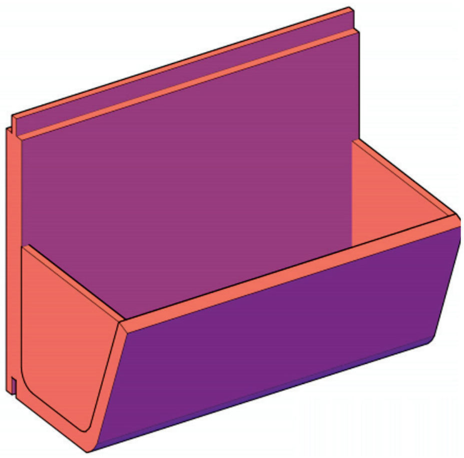
At each stage, from conception to implementation, students from different schools and disciplines were involved in order to gain knowledge around the subject, improve their motor skills and increase collaboration. In the following sections, the first designs and prototypical implementations of the developed greening systems are presented and impressions from the construction process are offered. Furthermore, the built results of the implementation workshops in the federal states are presented.

2.1. Greening Systems for School Interiors and Facades

The illustrations of the final designs of the facade and interior greening systems, made by students of the Camillo Sitte Building Technology Center, Vienna (subsequently referred to as "CSBT"), are shown in Figure 1. The ideas were developed in collaboration with students of the Higher Federal Teaching and Research Institute for Horticulture and Austrian Federal Gardens at Schönbrunn, Vienna (subsequently referred to as "HBLFA"), who subsequently provided suggestions for the choice of plants (shown only schematically in Figure 1). The design posters of the respective groups of students can be viewed on the project homepage.



(**a**)



(**b**)

Figure 1. *Cont.*

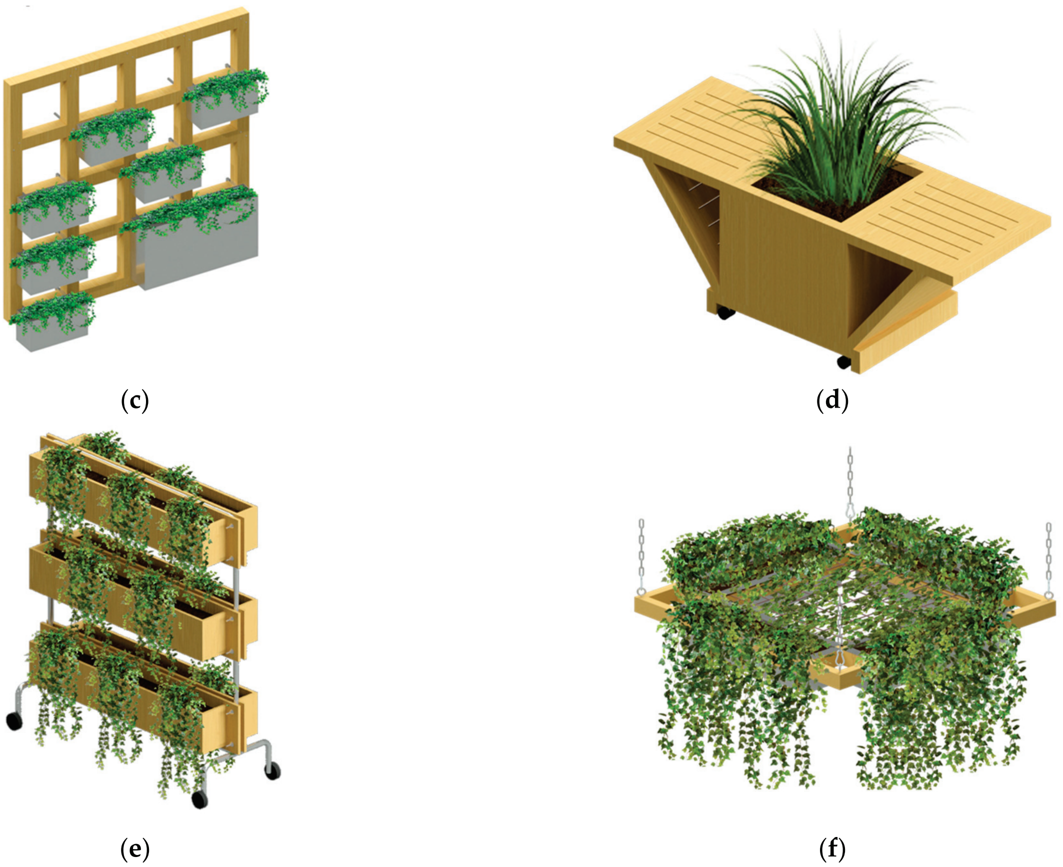


Figure 1. First drafts of the facade and interior greening systems of the participating students of the Camillo Sitte Bautechnikum in Vienna: (**a**) facade greening system "The Green Plug" made of clinker bricks; (**b**) facade trough made of clinker bricks; (**c**) modular wall greening system; (**d**) plantable seating furniture "Green Domino"; (**e**) plantable mobile partition wall; (**f**) greened hanging system "Green Cloud".

The specifics of the developed facade and interior greening systems can be described as follows:

- Facade greening system "The Green Plug":
  This specially shaped molded brick, which can be produced by pressing, can be used to form continuous troughs for a greened clinker facade with tongue and groove joints. The system, like most clinker facades, follows the principle of a ventilated facade, which must be fixed at regular intervals by dowelling to the supporting wall structure. Irrigation can be provided by simple drip hoses.
  Planting—for facade application: *Hosta tardiana, Fuchsia magellanica, Bergenia cordifolia, Heuchera micrantha, Arum italicum, Brunnera macrophylla; for indoor application: Calathea makoyana, Begonia maculata, Peperomia, Chlorophytum comosum, Monstera adansonii, Syngonium podophyllum*.
- Clinker brick facade trough:
  This facade greening system consists of 80 cm high and 100 cm wide brick troughs that can be placed on top of each other in a tongue and groove system. Due to the large troughs, the plants have plenty of root space, which also serves to store water and therefore requires less watering. Here, too, fastening to the outer wall construction is done by facade anchors. Mounting on interior walls is also possible in principle, although in this case it may be advantageous to reduce the dimensions of the troughs.
  Planting—for facade application: *Festuca glauca, Hylotelephium telephium, Sempervivum,*

Yucca gloriosa, Cotoneaster dammeri, Campanula poscharskyana, Thymus praecox, Phlox subulate, Hypericum, Rosmarinus officinalis.

- Modular wall greening system:
  This is a modular greening system with a grid-shaped wooden substructure, which is intended for mounting on a load-bearing interior wall. The plant troughs, made of sheet metal, can be hung in any position on the wooden grid structure and vary in their dimensions. This allows for individual adaptability in terms of size and plant density of the overall system.
  Planting—for indoor application: *Senecio rowleyanus, Callisa repens, Ficus pumila, Ceropegia linearis, Calathea, Peperomia glabella, Chlorophytum comosum, Adiantum capillus-veneris*.
- Greened seating furniture "Green Domino":
  The idea of this greening system is to create a large-scale seating landscape, e.g., for auditoriums or break rooms, by arranging several elements rotated by 90° in a domino-like manner. This invites students to linger in a green oasis and encourages them to change the arrangements of the individual furniture according to their needs. Wheels attached to the bottom allow easy movement of the wooden greening system, which is made without metal connectors.
  Planting—for indoor application: *Senecio rowleyanus, Syngonium podophyllum, Zantedeschia aethiopica, Epipremnum aureum, Peperomia obtusifolia, Philodendron erubescens, Maranta leuconeura, Aglaonema commutatum, Ficus pumila, Ctenanthe burle-marxii*.
- Plantable mobile partition:
  The original design of this system utilizes a used heavy-duty clothes bar, which is converted into a greening system by simple adaptation. For the design at the CSBT's construction yard, the variant with wooden greening troughs on both sides was chosen. These were lined with pond foil and have an integrated water storage layer, enabling a design without water drainage.
  Planting—for indoor application: *Bergenia, Spathiphyllum calathea, Adiantum raddianum, Aglaonema commutatum, Anthurium andreanum*.
- Greened hanging system "Green Cloud":
  This flat greening system is suspended from the ceiling if the room is high enough, creating a "green cloud" above the heads of students and teachers. The square wooden grid construction has a metal lattice in the center. The four elongated aluminum troughs are placed in the openings of the wooden structure, allowing the plants to grow over the metal lattice and hang down from the outer sides.
  Planting—for indoor application: *Chlorophytum, Asparagus densiflorus, Philodendron, Monstera, Tradiscantie, Acalypha hispida, Nematanthus gregarious, Nephrolepis exaltata, Hoya, Epipremnum aureum*.

After completion of the designs, preliminary construction guidelines were developed. This created the basis for implementing the first prototypes at the CSBT construction yard (see Figure 2). Through the practical, partly empirical implementations, further findings and constructive optimizations were incorporated into the completion of the respective building manuals, which were created for as broad a target group as possible. In advance, it must be decided whether the required materials will be prefabricated in their final dimensions by a hardware store, a carpentry shop or similar, or whether the students will carry out the work themselves under supervision. This depends primarily on the infrastructure of the school itself, which, in the case of the CSBT, allowed all the work steps to be carried out in the building yard. The students' achievements were presented at a public event on-site (see Figure 3). The greening systems have since been in use in the school building.

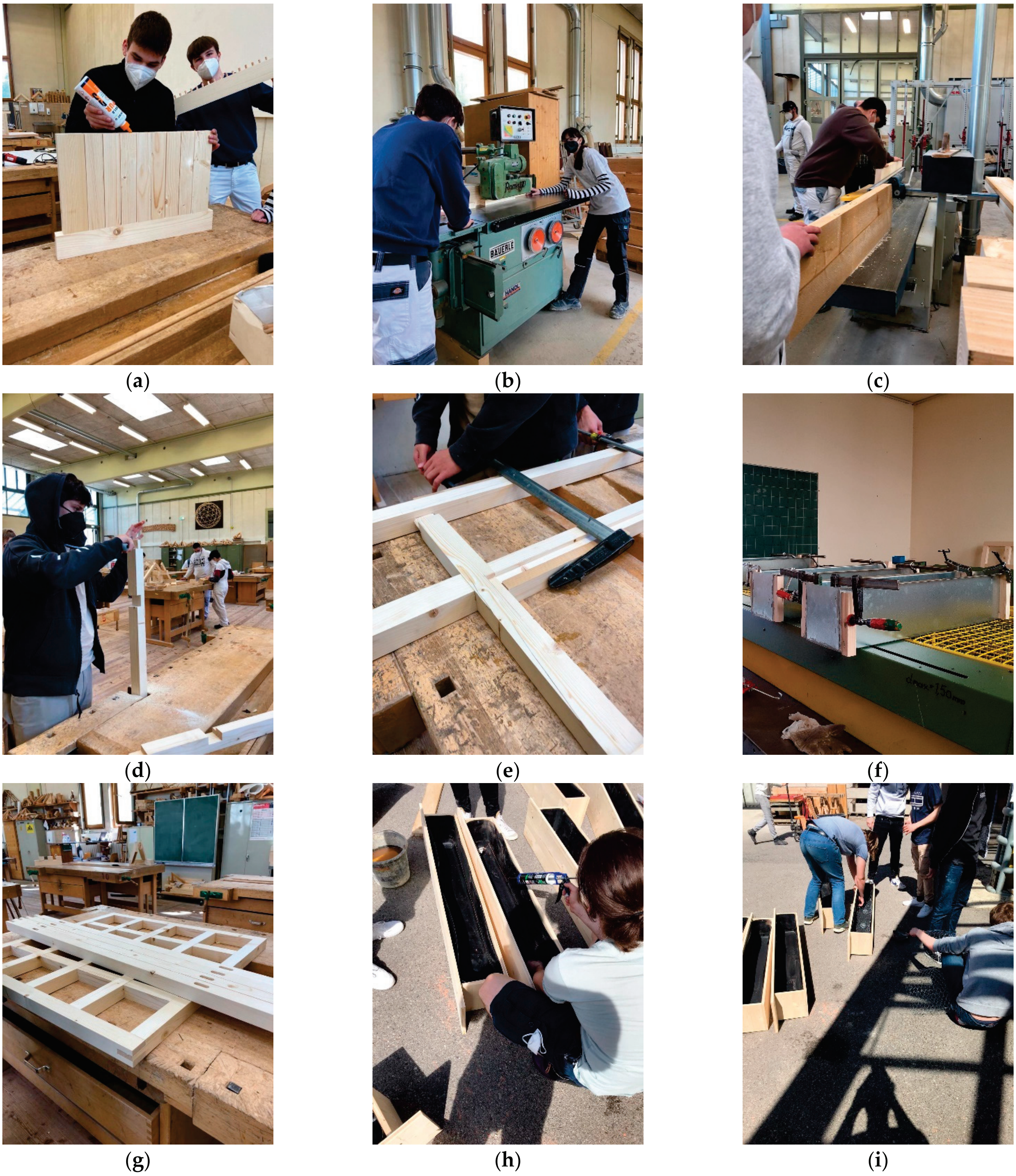


Figure 2. Construction of the prototypes of the indoor greening systems in May 2021 at the construction yard of the Camillo Sitte Bautechnikum in Vienna: (**a**–**c**) plantable seating furniture "Green Domino"; (**d**–**f**) plantable hanging system "Green Cloud"; (**g**) modular wall greening system; (**h**,**i**) plantable mobile partition.

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

Figure 3. Presentation of the prototypes of the indoor greening systems at a public event in June 2021 at the Camillo Sitte Bautechnikum in Vienna: (**a**) modular wall greening system; (**b**) plantable seating furniture "Green Domino"; (**c**) plantable mobile partition wall; (**d**) plantable hanging system "Green Cloud".

2.2. Greening Systems for School Open Space

From the beginning, the focus was on the climate effectiveness of the systems, which is why the largest possible plant volume was to be provided. In addition, materials should be used that are as cost-efficient, ecological, and easy to process as possible, which is reflected in the dominant use of wood as the primary load-bearing structure. Again, the design posters from the respective student groups are publicly available on the project homepage.

The following six greening systems for the schools' open spaces were developed (final designs are shown in Figure 4):

- "GreenClassroom" greened pergola:
  This spacious pergola allows outdoor classes to be held (the "open space classroom" principle) and can be used for individual purposes during breaks. Due to its modularity, it is possible to adapt the dimensions to the intended class size. Stretching from one wooden pillar to the next, planting troughs with climbing support for various plants are provided to green the pergola as much as possible. The addition of opaque wall and ceiling panels with respect to year-round usability of the pergola has been considered.
  Planting—for outdoor application: *Clematis alpina*, *Wisteria floribunda*, *Actinidia arguta*, *Vitis vinifera*, *Rosa lucieae*.

- Plantable hanging chair "Green Trio":
  The name originated from the idea of always arranging three such hanging chairs around a central area, e.g., an existing tree, thus increasing the tilt resistance of the individual hanging chairs in addition to their special appearance. This greening system, like the other systems, is primarily made of wood, but it also has load-bearing steel cables with which the hanging chair is suspended from the supporting structure. The greenery is provided by climbing plants, which are inserted either into the existing soil or into wooden troughs that can be positioned behind the hanging chair.
  Planting—for outdoor application: *Clerodendrum thomsoniae, Lonicera caprifolium*.
- Raised bed "The Vessel":
  The special features of this raised bed are the integrated seating area and the storage space underneath for all sorts of garden utensils. The construction is made entirely of wood. The walls of the raised bed facing the soil body should be protected from moisture by a waterproofing membrane. The raised bed should be permeable to the soil below to avoid water accumulation and allow soil organisms to bond with the new soil body. A small-meshed grid avoids the entry of voles.
  Planting—for outdoor application: all kinds of fruits, vegetables and herbs, such as berries, salads, zucchini, squash, onion, rosemary, hyssop, etc.
- Greened pergola "T-Bench":
  This pergola was named for its shape, which resembles a T. In the center of the pergola is a plant trough for the climbing plants in order to cover the roof, providing the desired shade. Benches are placed on either side of the planting trough, hiding the trough and allowing the climbing plants to grow out of the gap between the benches. An alternative design for the T-Bench is to omit the bench on one side and instead provide a place to park bicycles.
  Planting—for outdoor application: *Vitis silvestris, Hedera helix, Clematis, Phaseolus coccineus, Thunbergia alata, Ipomoea, Tropaeolum*.
- Pergola with play equipment "Place Evergreen":
  Inspired by the shape of a honeycomb, this pergola has six sides of equal length and can thus be extended by another honeycomb element on each side. The design provides for two different modules that can be combined with each other as requested: on the one hand, a playground module with various playground equipment and a climbing net on the roof and, on the other hand, a relaxation module with Hollywood swings and a green roof.
  Planting—for outdoor application: *Clematis alpina, Wisteria floribunda, Actinidia arguta, Vitis vinifera, Rosa lucieae*.
- Greened fountain: This greening system is designed to create a feel-good oasis for hot summer days: In the center is a water area with water plants and a solar fountain. The seating areas next to it are bordered on the back by a green wall of climbing plants on a climbing scaffold. The watering of the climbing plants is solar-powered as well.
  Planting—for outdoor application: *Euonymus fortunei, Clematis alpina, Lonicera caprifolium, Pygmaea Chrysantha, Hydrocharis morsus-ranae, Hottonia palustris, Stratiotes aloides, Hippuris vulgaris, Veronica beccabunga*.

Of the six open space greening systems, two, the "Green Trio" and "T-Bench" systems, were implemented at the CSBT construction yard (see Figure 5). The "Green Classroom," "T-Bench," and "The Vessel" were, among others, implemented at the greening workshops in the federal states (see Section 2.3). The systems "Place Evergreen" and the greened fountain have not yet been implemented due to their complexity.

(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 4. First drafts of the open space greening systems of the participating students of the Camillo Sitte Bautechnikum in Vienna: (**a**) greened pergola "GreenClassroom"; (**b**) plantable hanging chair "Green Trio"; (**c**) raised bed "The Vessel"; (**d**) pergola "T-Bench"; (**e**) pergola with playground equipment "Place Evergreen"; (**f**) greened fountain.

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

(**d**) (**e**) (**f**)

Figure 5. Open-space greening systems built by students at CSBT in Vienna: (**a**–**c**) hanging chair "Green Trio"; (**d**–**f**) pergola "T-Bench".

As with the indoor greening systems, the construction of the outdoor systems requires the availability of appropriate tools and machines as well as the know-how to operate them. In the final elaboration of the construction manuals, the applicability for a broad target group was taken into account. Due to the size and complexity of some of the systems, however, it is advisable to enlist professional support, for example in the handling of wood.

Rebuilding of the proposed greening systems is at the builders' and users' own risk, as the building instructions only represent the rough design intentions of the editors and do not take any safety-relevant measures into account. The teachers and supervisors responsible for the construction must be aware of this and must take the necessary safety precautions when working with students. When selecting the installation site, the static, fire protection, building physics and other conditions must be considered and, if necessary, the approval of the building owner must be obtained. For long-term functioning of the system, care should also be taken to ensure suitable lighting, watering and fertilization for the plants used and to replace the plant substrate at regular intervals (approximately every 3 years). It is recommended to hire a specialized company for maintenance and extensive care work. Dead plant parts are to be removed continuously and replaced by new ones if necessary. This work can be done by students or by elected responsible persons.

2.3. Results of the Greening Workshops in the Federal States

After completion of the greening systems including the DIY-instruction manuals by CSBT students together with the project team, the individual workshops took place in the selected schools of the federal states. Different greening systems for indoor and outdoor areas were implemented. The results of these greening workshops are shown in Figure 6.

Figure 6. Results of the greening workshops in Austria's provinces: (**a**) Korneuburg (Lower Austria)—pergola "T-Bench"; (**b**) Wörgl (Tyrol)—pergola "Green Classroom"; (**c**) St. Johann (Salzburg)—climbing plants; (**d**) Maria Gail (Carinthia)—mobile green wall; (**e**) Graz (Styria)—mobile green wall; (**f**) Kirchdorf (Upper Austria)—pergola "Green Classroom"; (**g**) Neusiedl (Burgenland)—raised bed; (**h**) Lauterach (Vorarlberg)—climbing plants.

The following greening systems were implemented during the workshops:

- Korneuburg (Lower Austria):
  The implemented greening system corresponds to a double version of the pergola "T-Bench", which was erected on concrete slabs. The climbing plants were inserted directly into the ground. The sides of the benches were covered for visual reasons. For the care of the plants, the backrest on one side of the bench can be removed with only a few screws.
- Wörgl (Tyrol):
  The implementation is based on the greened pergola "Green Classroom", whereby the dimensions were adapted to minimize the wood waste. In one corner, a free space was provided for the integration of a stove, which will be retrofitted by the school.
- St. Johann (Salzburg):
  Since the school in St. Johann already had a large-scale climbing trellis on several exterior wall surfaces, but the old climbing plants had already died, the principal decided to use the existing trellis and add new climbing plants. Therefore, no further greening system was implemented here.
- Maria Gail (Carinthia):
  For the elementary school in Maria Gail near Villach, the principle of the mobile green partition was adapted and simplified for safety reasons. Instead of the clothes rail the construction was made of wood. Since the construction of such a greening system is not feasible with elementary school children, the wooden construction was prefabricated in Vienna, so that only the fleece, the substrate and the plants had to be inserted at the workshop.
- Graz (Styria):
  In the high school in Graz, the same mobile green walls were erected as in Maria Gail. In contrast to the elementary school, however, the wooden construction was built together with students from the upper school, which promoted the interaction of different age groups and school levels.
- Kirchdorf (Upper Austria):
  Like Wörgl, a slightly modified version of the "Green Classroom" pergola was built in Kirchdorf. Here, the plant troughs as well as the bench are arranged on one side only, so that people sit with their back to the sports field, with a certain separation provided by the greenery.
- Neusiedl (Burgenland):
  At the Pannoneum Neusiedl School of Economics and Tourism, a raised bed for the independent cultivation of fruit and vegetables was built by the students. In contrast to the design of the raised bed "The Vessel", a bench with storage space underneath was omitted.
- Lauterach (Vorarlberg):
  Due to the long distance to Vienna, the process of planning and implementing a school greening at the secondary school in Lauterach was supervised exclusively online. The result of the planning was a building-high greening of a windowless wall with scaffolding climbers. In addition, smaller greening measures were also implemented in the building.

The results of the greening workshops show that the construction of simple systems for the greening of schools can be well implemented within the framework of handicraft lessons. The perquisite is good preparation and planning to achieve the desired greening goal. As can be seen in Figure 6, the systems are largely made of ecological materials and their design relates to the needs and requirements of the schools. The greening measures also contribute to an aesthetic enhancement of the school environment. To assist teaching staff in the planning process, the construction manuals for the developed low-cost greening systems can be downloaded free of charge from the project homepage. An input mask allows the selection between systems for indoor, open space and facade greening.

Depending on the choice, a subpage opens with all relevant information on the individual greening systems and download links to the construction manuals.

3. Discussion

3.1. Greening of Schools

Making today's schools and other educational institutions more ecological in order to anchor the idea of sustainability in the younger generation is currently an important topic, which can be seen not at least in the large number of scientific publications. However, as with any structural change, there are numerous obstacles to rapid implementation, as Jabbour, Sarkis, de Sousa Jabbour and Govindan [4] examined using two case studies in Brazil. They found that the process of mainstreaming environmental issues usually starts with research and teaching and depends on the personal motivation of a few or individual researchers.

The same phenomenon was observed in the development of the low-cost systems presented in this publication, which would not have been possible in this quality without the commitment and partly unpaid work of the teachers involved. Likewise, the implementation of greening measures at various schools depends on the initiative of the school management or an individual teacher, as long as the respective building owner (in Austria, for example, this is the Federal Real Estate Company BIG for federal schools) does not make school greening systems to a general equipment standard.

The importance of environmental education and the integration of sustainability programs in schools is also demonstrated by Denan et al. [5] using four case studies in Malaysia, Indonesia and Thailand. The findings show that many schools have already developed an awareness of environmental education. However, they argue that support from relevant authorities, potential sponsors, nongovernmental organizations (NGOs), and communities is essential for the increased use of green technology. Similarly, the environment of schools needs to be completely reformed to include climate-smart building designs and materials, and to provide sufficient green space and space for outdoor activities. This is also a particular goal of the present research project, which would not have been possible without the support of local authorities either.

A study by Cole and Hamilton [6] examines a school building before and after it is converted into a "teaching green building" with the goal of improving environmental education. A survey of green building knowledge and environmentally conscious behaviors of students in this green middle school and a reference school showed significantly higher levels of green building knowledge among students in the green school. No differences were found between the two schools in terms of environmentally conscious behavior. Here, the general school practices were of greater importance than the green building itself.

A large-scale questionnaire survey by Yamanoi et al. [7], involving over 600 elementary and secondary teachers, provided information on the factors that determine the implementation of nature-based education by science teachers. The main influencing factor identified in the survey was the degree of closeness to nature of the teachers themselves. This was followed by factors such as teachers' ecological knowledge, frequency of nature experiences in childhood, and the environmental friendliness of the school. In order to promote nature education in schools, it is therefore important to increase teachers' closeness to nature and ecological knowledge and to provide more green spaces in schools.

3.2. Plants in the School Interior

The installation of greening systems such as green walls or vertical gardens in school interiors can improve learning and increase student attention. For example, a curriculum presented by McCullough, Martin, and Sajady [8] includes the implementation of such living wall systems in classrooms to interactively connect students with nature indoors. This could provide a hands-on connection to the subject areas of science, technology, art, and mathematics, which also applies to the results of this research.

Pacini, Edelmann, Großschedl, and Schlüter [9] also show the advantages of integrating green walls into school lessons and have designed a prototypical teaching unit for this purpose that includes three different phases: a descriptive, an investigative, and a communicative phase. In the descriptive phase, an inventory of the existing green wall is made. The investigative phase follows an exploratory approach, whereby public opinion is first surveyed and based on this, scientific investigations are carried out on the green wall. In the communicative phase, the results of the previous phases are prepared in such a way that they can be presented to a larger audience. In contrast to the procedure in Section 4.1, the focus here is on the scientifically oriented investigation of greening systems, while in the present study the creative and design aspect of developing new greening solutions represents the main teaching content. Ideally, both methods are combined, so that greening systems are first developed with a school class and scientific investigations are carried out on these systems at a later stage. In this way, the topic of greening buildings could be dealt with as a class project over the course of an entire school year and thus an essential sustainability topic could be brought closer to the students in a practical way.

In addition to the added educational value of integrating indoor greening into the school curriculum, plants can also improve the indoor environment. In a case study by Danielski, Svensson, Weimer, Lorentzen, and Warne [10], a 10% lower CO_2 concentration and slightly higher and more stable temperatures were measured in two classrooms in a secondary school in Sweden during the winter period.

3.3. Plants in the School Open Space

In addition to the many known positive effects of green spaces and plants on the environment, the influences on people are of equal importance. For example, Jansson, Gunnarsson, Mårtensson, and Andersson [11] studied the positive impact of greening school open spaces, especially on children up to the age of eleven. They found the greatest impact can be achieved when children were involved from early planning through ongoing maintenance of the greening. This could foster positive attitudes among children and caring behavior toward plants. At two Swedish schools, in a four-year process, children were involved in the planning, planting, management, and maintenance of the greening of the school grounds and were regularly surveyed about it. It was investigated that children's involvement in the planning phase was crucial for the functionality of the school grounds, while children's attitudes towards greening were determined by their long-term involvement in its management and maintenance [12]. Thus, in the present study students were involved from the planning phase to the construction of the greening systems, and they have also been introduced in the respective maintenance.

The influence of school garden on cognitive and social skills of primary school children was noted in a study by Amiri, Geravandi, and Rostami (2021). The results showed a significant difference between the students' abilities before and after the study period. Changes in students' attitudes towards plants, care for nature, sense of belonging to nature, and in the mood and their morals could be detected. Overall, it is postulated that school gardens are an effective educational tool that can help students develop their social behavior.

In a case study of two elementary schools in Melbourne, Australia, Onori, Lavau, and Fletcher [13] examined the various factors affecting the implementation of greening measures in schools. Four key areas have emerged for implementation:

1. Professional roles and relationships: This includes leadership by a competent project leader, the appointment of a dedicated project manager, and the hiring of contractors with appropriate expertise (e.g., for green maintenance, irrigation system maintenance, etc.). Attention should also be paid to contracting as directly as possible and to good working relationships (including through shared sustainability values).
2. Planning and design: criteria such as site-specific planning and design and an investment in high-quality equipment and long-term maintenance should be considered, as

well as the school's technical expertise and a timely transfer of responsibilities and expertise related to the greening effort when staff changes.

3. Value to the school community: the focus is on disseminating knowledge about the positive effects of the implemented greening measures on the well-being and performance of the students. Further, a connection to the school's core concerns should be done, and learning opportunities throughout all phases of the project should be identified.
4. Engagement of the broader community: there are multiple opportunities for external support for greening projects, such as funding, resources, and expertise. This can create demonstration sites for sustainable practices and stimulate future projects in this direction. Additionally, recreational and learning opportunities can be provided for other community groups, creating a sense of community ownership for greening.

The criteria listed can also be applied to greening efforts in school interiors. Applied to the present study, the success of the process of developing and implementing low-cost greening systems can be explained by the fact that all four areas mentioned by Onori et al. were considered and optimized from the beginning (see Table 1). The result is functioning greening systems that are accepted and maintained by students and teachers and presented to the public on special occasions to motivate even more schools to develop their own ambitions for integrating greening solutions into the classroom.

Table 1. The four influencing factors for the implementation of greening measures according to Onori et al. [13] applied to the implementations at Camillo Sitte Bautechnikum.

Factor	Implementations at CSBT
Professional roles and relationships	The project management was carried out by the Vienna University of Technology—Research Department for Ecological Construction Technologies, as the necessary know-how and resources were available. The expertise for the practical implementation of the greening systems was available at the CSBT's construction yard. The definition of the planting, the irrigation, and the substrate was done by the HBLFA. The construction workshops in the provinces were led by the garden and landscape planner Dipl.-Ing. Ralf Dopheide e.U.
Planning and design	The planning and design were done by the participating students of the CSBT and the HBLFA. The planning was directly oriented to the needs of schools. A school or teaching staff with an affinity for greenery is responsible for maintenance.
Value for the school community	Four different school classes and numerous teachers from the participating schools and the building yard at the CSBT were involved in the development and subsequent constructional implementation of the greening systems. The finished systems are set up in the auditorium of the CSBT and are thus also available to future classes as teaching material or as a basis for student's theses.
Engagement of the broader community	The development of the greening systems was carried out within the framework of the research project "MehrGrüneSchulen" and was supported by this project in an advisory manner. The completed indoor greening systems were presented to the relevant interest groups and stakeholders in the school sector as well as to the funding agencies at a public school event. Since then, more visits from other interest groups have taken place.

4. Methods

4.1. Involvement of Students in Conceptual Design

The development of greening solutions with the direct and intensive involvement of students of the CSBT and the HBLFA, is crucial for the success of the project. Essential in this context is the cooperation with the above-mentioned schools as the primary target group. The students were able to plan the greening systems themselves, implement the first prototypes and manage them since then. At the same time, the participants were introduced to interdisciplinary work and actively participated in the design of their environment. The names of the participating students are listed on the designs and in the construction manuals, which are available for download on the project homepage.

The entire process of developing greening solutions was run through twice. In the first step, greening systems for indoor and facade application were addressed, and in the second step, systems for the open spaces of schools were discussed. In both occasions, a school class of the CSBT (a fourth and a second year class, respectively) and the HBLFA (a fifth and a fourth year class, respectively) took part and the development process was as follows (see Figure 7): Once the school classes were selected, inspirational documents for the students were created, to introduce them to the topic and presented in an online meeting by representatives of the project team. After the presentation, the students were divided into mixed groups, so that both CSBT and HBLFA were represented in each group. Each of the 12 groups was given an individual task to develop a design for a low-cost greening system for the school interior or open space (see Table 2). After a preparation period of about two weeks for research and initial idea collection, online meetings of the individual groups took place. The ideas of the groups were discussed and refined for further work. With a subsequent two-week elaboration period, the designs could be detailed in terms of construction, fastening, planting, substrate, and irrigation. The interim results were presented to the entire project team by the respective group members in an online workshop. After incorporating feedback from the project team, the first preliminary construction manuals were drafted. These served as the basis for the exemplary construction of four indoor and two outdoor greening systems at the CSBT construction yard. An overview of the final student designs is provided in Section 2.

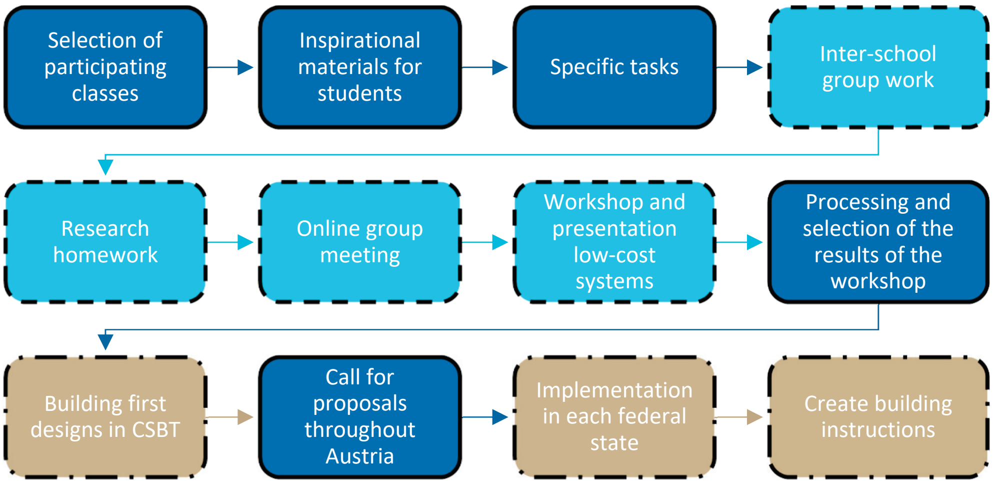


Figure 7. Development process of low-cost greening systems; dark blue, framed throughout: work in the project team; light blue, dashed framed: integration of the school classes of the CSBT and the HBLFA; beige, dash dot framed: joint work of the project team with students of the CSBT and other selected school classes throughout Austria.

Table 2. Assignments for participating school classes to design low-cost greening systems for school interiors or open spaces.

Nr.	System for	Task/Topic
1	Facade	Continuation of the "facade stone" project for north-facing facade
2	Facade	Continuation of the "facade stone" project for south-facing facade
3	Interior	Modular system made of recycled materials
4	Interior	Suspended modular system—for aisle areas
5	Interior	System with a seating option—for auditorium or dining room
6	Interior	Mobile system as green partition wall
7	Interior	Ceiling suspended system—for a south-facing class
8	Open space	Green pergola
9	Open space	Climbing plants
10	Open space	Raised bed
11	Open space	Shading through greenery
12	Open space	Open topic
13	Open space	Open topic

Table 2 shows the different tasks for the three thematic groups facade, interior and open space greening systems. These were described in a PDF document and sent to the student groups. The following aspects had to be considered:

- sufficient size (impact on climate and/or energy use);
- if necessary, artificial lighting (indoors);
- the appropriate fertilizer;
- suitable substrate (soil, perlite, etc. or hydroponics);
- water and/or power supply;
- consideration of specifications regarding fire protection;
- budget per greening max. EUR 2.500.

In total, four tasks on indoor greening systems could be elaborated. More freedom was given in the design of the various tasks of open-space greening systems. There were two open-topic groups, whereby the above-mentioned aspects also had to be taken into account.

4.2. Greening Workshops at Schools throughout Austria

One of the goals of the MehrGrüneSchulen research project is the structural implementation of a low-cost greening system at one school per federal state of Austria. In order to find interested schools and to evaluate the general interest of schools in greening measures, a nationwide call for applications was sent out. Included in the schools' application was the opportunity to submit a specific greening request. Out of 43 responses received by the deadline, nine schools, listed in Table 3, were selected that best met the requirements of the research project. Since several systems had already been planned and implemented at the CSBT, as described in Section 4.1, no other school was chosen from Vienna. For information on the greening measures implemented, see Section 2.

Table 3. Schools selected for implementation of low-cost greening measures.

Nr.	Federal State	City	School
1	Vienna	Vienna	Technical college (CSBT)
2	Burgenland	Neusiedl	Business and tourism school
3	Carinthia	Maria Gail	Elementary school
4	Lower Austria	Korneuburg	Commercial college
5	Upper Austria	Kirchdorf	High school
6	Salzburg	St. Johann	Commercial college
7	Styria	Graz	High school
8	Tyrol	Wörgl	Commercial college
9	Vorarlberg	Lauterach	High school

The greening workshops in the federal states took place between September 2021 and June 2022. Apart from the first implementation in Vienna at the CSBT construction yard, all implementations in the federal states followed the sequence shown in Figure 8: Once the participating schools were selected, initial informational materials on the developed greening systems, shown in Sections 2.1 and 2.2, were distributed and schools were asked to indicate their preferences. After individual consultation with the schools and adaptation of the greening systems to their respective ideas and possibilities, the workshop dates were arranged and the necessary preparations, such as the completion of detailed drawings and the acquisition of the required materials and plants, were made. A basic equipment of machines and tools were prepared and provided by the responsible garden and landscape planner of the project team and taken directly to the individual workshops. The workshops themselves, which usually took one or two days, always started with an introduction to the theoretical basics and general advantages of greening systems, which was adjusted to the age and skills of the participating students at each school. Furthermore, the greening system to be erected was described and its possible effects on the school space use and design were discussed. In the next step, the supporting wooden structure for the greening systems was erected together with the students on site, under the guidance and support of craftsmen from the project team. Students were supported at every step of the process in terms of accident prevention, handling of the tools used and structural wood protection. In the same way, substrate and plants were inserted and, if necessary, climbing cords were added.

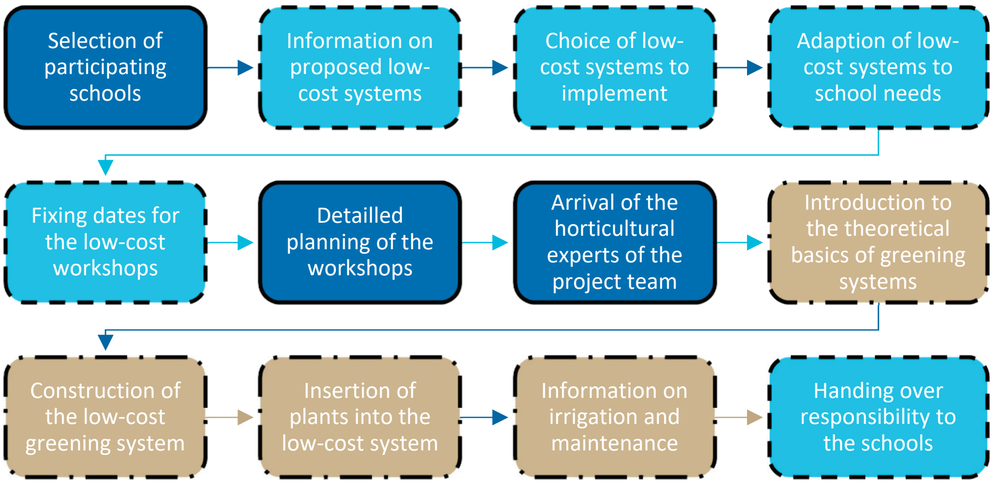


Figure 8. Realization of the low-cost workshops in the federal states; dark blue, framed throughout: work in the project team; light blue, dashed framed: integration of the school authorities; beige, dash dot framed: integration of the students of the selected school classes throughout Austria.

In the workshops, the participation of students did depend on their age and basic enthusiasm for handicraft work. In the implementation, the focus was on technical support and the transfer of know-how relevant to the work. At the end of each workshop, the project team handed over responsibility for the systems to the schools and provided tips and tricks for the maintenance and care of the plants and the whole system.

5. Conclusions

In the course of this study, a total of twelve low-cost greening systems for school interiors and open spaces were developed in an interdisciplinary collaboration between a technical school and a horticultural school, six of which were implemented and greened at the technical school's construction yard. In addition, the constructional implementation of the adapted student designs took place at nine more schools throughout Austria, whereby school classes were involved in the construction and greening process on site.

For most of the developed greening systems, construction manuals were developed for independent replication by other interested schools and made freely available to the public. This way, the implementation of green infrastructure in Austria's schools is being advanced and, at the same time, climate-friendly construction, the development of social and moral skills, and the relationship and interaction with nature are being promoted. This contributes to the gradual improvement of air quality and microclimatic conditions in and around schools and can increase the acceptance and awareness of building greening. In a participatory process, students and teaching staff design areas of their school premises themselves and acquire them through regular use and care of the plants, which can be seen as a continuous process of learning and thus symbolic for the school.

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Data Availability Statement: The data presented in this study are openly available at the TU-Wien project homepage at https://www.obt.tuwien.ac.at/mehrgrueneschulen/begruenungssysteme-und-finanzierung/ (accessed on 28 November 2022).

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Article

Vertical Greening Systems: A Critical Comparison of Do-It-Yourself Designs

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Abstract: Due to the increasing shortage of space in urban areas, vertical greening systems (VGSs) are becoming increasingly popular as a means to provide increased urban greening using building façades. VGSs are usually installed and managed by experts due to technical complexity, however the role of local communities is becoming increasingly important through Do-It-Yourself (DIY) practices. This study aims to explore low-cost VGSs and provide design suggestions and maintenance indications to encourage the expanded use of in situ small-scale VGSs. Firstly, an exploratory review of VGS designs proposed in the scientific literature, and by commercial and community-based solutions was conducted taking DIY potential into account to define eight basic design models categorized through six structural criteria. Then, seven community garden groups were interviewed to inform a critical comparison of the eight design models. Data collected was synthesized to develop a star rating system, thus providing a quick comparative tool. The star rating system shows the performance of five relevant DIY design parameters for each VGS model. The current research may assist in the accessibility of green technologies and facilitate community-scale implementation of DIY vertical greening.

Keywords: urban greening; Do-It-Yourself; green walls; community awareness; co-design processes; vertical greening systems

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1. Introduction

Increasing population densities in urban areas will require the reconsideration of the structure of cities, along with building requirements to pursue committed and strategic actions to increase the livability of the built environment. Green urban areas are considered essential places that support people's physical and mental health and wellbeing [1], however urbanization and land-use changes put public green areas under increasing pressure [2]. The UN Sustainable Development Goal No. 11: Make cities inclusive, safe, resilient and sustainable [3] introduces the concept of Green Infrastructures (GI) and Nature-based Solutions (NBSs) as strategies to design more sustainable cities. NBSs are applied to address environmental challenges within urban contexts, whilst additionally providing social and economic benefits [4,5]. GIs are described as a network of multifunctional green spaces covered by vegetation, such as parks, green corridors, private and public gardens, green roofs and green walls [6]. GIs harness NBSs in urban areas to deliver ecologically sound outcomes [7], which have been recognized by both scientists and politicians to improve city habitability [8].

Urban horticulture is a form of NBS that can contribute to supporting mental health and wellbeing [9], and form part of a systemic approach to face emerging societal challenges [10]. Urban agriculture phenomenon offers the opportunity to transform urban space and promote place-making for social purposes in both high and low-income countries [11]. The benefits notwithstanding, the move towards urban gardening and the re-greening of cities is constrained due to the lack of space in cities with high density populations [12], as well as soil contaminations and public safety concerning home gardening and urban farming [13]. This has led to an increase in interest in alternative GI technologies; notably green roofs and vertical greening systems (VGSs), which allow for the space-efficient integration of vegetated surfaces in urban areas [14]. A growing body of evidence suggests VGS technology can improve air quality [15], mitigate the urban heat island effect [16], improve building performance by acting as thermal insulation [17], support biodiversity in cities [18] and manage stormwater [19]. In some cases, VGSs are adopted as NBSs used to revitalize and regenerate urban vacant lands [20] and to promote a biophilic urbanisms [21].

However, as VGS technology is relatively new, and proprietary systems require substantial technical knowledge to install and manage, the feasibility of implementing VGS at a community scale is often challenging. In many cases, the most effective vertical greening initiatives are managed by local governments which collaborate with citizens and private sector to foster the implementation of community-scale and localized interventions [22]. Rupp et al. [23] demonstrated that highly intensive civic engagement and active participation in planning and implementing urban greening results in more effective and accepted interventions.

In this framework, Do-It-Yourself (DIY) urban greening initiatives are frequently adopted by citizens to add greenery to urban environments and improve the surrounding built environment [24]. DIY urban greening refers to the practice in which non-expert community's members create or repurpose urban spaces using non-professional materials and processes [25]. DIY urban greening as an informal civic initiative could increase citizens' participation in the process of urban sustainable transition, and promote community empowerment and social inclusiveness [26]. DIY activities could also promote VGSs as educative tools [27] for the community-based social and ecological transformation of urban spaces. However, the public understanding of achievable DIY VGS designs and the technical considerations involved is lacking, as are recommendations on designs that take into account the various types of structure or irrigation systems, which will change depending on the motivation for each VGS application. All these aspects influence the sustainability and cost-effectiveness of VGSs, which also differ case by case. In many cases, technical requirements are inaccessible to the public or not known at all, because they are usually targeted at experts who design, construct, install and maintain vertical greening professionally. These factors are highly reliant on various economic, technical, and environmental influences, as well as commitment and engagement, which will also impact the effectiveness of the system and user satisfaction. Therefore, the design process of a VGS is crucial to create a sustainable and successful greening solution which meets community needs and limitations [28]. Decision-making for designing the most appropriate VGS could be challenging for inexpert individuals or communities and sharing knowledge can support successful co-design processes that involve local governments, private sector and citizens [29].

In order to make more accessible vertical green wall technologies in the DIY urbanism [30], this study reports on and evaluates low cost product designs to encourage VGS applications in a low-income urban settlement or at a residential scale. Due to the complex and multifaceted nature of VGSs, this study is divided into two stages: (1) the analysis of different technical solutions based on a review of the published literature, on the most common commercial solutions and DIY systems and the experience of local stakeholders; (2) a critical comparison between VGS design models using a simple rating system to assess DIY performance. Although previous studies have focused on technical features to improve the ornamental and functional role of VGSs, the aim of this work was to provide a design guideline for individuals and communities who want to install low-budget or small-scale green walls. The guideline consists of a set of safe design considerations, maintenance indications and planting recommendations provided to users in order to promote positive experiences of VGSs because it's a relatively new greening technology and it will be developed step by step [31]. The rating system approach aims to provide user-friendly design information based on priorities and needs expressed by non-expert individuals or communities for implementing green walls as urban greening tools. Thus, the investigations' goal was not to provide quantitative data, but rather to provide qualitative analysis based on community engagement.

An Introduction to VGSs for the Greening Improvement in Urban Areas

The concept of green walls or vertical greening systems (VGS) applies to all systems that can sustain vegetation that grow vertically on, up or within a surface, such as façades or walls, without any or with limited ground level space use [32]. These systems partially or completely cover the building wall with supporting structures for vegetation, which may include a plant growth medium. Although the use of VGS is an old design practice for greening cities [33,34]), new technological solutions are becoming more frequently applied to VGSs to address sustainability in urban areas [35]. Overall, the terms 'vertical greening system', or 'vertical garden' can be seen as over-arching umbrella terms used to describe all forms of vegetated wall surfaces [36,37]. Throughout the green infrastructure literature, different green wall proponents have adopted a variety of definitions, classification systems and terminology. Pérez & Perini [38] generally categorised VGSs into two different groups: green façades and living wall systems (LWS). Green façades are the most traditional VGSs [39], which utilises hanging or climbing plants, such as lianas, vines or scramblers, as vegetation cover. A common characteristic to identify these systems are plants rooted at the base of walls or in planter boxes, which can be attached to the wall at a height or at the base. Green façades were categorised as either direct or indirect designs [40], according to the location of the vegetation, either directly attached to the wall or supported by structures to allow plants to climb and spread.

Comparatively, LWSs were recently introduced to increase the variety of plants that can be cultivated vertically, with the aim to obtain a more uniform vegetated surface in high buildings [36]. LWSs can be "self-sustained", also known as "free-standing", or "wall-attached" systems, and they may be structured as pre-vegetated modular fixtures or continuous pocketed frames, which are attached to the wall. Both structures—modular and continuous—are indirect systems that contain and isolate the plant growth media from the building wall surface. Therefore, LWSs, as self-sufficient systems, differ from green façades by allowing plant growth without the need for rooting into the natural ground surface. Despite their ornamental values, LWSs require the use of expensive materials and frequent management, often affecting their cost effectiveness and applicability in any context [41]. Additionally, they require specific technical knowledge to select the most appropriate plant species and frequent maintenance interventions.

Modular LWSs include a huge variety of systems that differ in structure, weight, number of components and assembling complexity, being are designed to improve the flexibility and adaptability of VGSs to user's needs. For that reason, only modular VGS structures have been considered and analysed for DIY applications.

2. Methodology

2.1. Categorisation of VGS Models for DIY Application

An exploratory literature search of existing VGS typology was conducted in order to explore VGS models that have DIY potential (from design stage until maintenance) and could be integrated into a community's decision-making process in urban design and gardening. The search was based on VGS technical considerations identified in the published literature, existing market products, online DIY tutorials and community garden experiences. The academic databases, ScienceDirect and Science Research, as well as the online search engines Google Scholar, Academia and Research Gate, were searched to identify projects adopted for community purposes all over the world. Additionally, the informal social media platform such as Youtube and Pinterest were also examined for related DIY initiatives.

Existing VGSs are classified based on criteria defined by previous studies, based on construction characteristics [36,37,42] and are described based on the following criteria: (1) structure, material and components; (2) irrigation and drainage systems; (3) type of vegetation; (4) indoor or outdoor application; (5) maintenance requirements; (6) aesthetic value. This allowed for the synthesis of VGS design models which are DIY focused based on these criteria. Principal positive and negative aspects of each design model were also determined as below.

2.2. Comparison between VGS Design Models

A comparative star rating system was created to rank designs for various applications, with the goal to assist communities or individuals in the selection of the most appropriate VGS design model among those identified during the categorisation stage. The intention was not only to benchmark the perceived performance of VGS design models, but also to communicate key information to inexpert makers.

The methodology was based on the participatory engagement of representative members (ranging from 1–3 people) from seven community garden groups located in Sydney Region (Sydney, New South Wales, Australia) who were interviewed for this research (locations in Figure 1 and Table 1). The community garden groups engaged in this investigation have the largest membership in the Sydney Region. Additionally, the representative members were deemed to be 'senior' or high ranking in their respective community groups. In the first instance, interviews were conducted to confirm the DIY appropriateness of the designs, and subsequently to provide qualitative data enabling the comparison ratings assigned to each of eight VGS designs. The participatory engagement was useful to explore the local-scale scenario of urban and sub-urban community gardens and to prioritise the main needs and challenges expressed by stakeholders.

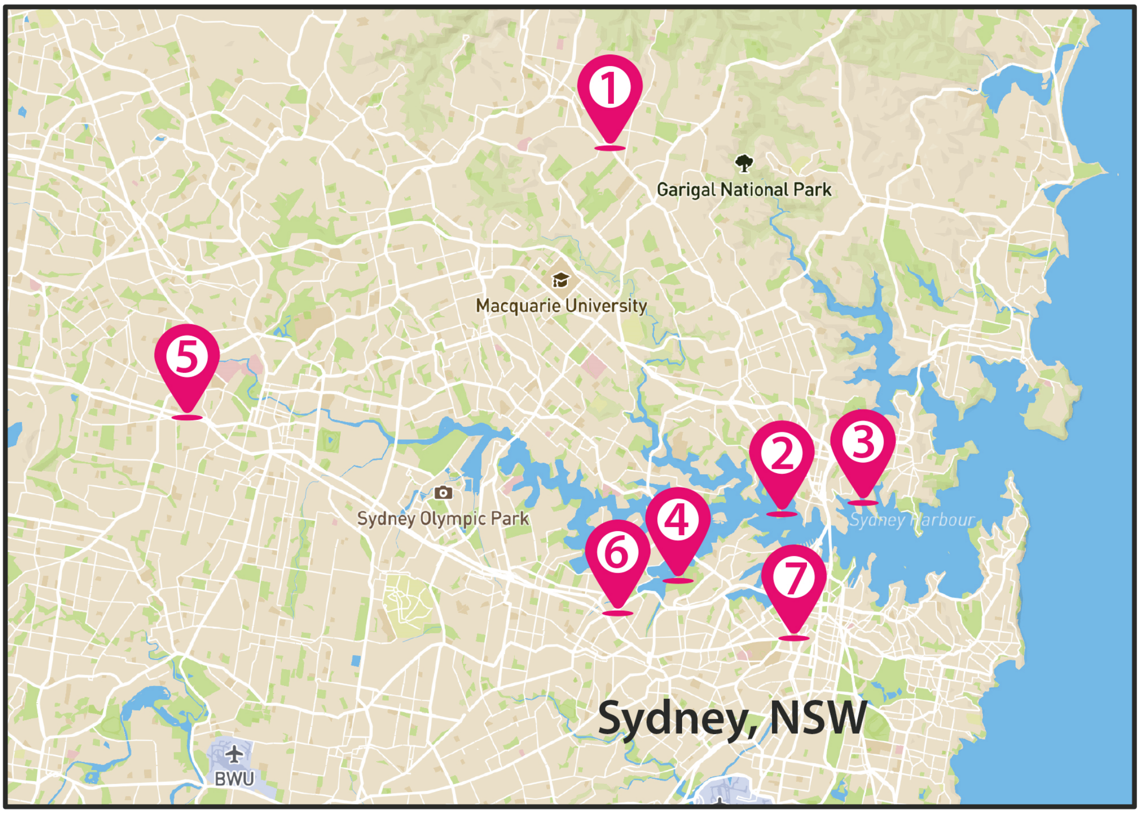

Figure 1. City map of Sydney (NSW, Australia) with location of community garden groups (their names are reported in Table 1), modified from [43].

Table 1. Details of interviews to Community Garden Groups.

	Stakeholder	Location
1	Turramurra Comunity Garden	Turramurra, NSW
2	Coal Loader Community Garden	Waverton, NSW
3	Milson Community Garden	Milson Point, NSW
4	Glovers Garden	Lilyfield, NSW
5	Wentworthville Community Garden	Wentworthville, NSW
6	Taringa St Community Garden	Ashfield, NSW
7	Ultimo Community Garden	Ultimo, NSW

Five main criteria were identified for inclusion into the rating tool, which were identified through semi-informal interviews with community garden stakeholders based on their own experiences: (1) DIY friendliness, (2) cost effectiveness, (3) integration with existing buildings, (4) maintenance, (5) drainage and irrigation. These criteria have been selected with a priority of addressing major community needs and limitations, thus facilitating the selection of the most appropriate design model. At least three stakeholders from each community garden group were asked to give a score from one to five for each criterion for each VGS model based on their own experience. The evaluation process for each criterion has been guided by the qualitative descriptive questions shown in Table 2. The scores were then converted into a comparative star rating system, which allows for a user friendly evaluation to facilitate the selection of the most suitable and achievable VGS design for the needs of an individual or community group. Stakeholders were involved separately during semi-informal interviews in order to outline differences between community gardens.

Table 2. Questions used to guide stakeholders of community gardens into scoring each criterion for VGS models evaluation according to their experience. Each criterion is described using significant questions that have the same weight. The final score of each criterion is obtained by the arithmetic mean of the values assigned to each question.

Criterion	Description	Rating Range
DIY friendly	How easy is the VGS to DIY? How easily can the materials be sourced? Is it possible to use recycled/repurposed materials and components? How easy is the assembly? Can the VGS be designed, developed and constructed without the supervision of an expert or professional?	One star (not DIY friendly) to five stars (very DIY friendly)
Cost effective	How budget friendly is the VGS? Are there operational costs during the VGS's life cycle? Is it possible to reduce cost using recycled materials and components?	One star (least cost effective) to five stars (most cost effective)
Integration with existing buildings	How easy is the VGS to implement onto a vertical surface? Is the VGS adaptable to different sized and shaped surfaces? Does the VGS need any specific structural support?	One star (not easy to integrate) to five stars (easy to integrate)
Maintenance	How easy is the VGS to maintain? How frequent is the required maintenance? Must experts carry out maintenance? How many people are required for maintenance?	One star (not easy to operate and maintain) to five stars (easy to operate and maintain)
Drainage and Irrigation	How complex is the drainage and irrigation system to install and operate? How many components does the irrigation system require? Does the VGS need a fertigation system?	One star (complex drainage and irrigation) to five stars (simple drainage and irrigation)

3. Analysis and Results

3.1. Categorisation of VGS Models for DIY Application

Using the classification definitions outlined by Manso & Castro-Gomes [36] and Radosavljevic et al. [44], the proposed DIY VGSs were classified into eight design categories, maintaining the distinction between green façades and LWS (Figure 2).

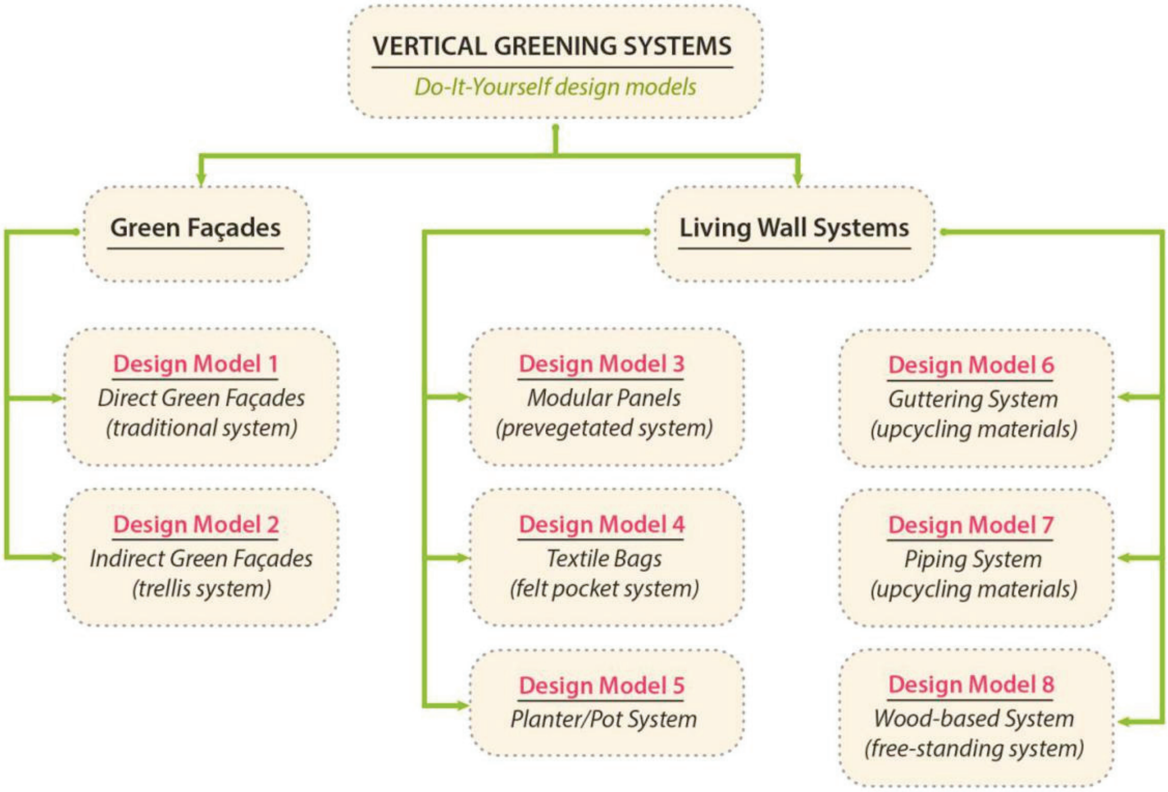

Figure 2. Categorization of VGS design models for DIY applications based on previous study classification.

3.2. Design Models 1 & 2: Features of Green Façades

Direct green façades (Design model 1, Figure 3) take inspiration from ancient architecture techniques from the Mediterranean region and Central Europe of covering palace façades with vines and climbing plants that became popular in Berlin (Germany) between 1980 and 1997 [33]. Design model 1 is the simplest design and was the most low-cost model of VGS [45] which can be easily implemented in high density urban areas, especially in outdoor environments, due to the limited number of materials required to build it.

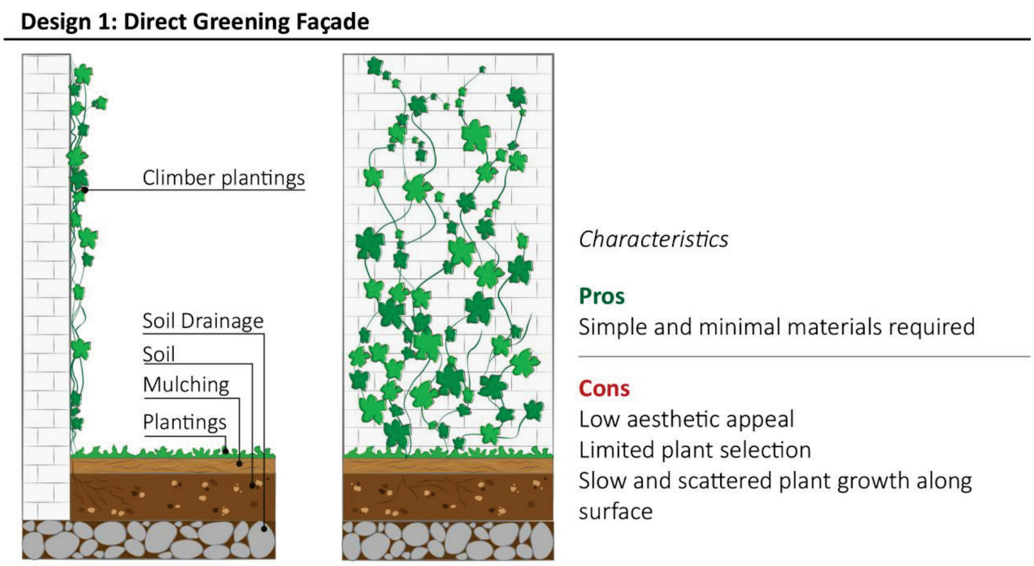

Figure 3. Features of Direct Green Façade with the summary of most relevant characteristics highlighted by community representatives during interviews.

Design model 2 uses vertical support structures; such as bamboo, wood, steel, aluminum or HDPE; as a trellis to guide plant growth, and in turn, increase coverage of the building surface and reduce the risk of VGS collapse (Figure 4). This VGS model is often applied on residential fences and commercial building facades as low-budget greening solution. Modular or continuous trellis, mesh, nets, wires or cables, running horizontally or vertically assist and control plant growth, providing an anchor for plants to grasp and attach to. It is also known as a "double-skin façade" because the vertical vegetated structure creates an air gap with the building surface to preserve the integrity.

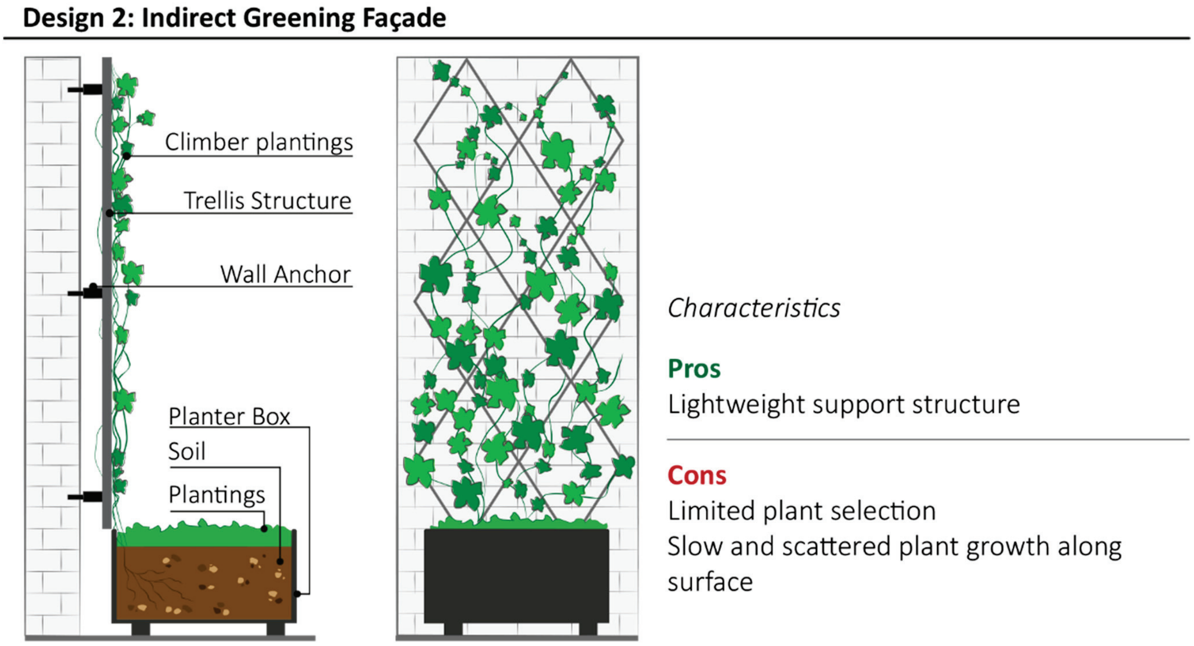

Figure 4. Schematic structure of Indirect Green with the summary of most relevant characteristics highlighted by community representatives during interviews.

Vegetation choice is the most limiting factor for the implementation of Design models 1 and 2. Direct green façades require self-clinging climber plant species, such as *Hedera helix*, *Parthenocissus tricuspidata*, *Wisteria* sp. and *Vitis* sp., which utilise adhesive pads or clinging aerial rootlets to attach and spread on a wall surface. Design model 1 is a self-supporting system that requires a medium–long period to cover large areas of building surface, depending on the plant species used. Indeed, evergreen plant species should be used to ensure ornamental value year-round.

Design model 2 also allows the use of species such as *Trachelospermum jasminoides*, *Lonicera nitida* and *Passiflora caerulea*, thanks to the support structure. Cable systems are commonly used for sustaining fast growing plants with denser foliage, while wire-net systems are applied for slow growing plant species that require small grid intervals to ensure extensive coverage [46]. Using deciduous plants, such as *Vitis vinifera*, may cause the depreciation of the VGS due to leaf loss in autumn and winter. The main disadvantage of this VGS model is the potential lack of aesthetic appeal caused by the uneven and slow growth of plants. Direct and indirect systems of green façades provide almost the same benefits relating to building heating, energy saving for cooling and temperature decrease [40], but they are considered the least effective VGS to achieve benefit for noise reduction due to the lack of the growing media in close proximity to the building façade that is mainly responsible of sound insulation [37]. In most cases, vertical irrigation and drainage systems are not required, because plants are placed at the basement of building façade. Manual irrigation is sufficient to maintain the VGS, however drip, sprinkler or wicking irrigation can be installed in the planter box if automatic watering is required.

3.3. Design Model 3: Modular Panel System

Design model 3 represents a modular pre-vegetated panel, based on commercial style products. Commonly, this type of VGS is characterised by a structural waterproof box panel (e.g., polystyrene or HDPE) that often contains an inorganic (e.g., mineral wool, felt or perlite) or organic (soil, potting mix) light-weight substrate, wrapped in a geotextile and equipped with a fertigation system (Figure 5) [42]. Alternatively, DIY designs of this type can be obtained by upcycling old wood pallets as demonstrated by) Pruitt et al. [47]. For those systems that are hydroponic, regular and automatic watering and fertilization is required [48], especially for inorganic substrate panels, to sustain vegetation growth. Additionally, drainage systems must be designed at the basement of the VGS.

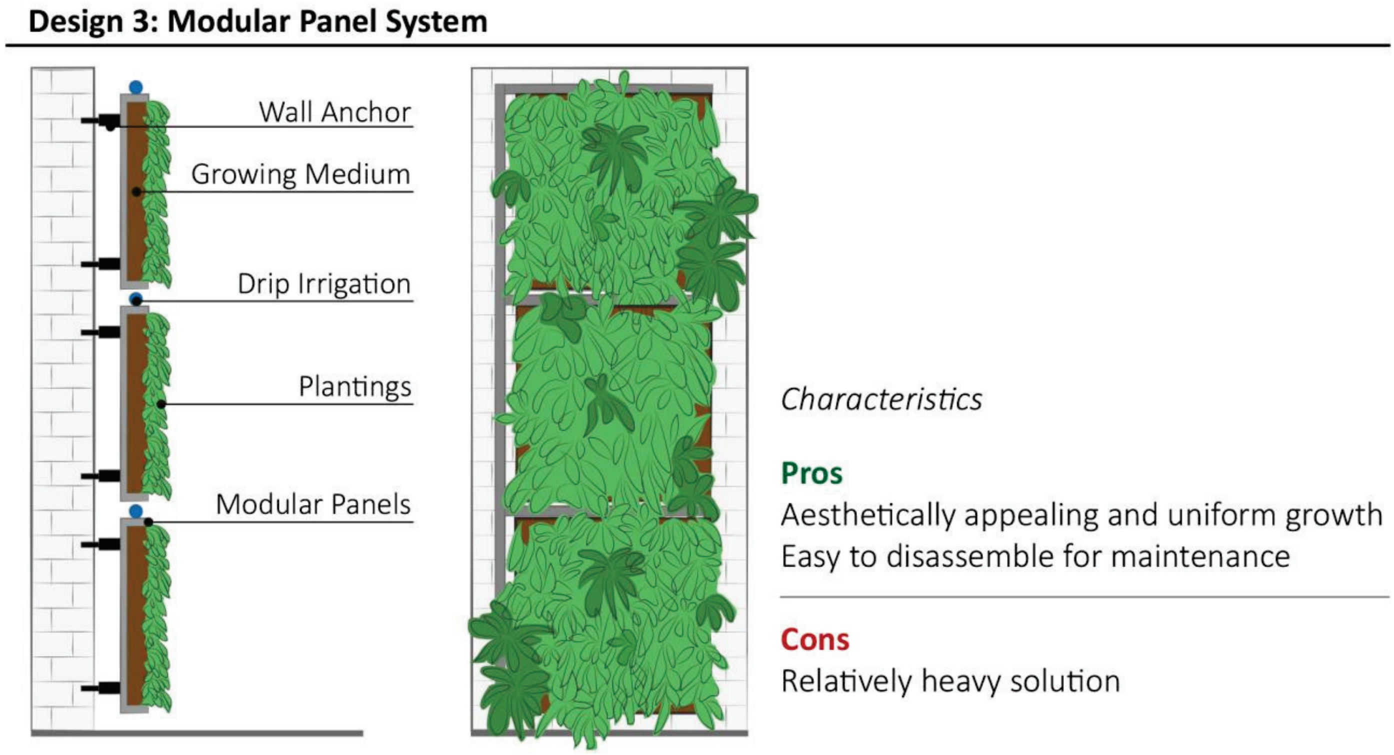

Figure 5. Schematic structure of Modular Panel System with the most relevant characteristics highlighted by stakeholders during interviews.

The waterproof insulation of VGS panels is mandatory to preserve the integrity of building façades from moisture [49]. Modular panel systems are designed to be anchored to the building through a support frame creating a void space between the panel and the surface, providing a better thermal performance than other VGSs [50] and enhanced noise insulation [51]. Due to the versatile structure, Design model 3 is suitable for rapid coverage of whole or part of large building surfaces [35]. This design system supports a wider group of evergreen plants, such as *Cholorophytum comosum*, *Sedum* spp., *Spathiphyllum wallisii*, *Epipremnum aureum* and other perennial or annual species for indoor and outdoor applications. Pre-vegetated systems ensure a high aesthetic result after installation, but maintenance is the key factor to preserve high ornamental appeal.

3.4. Design Model 4: Textile Bag System

Design model 4 is constructed from a textile material, such as felt, geotextile, burlap, tarpaulin, or any other cloth strong enough to withstand water and weathering as well as the weight of the system itself (Figure 6). Plants and growing medium, such as soil, coconut fiber substrates, felt, expanded clay pellets, sphagnum or mineral wool, are usually contained within textile pockets. The fertigation system is selected based on the growing medium: wicking or subirrigation systems are more appropriate for felt or inorganic substrates, while surface drip irrigation or manual watering is suitable for soil-based systems. Excess irrigation water is drained from the system by cutting holes near the base of each pocket such as to provide optimal conditions for the plant species used. The main advantage of this VGS model is the lightweight nature of the structure, due to the extensive use of textiles, and the flexibility of application on sloped building surfaces. This VGS model may be used for large-scale projects or small-scale applications, such as domestic aromatic gardens, due to its modular structure. The main disadvantage of this VGS model is the lack of space for plant roots provided by the pockets. These pockets can contain plants such as small vegetables and aromatic herbs, rooted directly to the growing media or using the "root-wrapping system", whereby roots are wrapped into a felt textile lightening the structure's weight. Moreover, the modular pocket framework simplifies the replacement of plants during maintenance interventions.

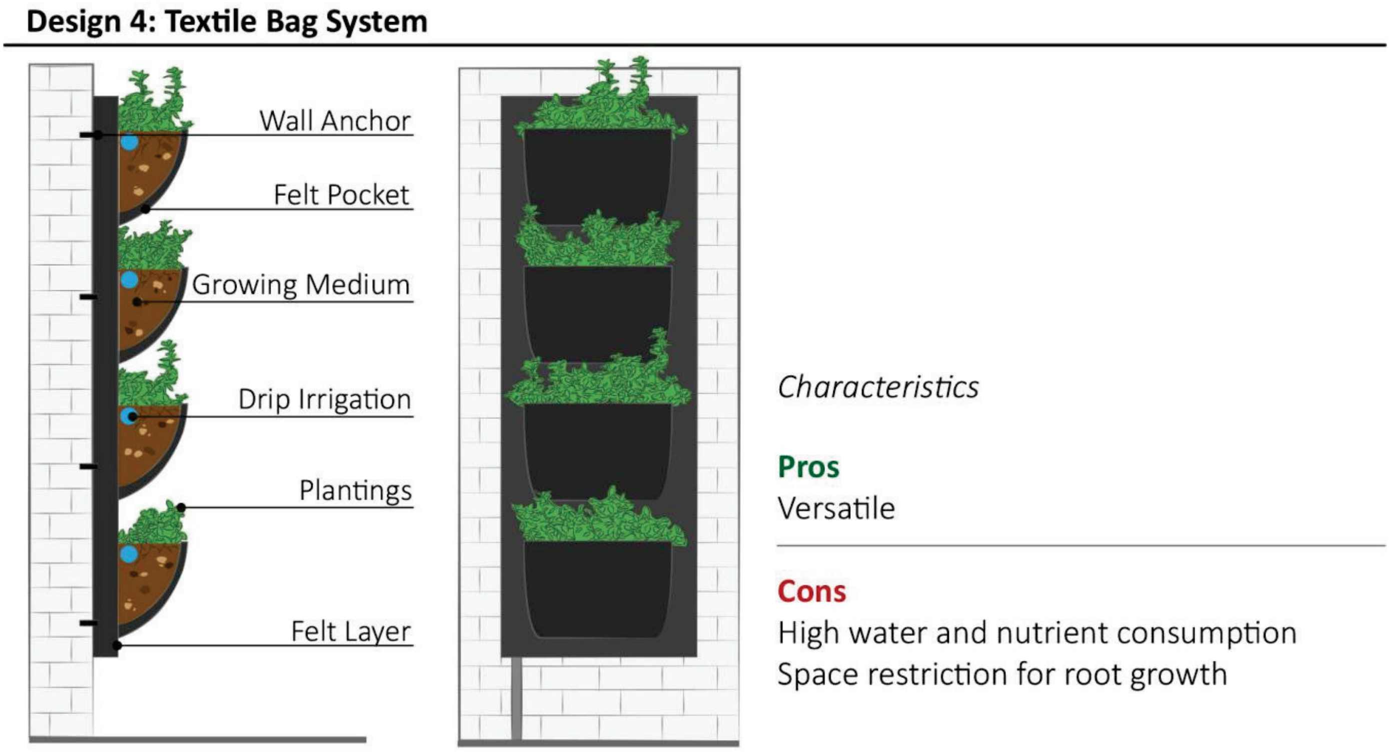

Figure 6. Schematic structure of Textile Bag System with the summary of most relevant characteristics highlighted by community representatives during interviews.

3.5. Design Model 5: Planter/Pot System

Design model 5 consists of a modular VGS which utilises planter boxes or pots attached to a support structure. Components of this design model vary in shape, material, and structure. This VGS system is characterised by its use of relatively simple and common materials and components, adopted for multiple creative applications in indoor and outdoor environments (Figure 7). This design model is versatile and DIY systems are commonly created by upcycling materials such as plastic drink bottles [48] Depending on the structure and form of growing container, a large variety of shrub plants, aromatic herbs and edible plants can be cultivated in this model of VGS, while simultaneously providing high aesthetic value. Soil substrates are commonly used, but also light-weight substrates, such as coconut fibers, expanded clay pellets or sphagnum, can be added to reduce the whole system's weight and to increase water drainage. Hand watering is recommended for small scale VGS of this design, while automatic or semi-automatic piped irrigation network is required for medium-large scale planter box systems. Depending on the structure of the VGS, a drip line irrigation network placed along the top of row is suitable for systems with planter boxes placed close to one other. Excess water can drain from each container by cutting holes at the base of planter boxes, while additional planter boxes can be placed at the base of the VGS to collect excessive water flow.

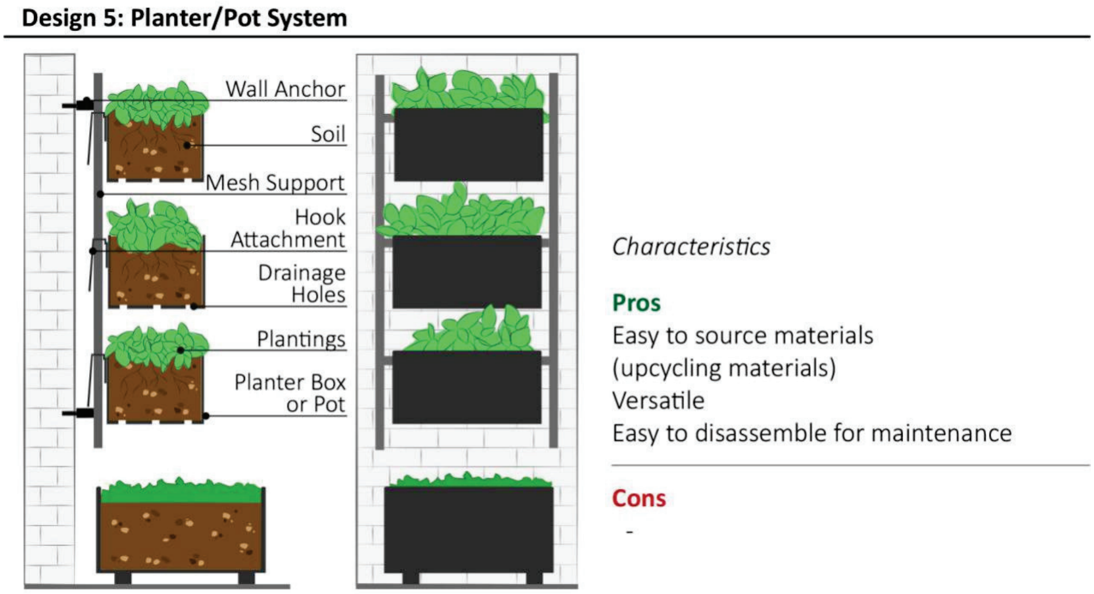

Figure 7. Schematic structure of Planter/Pot System with the summary of most relevant characteristics highlighted by community representatives during interviews.3.6. Design model 6: Guttering System.

Design model 6 uses materials such as discarded rain gutters as vessels for growing plants, following the design proposed by Houz [52] This system is a creative DIY solution, and potentially the most cost effective VGS, which aims to improve sustainability by upcycling durable materials. A drip irrigation network can be installed along the top surface of the substrate, while excess water can easily flow downwards using gravity if gutters are placed on a slight angle. Otherwise, holes at the bottom of gutters can be cut for water drainage (Figure 8). The main disadvantage of this system is the limited depth and volume of growth substrate, thus limiting plant selection to those with shallow roots, such as succulents, strawberries and some ornamental plants. The aesthetic appeal of this system mainly depends by the creativity and ability of its makers in restoring old materials.

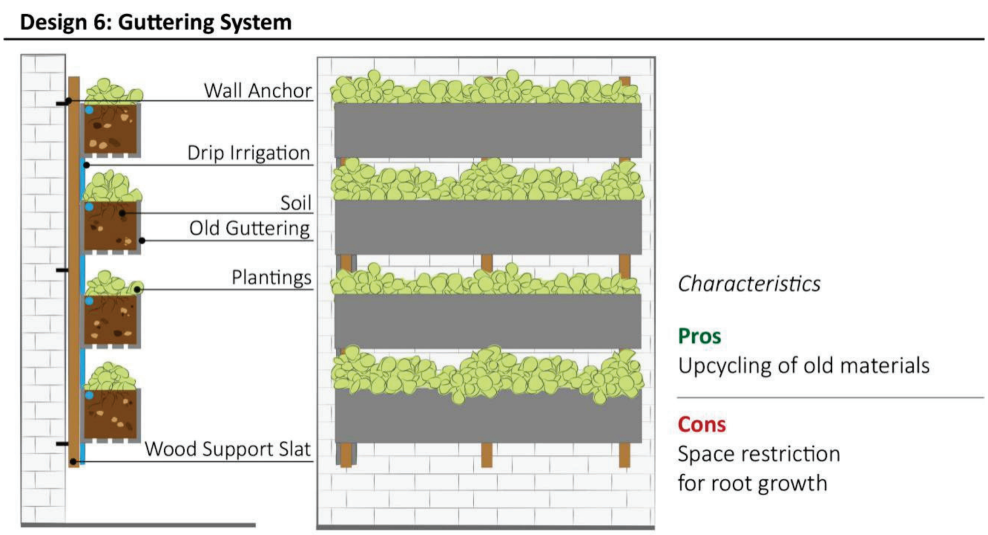

Figure 8. Schematic structure of Guttering System with the summary of most relevant characteristics highlighted by community representatives during interviews.

3.6. Design Model 7: Piping System

Design model 7 uses old PVC pipes as the key structural component of the system, which can be directly attached to the wall through masonry screws and pipe saddle clips (Figure 9). Different pipe sections can be connected to each other through piping and plumbing fitting to obtain creative structures adapted to user needs. Pipes filled with a cultivation substrate (soil or other light-weight substrates) are used as vessels to hold the plant roots. Alternatively, planter pots—large enough for houseplants—may be placed into the piping cut outs, thus confining the cultivation substrate. Additionally, this method allows for easy cleaning and maintenance, as pots can be pulled out and replaced when needed. Depending on the size of the pots and pipes, this solution can be useful to increase the depth of the growing medium as pots can slightly extend past the piping edge. Edible plants, such as small vegetables, are commonly cultivated in piping systems. The linear structure allows an integrated drip irrigation system to be installed along each level. It is also recommended to drill drainage holes along the base of the horizontal pipes for excess water to seep through.

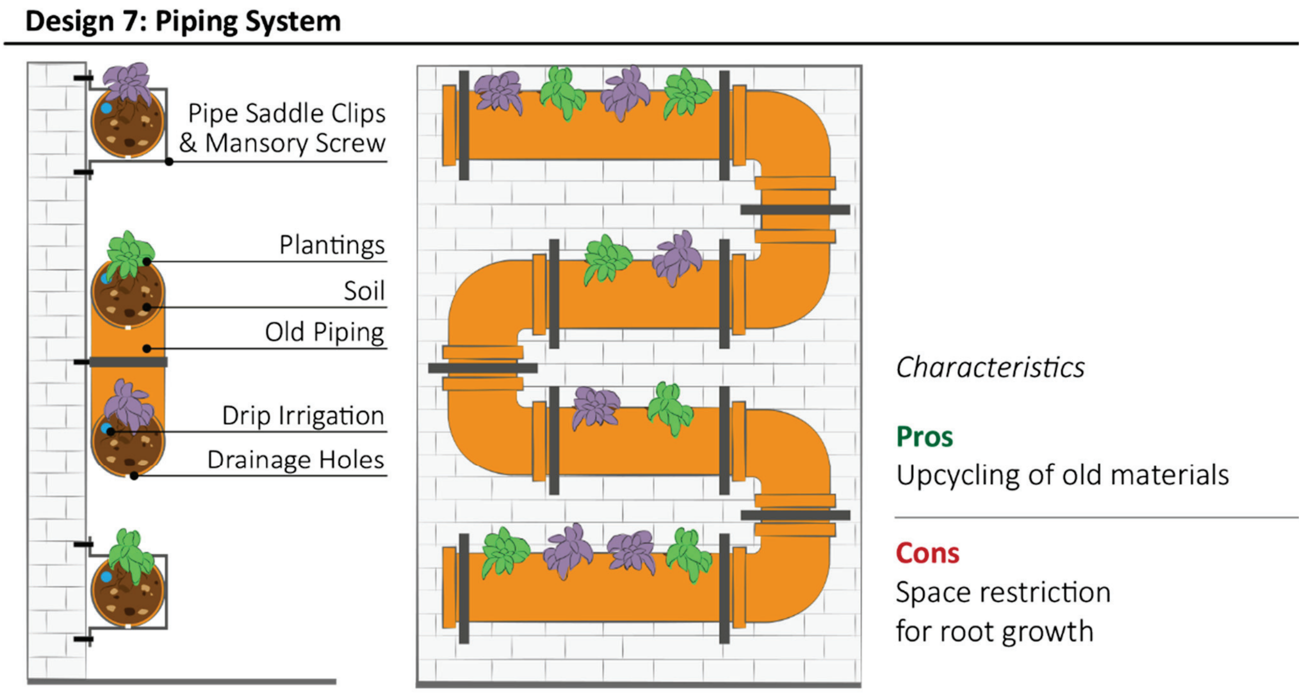

Figure 9. Schematic structure of Piping System with the summary of most relevant characteristics highlighted by community representatives during interviews.

3.7. Design Model 8: Freestanding Wood-Based System

This system is structured using stacked wooden crates to enable vertical greening (Figure 10). Old wooden crates can be upcycled to hold growing media and plantings [53]. They are usually stacked and fixed together, using longer wooden planks as a support structure, allowing the unit to be freestanding. The structural dimensioning and a rough calculation of the system's weight are essential to prevent overloading and collapse. The application of an external wood treatment, such as an oil-based finish, is necessary to avoid aesthetic and structural damage. Appropriate drainage systems and the use of porous and lightweight growing medium increase the wood's durability and longevity. Moreover, the use of geotextile fabric to contain the growth medium and allow air and water to flow to through it may reduce the risk of moisture accumulation. Drip irrigation systems can be integrated into the vertical structure for regular watering. This model of VGS broadens the selection of plant species thanks to the growing medium volume provided by the wood crates.

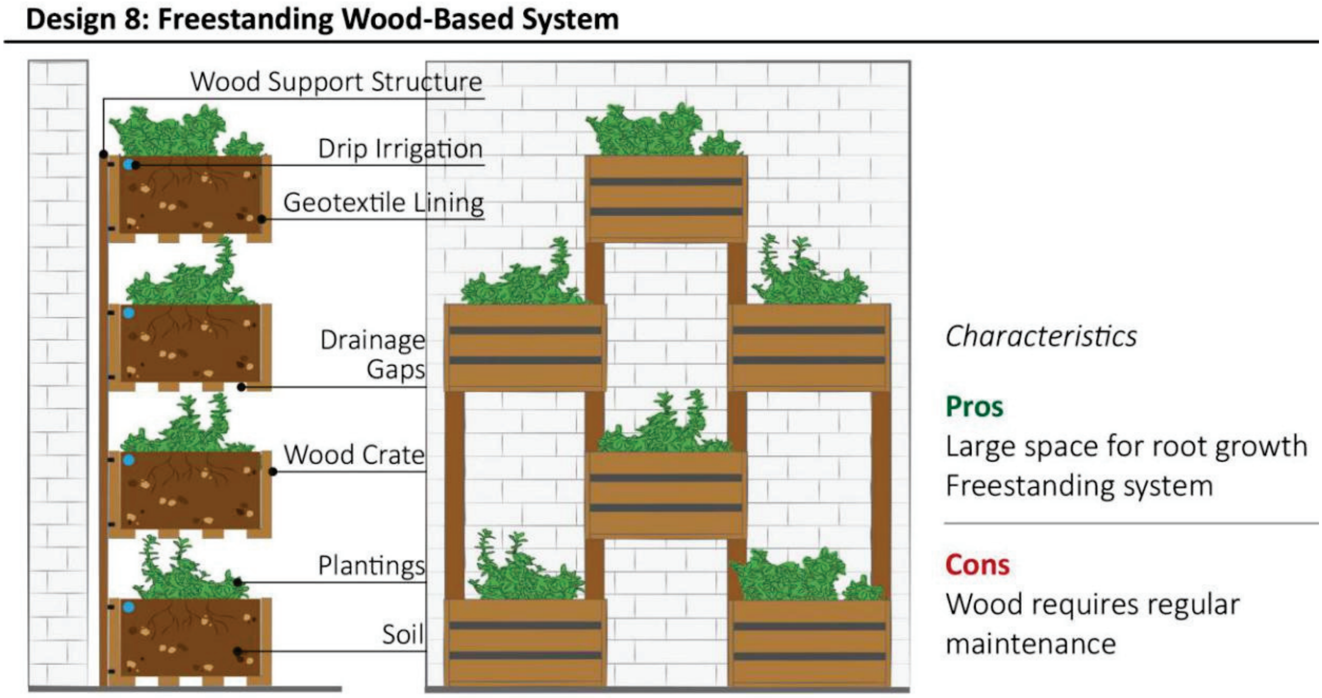

Figure 10. Schematic structure of Freestanding Wood-based System with the summary of most relevant characteristics highlighted by community representatives during interviews.

3.8. Comparison between VGS Design Models

The summary of eight VGS design models' characteristics is presented in Table 3. Comparing the above eight designs demonstrates the relative suitability and achievability each design has for a given application. Indications were obtained by integrating interview results and the analysis of scientific and grey literature.

Table 3. Schematic description of VGS design models based on selected six criteria.

	Structure, Materials & Components	Irrigation and Drainage Systems	Vegetation	Indoor/Outdoor Application	Maintenance	Aesthetic Value
Design 1	None	Manual	Self-clinging climber plants	Outdoor	Routine: pruning to stimulate or avoid excessive growth	Low: non-homogenous surface coverage
Design 2	Vertical support structure (trellis, mesh, nets, wires or cables) in bamboo, wood, steel, aluminium or HDPE Wall anchors Planter box	Manual or automated and integrated into the planter box	Climbing plants	Outdoor	Routine: pruning to stimulate or avoid excessive growth Check the status of vertical support	Low
Design 3	Panel in HDPE, polystyrene, or wood Waterproof screen (PVC) to preserve surface building Growing medium: inorganic light-weight substrate (e.g., mineral wool, felt or perlite) or organic (soil) Wall anchors Wall support structure (steel rod or trellis)	Hydroponic system: Ferti-irrigation system using drip, sprinkler, or wicking irrigation systems Automated and integrated into the panel Drainage system to collect excessive water	High variety of evergreen and ornamental plant species	Outdoor & Indoor	Watering and fertilization Replacing plants Clearing fallen debris Cleaning ferti-irrigation system Check the status of panels and waterproof screen	High: large and flexible vegetation surface coverage
Design 4	Textile bag system in felt, geotextile, old burlap, tarpaulin Waterproof screen (PVC) to preserve surface building Growing medium: inorganic light-weight substrate (e.g., felt substrate, expanded clay pellets, sphagnum or mineral wool) or organic (soil or coconut fibre) Geotextile to contain growing medium Wall anchors Wall support structure (steel rod or trellis)	Manual or surface drip irrigation for organic substrates Wicking or integrated ferti-irrigation system for inorganic substrates Drainage system: holes at the base of each pocket	Small vegetables Aromatic herbs Ornamental plants	Outdoor & indoor (indicated for domestic-scale aromatic gardens)	Watering and fertilization Replacing plants (facilitated by pocket-based system) Cleaning ferti-irrigation system Check the status of textile material and of waterproof screen	Medium: depends mainly by the quality of textile bag system

Table 3. *Cont.*

	Structure, Materials & Components	Irrigation and Drainage Systems	Vegetation	Indoor/Outdoor Application	Maintenance	Aesthetic Value
Design 5	Pots, planter boxes, plastic bottles Growing medium: soil mixed with coconut fibre, expanded clay pellets and sphagnum Hook attachments Wall anchors Wall mesh support structure (steel rod or trellis)	Manual watering for small-scale systems Automated ferti-irrigation for large-scale system (dripline irrigation network) Drainage system: holes at the base of each planter box	Wide range of plants cultivated (ornamental, herbs and edible) depending by the planter box's size	Outdoor & indoor	Routine: pruning, watering and checking the status of irrigation system	High vegetation coverage Creative solutions
Design 6	Rain guttering Growing medium: soil Wall anchors Wall mesh support structure (steel rod or trellis)	Manual watering Surface automated drip irrigation network	Plants with shallow roots, such as succulents or some ornamental plants	Mainly outdoor application	Routine: pruning, watering and checking the status of irrigation system	Creative solution
Design 7	Old pipes Pots (optional) Growing medium: soil Wall anchors	Automated and integrated drip irrigation network (also sprinkler)	Edible plants: small vegetables and herbs Ornamental plants	Mainly outdoor application	Routine: pruning, watering and checking the status of irrigation system	Creative solution
Design 8	Wooden crates Vertical support structure of wooden planks (for self-sustaining system) Growing medium: soil mixed with coconut fibre, expanded clay pellets and sphagnum	Manual Automated and integrated drip irrigation network	Wide range of plant species cultivated	Outdoor & Indoor (indicated for dividing spaces and preserving social distance)	Routine: pruning, watering and checking the status of irrigation system Occasionally: checking the status of wood components	Creative and flexible solution

The star rating system is presented in Figure 11, comparing five essential design parameters of the eight VGS models, based on the engagement with the stakeholders of community garden groups interviewed and informed by their direct experience in designing, constructing and maintaining systems. Qualitative ranking was adopted to account for the stakeholders' assertions and to provide an insight into local and specific community gardeners' attitudes and challenges. Final scores concerning cost effective criteria shown in Figure 11 are not the results of the analysis of quantitative data collection because each community garden presents unique characteristics (such as dimensions and site) and strategies (e.g., using new or recycled materials) for implementing VGSs. Scores for each criterion are defined based on the specific experience of the seven case studies involved in the current research and they may change as the community members and locations differ due to the bottom-up attitude of community gardens and of Do-It-Yourself practice. The star rating system aims to provide an initial and non-site-specific assessment tool to guide communities into their first stages of the decision making process. Green façade designs obtained the highest scores, while more complex systems such as Modular Panels and Textile bag designs scored comparatively lower.

Figure 11. Star-based rating system that compares the VGS designs using community or domestic scale relevant criteria.

4. Discussion

4.1. A VGS Design Model for Any Requirement

Whilst we have categorised VGSs into eight design models, each design can be modified or customised according to the specific requirements and motivation of each VGS project.

With the exception of Design models 3 and 4, the interview feedback deemed to require specific skills, technical knowledge, tools and materials, the other VGSs were deemed to be generally highly DIY friendly. According to the community group interviewees, Design model 1 and 2 are the simplest VGSs to implement, using relatively lightweight materials, which are easy to source. However, the aesthetic value of these systems is dependent on the vegetation used [54], as some species may take longer to grow and spread than others. Due to the limited number of system components, direct and indirect green façades are easily integrated with building surfaces [55]. According to the community group interviewees, Design model 5 includes a wide range of creative solutions that can be easily integrated in different contexts due to its structural modularity and versatility. Design models 6, 7 and 8 are highly DIY friendly, but the freestanding model requires specific technical skills during assembly to ensure structural stability, while the other VGSs are anchored to the building's indoor or outdoor surface. Despite this, a key advantage of freestanding VGS is the boxed system allowing for a larger volume of soil to be used compared to the planter boxes, piping and guttering systems [56]. Another important positive feature of Design model 8 concerns the easy integration into indoor and outdoor spaces, because it does not require a supporting building wall, providing it with an alternative use as a vegetated screen.

Due to their simplicity in design and lack of structural requirements, green façades (Design models 1 and 2) were determined by community garden representatives to be the most cost-effective solutions. These systems were also relatively easy to maintain compared to living walls. On the other hand, Design model 3, which has greater perceived ornamental value by the community garden representatives, is the most expensive VGS solution due to its structural complexity. These VGSs are commonly supplied by companies expert in vertical greening and urban landscaping which also provide supervision for the installation [57]. The cost of this type of vegetated system will differ depending on factors including the supplier and manufacturer, installation requirements and the size of the system. Thus, Design model 3 is less budget or DIY friendly than the other systems tested here, and for this reason modular vegetated panels are usually adopted by end users able to support their higher initial costs. Design model 5 is a relatively cost-effective solution especially if planter pots are obtained by upcycling waste materials, such as plastic bottles and containers.

Considering that no VGS is completely maintenance free, Design models 3 and 5 are the easiest systems to maintain according to interview respondents, due to their modular structure that facilitates the replacement of components when required. Nonetheless, structural maintenance on commercial modular panel systems is commonly carried out by specialized experts (Design model 3). Direct and indirect green façades (Design models 1 and 2) require only basic maintenance, such as ongoing pruning and general plant care due to the type of climbing vegetation used. Other VGS design models present similar maintenance requirements, while the use of textile materials for Design model 4 may hinder the replacement of damaged parts and complicate routine maintenance to a degree.

The automated irrigation and drainage systems are the most critical components for VGSs, excluding direct and indirect green façades that are most commonly manually watered. Community group stakeholders' comments indicated that Design model 4 requires a more complex drainage and irrigation system than other VGSs due to the textile material and pocket structure. Moreover, Design models 3 and 4 are commonly set up as hydroponic systems that require a fertigation system for supplying nutrients to their inorganic plant growth substrates. Some form of drainage system is an essential component for all types of VGS to preserve the system's structure and vegetation health. Regardless of the type of irrigation and drainage systems used, all wooden surfaces and structural components should be treated with waterproof finish to increase product life. Moreover, all VGSs that are located in indoor environments require a reliable drainage system with a tank for excess water collection [58]. This aspect is particularly important for freestanding VGSs as they are commonly placed in indoor spaces where water leakage may present a serious safety hazard or risk to property damage.

4.2. Implementing DIY Vertical Greening with Communities in Real Setting

In order to support stakeholder co-design or participatory design practice, some preliminary evaluations should be considered regarding the motivation for wanting a vertical greening system, features of the selected site and the skills, time commitment and abilities of the community before choosing the most appropriate VGS [59]. The pivotal aspect for the successful implementation of a VGS will be accurate identification of available resources, skills and goals, which will be different for each installation also for each location and the different kind of people involved linked to their motivation.A co-design strategy should be applied with the purpose of: (1) sharing the motivation framework and knowledge concerning VGS amongst the stakeholder community members; (2) identifying barriers that could create a gap between the ideal project goal and practical implementation; (3) identifying resources and strategies to address this gap. Focus groups and dedicated workshops could be organized in order to facilitate the identification of the main drivers for co-designing the most affordable VGS according to community motivation and goals [60]. The definition of community motivation is the first important step to establish which type of VGS is the most appropriate for a given community's purpose. It is important for communities to identify what their needs, requirements and limitations are before starting to design a VGS. All communities are different; therefore the choice of design should capture the wide range of different levels of DIY ability, budget, time availability and resources. VGSs models can be customized based on the technical abilities of community members and the available budget to implement the project. The evaluation of community resources is particularly important for selecting appropriate cost-effective solutions for vertical greening, such as choosing to buy new products that include the provision of expert advice or the use of recycled materials. Moreover, it is also necessary to consider the time and commitment that the community's members can allocate to daily maintenance.

It is the authors' perspective that site selection should take into account the community's needs, limitations and how VGS specific design aspects will interact with the site before deciding the most appropriate VGS. The site location and orientation to sunlight, climate conditions for outdoor VGSs, the suitability of an existing wall structure for green wall retrofit, water provision, local regulations and the need for professional advice should be analysed before designing a VGS [61]. These design drivers can guide and facilitate the design of successful vertical greening solution. Elements of different systems can be combined to optimize the design and satisfy the community's needs, whilst complying with the site's limitations. There is not a 'one size fits all' approach for developing, designing and maintaining all types of vertical greening solutions [27].

4.3. Comparison between Commercial VGS and DIY Design Models

This work has showcased eight design models of VGSs capable of being installed by those without expertise in the field, however the degree of complexity in design and maintenance requirements is dependent on the design type. Some VGSs do not require any specific abilities, such as Design models 1 and 2, while others are reliant on specific materials and technical skills to construct them. Several commercial companies offer ready-to-use solutions and materials for simple design models which can facilitate DIY VGS installations. For example, multistory commercial systems may now offer wire trellis systems specifically designed to implement indirect green façades to cover wide building surfaces [62]. Nevertheless, support structures for small-scale or domestic VGSs can be easily constructed by recycling or upcycling disposed materials, such as sticks, nets and ropes.

The feedback from stakeholders identified Design model 3 as the most complex and challenging VGS to construct using DIY practice. It is thus unsurprising that several companies sell system components for this Design model type, which can help to bridge the gap between expert and inexpert VGS installers. Numerous commercial products of this design are available, with providers frequently offering assistance with the system installation [63], while other companies, offer DIY vertical garden kits provided with inorganic cultivation substrates and planter panel or boxes with holes in which to place plants for indoor applications. Construction challenges also apply to Design model 4, because it requires specific sewing skills.

Design model 5 is the most versatile and creative VGS, as a wide range of products can be used as planter boxes. Nonetheless, some companies, offer commercial products based on modular planter box structure, and support clients during the installation process. Available commercial products are likely to be more durable and stable, and they are recommended in contexts that require high surface coverage. However, more creative solutions are suggested to increase public engagement in the design and installation processes and to improve sustainability through upcycling materials.

Community garden groups most commonly prefer Design models 6, 7 and 8 which are DIY friendly and low-cost to implement and maintain. They are composed of recycled and upcycled materials, reflecting community gardens values on sustainability.

5. Conclusions and Future Directions

The findings from this study contribute to reducing the lack of DIY technical information related to VGS design choice and installation and indicate critical considerations that can arise during VGS implementation in small-scale urban spaces. The UN SD Goal 11 encourages the growing trend and common interest in urban vertical greening that should be supported by appropriate knowledge for beginners.

The involvement of stakeholders with expertise in community garden activities through informal interviews enabled the collection and organisation of information useful for DIY applications. In order to make VGSs as DIY urban interventions more accessible, stakeholder experience was used to define a user-friendly interpretation of vertical greening technology that has, in most cases, previously been described within a scientific and academic mindset. Knowledge dissemination about the importance of VGSs as green infrastructure and about their construction plays a pivotal role for community engagement in making more vertical greening and in promoting the participatory transition towards more sustainable and green cities.

Future work is required, and should focus on real world in situ examples, in order to provide concrete evidence and truly quantify the outcomes of this work in specific contexts. Given the great variability of building types and settlement systems where VGSs can be implemented, it is recommended that the applications of this technology, and the quantification of its success, be determined in as many specific building-districts as possible, so that the current evaluation model can provide more comprehensive information through revision [64].

Additionally, it is suggest that future work investigate if the methods used in this study be used to support cities with food through urban agriculture, and how much food could produce, as there is a here is a growing interest in making such systems dual purpose for food production. Such usage presents challenges related to the fate of air pollutants within urban environments, and whether this will affect the quality of food so produced. Significant further research will be required before these new systems can be used with confidence for food production. Similarly, research that enables the comparison of a food supply cultivation and the energy and water requirements can also be explored (Water-Energy and Food nexus).

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