

Article

Developing Sustainability Problem-Solving Skills Through Internet of Things Projects

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Abstract

This article explores the potential of an integrated pedagogical approach that combines project-based learning (PBL) with Internet of Things (IoT) technologies to achieve the United Nations' Sustainable Development Goals (SDGs). Within the context of Education for Sustainable Development (ESD), this model transforms students from passive consumers of information into active agents of change. The study demonstrates that leveraging IoT sensors enables students to tackle pressing and complex sustainability challenges by engaging them in a comprehensive problem-solving cycle—from collecting real-world data to developing innovative solutions. By analysing the existing scientific literature, the approach is shown to significantly improve critical thinking skills, systems thinking, creativity, and teamwork. The study also proposes a new conceptual framework (hypothesis), the *EcoHabits* model, whose effectiveness remains to be empirically validated. This model demonstrates IoT's potential to enhance sustainability competencies, improve health literacy, and promote individual and collective behaviour change. Despite its significant pedagogical benefits, the article identifies key implementation challenges, including the need for adequate teacher training and community collaboration. In conclusion, this innovative framework offers a promising solution for preparing future generations to address global issues and become active, responsible citizens of the 21st century.

Keywords: education for sustainable development; project-based learning; PBL; Internet of Things; IoT; Sustainable Development Goals; SDGs; critical thinking; systems thinking



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1. Introduction

The global landscape is currently defined by complex, interconnected challenges—such as climate change, resource scarcity, and social inequality—necessitating a fundamental reassessment of the role of education. Effectively addressing these crises requires a shift from traditional knowledge acquisition to the development of higher-order skills, specifically critical thinking and complex problem-solving in the next generation [1,2]. Against this background, education is established as a central tool for implementing this change, designed to cultivate students' ability to analyse and act purposefully on sustainable development challenges [3].

In response to this need, the Education for Sustainable Development (ESD) paradigm was established. ESD aims not only to promote awareness but also to equip individuals with the competence to make informed decisions and take responsible actions to balance

environmental, economic, and social goals [2]. Achieving these outcomes requires a pedagogical paradigm shift, moving beyond traditional didactics, which are often inadequate for developing higher-order skills. Engaging students with real and meaningful problems is key to overcoming rote learning [4].

The Internet of Things (IoT) technology offers a promising solution in this direction by facilitating research-oriented approaches. Utilising sensor networks grants students direct access to empirical data from their surrounding environment. This active collection, analysis, and interpretation of information in real-time not only stimulates critical thinking but also serves as a bridge between theoretical constructs and their practical, measurable manifestations [5]. Integrating IoT into the educational process offers significant potential for personalised learning. By using sensor technologies and real-time data analysis, IoT enables students to become citizen scientists. This allows them to identify and analyse local sustainability issues—such as classroom air quality or school garden water usage—and develop solutions based on empirical evidence [4].

This research-oriented method is the foundation of Project-Based Learning (PBL), which promotes critical thinking, systems thinking, creativity, and teamwork. All these competencies are key to addressing complex challenges [6]. The present study theoretically examines how the problem-solving cycle—comprising definition, data collection, analysis, and solution generation, all facilitated by IoT—serves as a powerful tool to foster critical thinking and problem-solving abilities in students. This approach prepares them to become active and informed participants in achieving sustainable development. Despite its clear potential, integrating IoT into the education sector faces significant hurdles. Key obstacles include technical integration difficulties, resource constraints, and the complexity of processing large volumes of heterogeneous data in real-time.

Furthermore, serious concerns arise regarding data security and confidentiality. Another critical issue is the lack of interoperability between multiple devices, platforms, and standards, which hinders the full implementation of IoT-based systems for personalised learning [7]. These challenges must be addressed to fully realise the IoT's potential to achieve a high degree of personalisation in education.

The main objective of this theoretical study is to analyse and justify how IoT-based projects focused on sustainable development can serve as an effective pedagogical tool for developing problem-solving skills in students. To achieve this, the study systematises and synthesises the existing scientific literature across three key areas: ESD, PBL, and the application of IoT technologies in a learning environment. The aim is to elucidate the specific mechanisms by which working with authentic data collected by IoT sensors facilitates the cognitive processes required for critical analysis and the creative generation of solutions [1,5].

This study addresses a significant gap in the scientific literature, as existing theoretical frameworks do not directly link the use of IoT to the development of complex problem-solving skills within the context of sustainable development, despite growing interest in technology-enabled learning [4]. While much research views IoT primarily as a technical tool for STEM education, few have analysed its role as a pedagogical catalyst that transforms students from passive consumers of information into active participants and initiators of change [6]. The findings of this study offer significant benefits to several key stakeholders. Firstly, they provide educators with a clear theoretical foundation and practical guidelines for integrating IoT projects into curricula, thus enriching their methodological toolkit. Secondly, for education policymakers, the study serves as a basis for evidence on the need for investments in technology and teacher professional development aimed at building 21st-century skills. Ultimately, the most significant contribution is to the students themselves, enabling them to acquire not just knowledge about sustainability, but also practical skills to

solve real-world problems. This approach prepares them not only for academic success but also for active civic participation in building a more sustainable and just future.

The primary contribution of this paper is conceptual, rather than empirical. This work combines a systematic synthesis of existing literature with an analysis of practical case studies to propose a new theoretical framework, the *EcoHabits* model, which serves as a hypothesis for future empirical validation rather than a final, tested outcome.

The remainder of this paper is structured as follows: Section 2 provides an overview of the literature on the three key areas (ESD, PBL, and IoT). Section 3 outlines the Mixed-Methods Design and the Systematic Literature Review procedure. Section 4 presents the Results, synthesising the key findings regarding pedagogical benefits, along with the different case study analyses. It then introduces the *EcoHabits* conceptual model as the study's main theoretical contribution. Section 5 presents a critical discussion of the pedagogical challenges and addresses the study's Limitations and Future Research Directions. Finally, Section 6 provides the main Conclusions of this work.

2. Literature Review

2.1. ESD and Problem-Solving in the Context of Global Challenges

The modern era is characterised by numerous complex and interconnected global challenges that threaten the ecological, social, and economic stability of the planet [1,2]. This growing crisis encompasses problems such as climate change—primarily caused by human activities and leading to extreme weather events and rising sea levels—the depletion of natural resources, biodiversity loss, and growing social inequality between economic classes and countries. This complex network of problems necessitates a holistic approach to resolution [1].

Addressing these challenges requires not only technological and political measures, but also a profound transformation in public thinking and behaviour. In response to urgent global challenges, the United Nations (UN) adopted the 2030 Agenda for Sustainable Development in 2015. This agenda outlines 17 Sustainable Development Goals (SDGs), serving as a universal roadmap for achieving a better, more sustainable future for all [8]. These goals encompass a broad range of areas, including eradicating poverty (SDG 1), ensuring quality education (SDG 4), and addressing climate change (SDG 13). The achievement of the SDGs depends on the collective efforts of governments, organisations, and, most importantly, individual citizens [3].

Unlike previous initiatives, the SDGs are not aimed solely at developing countries; instead, they call on all nations to make collective and coordinated efforts to address global challenges [8]. Achieving the SDGs requires not only institutional transformation, but also the active engagement of society and individuals, placing education at the centre [3,9]. In this context, education plays a crucial role, serving as a key tool for raising awareness and developing the necessary skills to achieve these ambitious goals [2].

It is in this context that ESD is positioned as a key tool for achieving these goals. ESD seeks to integrate sustainability principles into all aspects of the learning process, promoting not only knowledge but also the critical thinking, values, and behaviours necessary for building a sustainable future [9]. To be effective, ESD must go beyond traditional approaches, providing students with opportunities to actively participate in solving real-world problems. Therefore, pedagogical innovations that support learning through authentic experiences are crucial for preparing young people to navigate the complex challenges of the new era [4,6].

ESD is a fundamental pedagogical approach aimed at transforming society. Unlike traditional environmental education, which focuses primarily on ecological knowledge, ESD is a holistic and transformative process. It integrates the social, economic, and environ-

mental aspects of sustainability into the curriculum and school environment [9–11]. The principles of ESD are explicitly enshrined in SDG 4: Quality Education [8], making it a key tool for achieving all other goals—from poverty reduction to climate action [2].

The main goal of ESD is to enable students to become informed and active citizens, capable of making informed decisions and taking actions that contribute to sustainability both locally and globally [11]. This requires not only understanding the complex causal relationships between human activity and the environment, but also developing key competencies such as systems thinking, the ability to collaborate, and problem-solving skills. Through ESD, schools are transformed into laboratories for sustainability, where students can experiment with solutions to real-world problems [12].

Effective ESD requires a significant departure from traditional didactic approaches. Instead of passive absorption of information, it promotes interactive, engaging learning closely related to the real world. Concepts such as PBL and experiential learning are at the heart of ESD, as they allow students to work on authentic problems, collect data, analyse situations, and develop and implement their own solutions [4,13]. In this way, ESD does not simply teach about sustainability, but makes it an integral part of the daily learning process, encouraging reflection and collective responsibility [14]. This approach is crucial for building future generations who not only understand the challenges but also possess the necessary skills and motivation to overcome them.

The concept of ESD is a holistic and transformative approach to education, with the primary goal of equipping students with the knowledge, skills, values, and attitudes necessary to address the complex challenges of the present and the future [11]. As an essential element of the UN Global 2030 Agenda, ESD is seen as a key catalyst for achieving all 17 SDGs [8].

ESD focuses on integrating the social, economic, and environmental dimensions of sustainability into all aspects of education. It is not a separate subject, but an interdisciplinary approach that permeates the entire curriculum, encompassing science, history, the arts, and mathematics. This holistic perspective aims to show students that global problems are interconnected and that solutions to one often have consequences for others [15]. For example, addressing climate change is directly linked to economic practices, social equity, and resource consumption. One of the key goals of ESD is to develop systems thinking in students. Rather than viewing problems in isolation, they learn to see them as elements of larger, dynamic systems. This approach allows them to identify complex relationships between different factors—for instance, how consumption habits (an economic factor) lead to increased waste (an environmental factor) and how this, in turn, affects community health (a social aspect). Systems thinking is essential for understanding complex problems and developing solutions that do not create new challenges [16].

ESD is also closely linked to the development of critical thinking. In an age of information overload and fake news, students need to be able to analyse and evaluate the credibility of information, especially when it comes to sensitive topics such as climate change or poverty. ESD encourages them to question established models and assumptions, consider different perspectives, and form their own well-argued positions. This ability to critically analyse helps them navigate complex debates and make informed choices [17].

In addition to cognitive skills, ESD places a strong emphasis on developing teamwork and collaboration. Since global challenges require collective action, ESD projects often focus on solving real-world problems in the community. This necessitates students working together, communicating effectively, compromising, and integrating different ideas to achieve a common goal. This develops their emotional intelligence and social skills, which are critical for their successful participation in society [18].

An essential aspect of ESD is the required change in pedagogical approaches. To develop the necessary skills, it is critical to transition from traditional lecture-based teaching to active, learner-centred learning. Methods such as PBL and inquiry-based learning enable students to engage with authentic problems, making the learning process more meaningful and motivating. In this way, students not only learn sustainability theory but also apply it in practice, leading to a deeper understanding and appreciation of the concepts [19].

ESD, therefore, also transforms the role of the teacher. Instead of being a mere source of information, the teacher becomes a facilitator and mentor who guides students on their own journey of inquiry. They encourage curiosity, ask provocative questions, and create an environment in which students feel safe to experiment and make mistakes [20]. This shift is crucial in developing independent and self-thinking individuals who are capable of solving problems.

Despite its critical importance, ESD implementation faces numerous challenges within traditional education systems [21]. These challenges include:

- Curricular rigidity: Overloaded curricula leave insufficient space for the interdisciplinary and project-based approaches characteristic of ESD.
- Insufficient teacher training: Many educators lack the necessary knowledge and skills to effectively implement new pedagogical methods and facilitate complex sustainability projects.
- Over-reliance on standardised testing: Excessive emphasis on exams, which cannot adequately measure the development of systems and critical thinking, discourages teachers from adopting innovative approaches.

These challenges hinder ESD's full integration, necessitating a comprehensive reform of the education system that shifts the focus from knowledge transmission to the development of key skills. Nevertheless, ESD remains a fundamental concept for the current millennium. It prepares students to become active participants in solving global problems. By purposefully fostering critical and systems thinking, collaboration, and values, ESD positions the education system as an engine of social transformation, crucial for building a more sustainable and equitable future for all [9].

2.2. PBL as a Pedagogical Approach

The transition to a more effective model of education necessitates a fundamental transformation of pedagogical practices. Project-Based Learning (PBL) is an approach that stands out with high potential, creating conditions for students to engage with authentic problems and apply their knowledge in real-world contexts [19]. Furthermore, the integration of modern technologies (such as IoT), coupled with an emphasis on ESD, provides students with tools for data analysis, understanding cause-and-effect relationships, and collaborative solution development. These practices facilitate a transition from purely theoretical knowledge to practically oriented action.

In essence, PBL is an innovative and highly effective pedagogical approach that emphasises active, investigative learning [22]. Unlike traditional didactic models focused on the one-way transmission of knowledge, PBL places the student at the centre of the educational process, engaging them in the in-depth study of authentic and multi-layered real-world problems [23]. The primary goal of this approach is not only the acquisition of subject knowledge, but also the development of critical thinking, creativity, collaboration skills, and effective communication [12].

The guiding principle of PBL is the concept of learning by doing [24]. Instead of passively receiving a given problem, students actively participate in its resolution. This process typically begins with the formulation of a significant, open-ended question or challenge that requires them to conduct research, collect and analyse data, and develop

a specific product or solution [22]. PBL thereby encourages students to take personal responsibility for their learning, motivating them to search for information, collaborate with peers, and apply acquired knowledge in practical contexts.

A characteristic feature of PBL is its emphasis on an interdisciplinary approach. Real, authentic problems can rarely be addressed solely within a single subject. For example, a project tackling air pollution may require knowledge from physics (measurement through sensors), chemistry (analysis of air composition), biology (assessment of human health impacts), and civic education (development of environmental policies) [23]. Such integration enables students to make sense of the complexity and interconnectedness of sustainable development challenges, thereby stimulating the growth of systems thinking. Learning is transformed into a meaningful, lasting experience that prepares young people for future challenges [13].

The accumulated scientific literature provides convincing evidence that PBL is an effective tool for promoting problem-solving skills. Empirical studies have shown that students taught through PBL models achieve higher results compared to their peers who undergo traditional pedagogical practices. In the fields of science, mathematics, and engineering, numerous studies have demonstrated that PBL has a significant positive impact on the development of critical thinking and the ability to tackle complex problems [4,25–27].

One of the key contributions of PBL is its potential to develop analytical and logical reasoning skills. Working on projects based on loosely structured or open-ended problems compels students to go beyond ready-made solutions. In this process, they must identify the problem, collect and interpret information, and generate their own reasoned solutions—activities that form the basis of critical thinking [22,26,28].

PBL also contributes significantly to the development of systems thinking and creativity. Participation in complex, interdisciplinary projects enables students to recognise the interrelationships between different areas of knowledge and formulate innovative solutions that are difficult to achieve within isolated subject learning [26]. Available empirical data confirm that PBL stimulates the creative application of knowledge to address new and unforeseen challenges [25–27]. This is especially significant in the context of sustainable development, where unambiguous and universally applicable solutions are rare. Furthermore, PBL plays a key role in preparing students for real social and professional contexts, supporting the development of 21st-century skills.

Empirical research consistently shows that participation in project-based activities significantly improves competencies such as collaboration, communication, and leadership [12,29]. Working in teams on specific projects requires students to discuss ideas actively, reach consensus on decisions, and assign responsibilities—skills that are crucial for both their future professional development and their full participation in public life.

Although a significant portion of the available research emphasises the positive impact of PBL, several authors highlight that multiple factors contribute to its effectiveness. Among them, the quality of the project design, the support and guidance provided by the teacher, and access to appropriate resources are of particular importance [30]. Despite these limitations, meta-analyses show that, when correctly and consistently implemented, PBL leads to higher levels of knowledge acquisition and retention, as well as a better ability to transfer and apply what has been learned in new and diverse contexts, compared to traditional learning models [25–27,31].

Although ESD and PBL are considered separate concepts, they have a deep and complementary relationship that makes them an extremely effective tandem for modern education [16]. ESD provides the conceptual framework—why sustainability is critical and what changes are needed—while PBL offers the practical methodology—how to develop the necessary skills [30]. This synergy is vital as it transforms the theoretical

principles of ESD into active, experiential learning focused on authentic problems. As a naturally interdisciplinary method, PBL encourages students to combine knowledge from different fields, aligning fully with ESD's goal of achieving a holistic understanding of the interrelationships between systems. Ultimately, this integration is key to building future generations who not only possess knowledge about sustainability but also have the necessary skills and confidence to act as active participants in its implementation.

2.3. Key Problem-Solving Skills

It is clear that in an increasingly complex and interconnected world, traditional educational approaches focused on memorising facts and routine tasks are no longer adequate. Modern challenges require individuals to possess a set of new, transversal skills that extend beyond subject knowledge. These skills, often referred to as soft or critical, are vital for adapting, innovating, and effectively addressing the complex problems of our time. Despite their crucial importance, many modern education systems still fail to adequately integrate the development of these competencies into their curricula [17,19].

Problem-solving is one of the most critical competencies, extending beyond traditional academic knowledge. It is defined as the systematic process of identifying, analysing, and solving problems in an effective and informed manner [18].

Unlike simply finding an answer, problem-solving requires the ability to understand root causes, generate possible solutions, evaluate their potential consequences, and select the most appropriate strategy. In a world filled with complex, often unpredictable challenges, this competency is vital both personally and professionally. As a process, problem-solving follows several basic steps, which typically include:

- Identifying and defining the problem: Clearly stating the problem is the first and most crucial step.
- Root cause analysis: Going beyond the symptoms to understand the underlying factors that led to the problem.
- Generating alternative solutions: Creating multiple possible solutions, without initial evaluation.
- Evaluating and selecting the best solution: Weighing the advantages and disadvantages of each solution.
- Implementing the solution: Putting the chosen strategy into action.
- Monitoring and evaluating results: Tracking the effect of the solution and adjusting the approach if necessary.

This process is not linear, but cyclical and iterative [32]. Effective problem solvers continually learn from results and adapt their approaches to achieve better outcomes [33]. Indeed, the importance of problem-solving is particularly evident in the context of global crises. Social crises, for example, require the ability to understand the causes of inequality and to develop sustainable solutions that address not only the symptoms but also the underlying factors. Similarly, environmental degradation cannot be solved by scientific facts alone; it requires responsible leaders and citizens who can:

- Identify complex problems (e.g., water pollution, health pressures);
- Analyse their roots (e.g., industrial waste, agriculture, unhealthy habits);
- Propose innovative solutions (e.g., new treatment technologies, regulations, education);
- Implement solutions in practice.

Problem-solving is closely related to other key skills and depends largely on their application. Critical thinking is a fundamental basis of this process, especially during the definition and analysis stages. It enables an individual to assess the reliability of information, identify logical inconsistencies, and objectively analyse the problem. In the

absence of critical thinking, an individual risks focusing on an ill-defined problem or choosing an ineffective solution based on false premises [34].

Therefore, critical thinking is characterised as the ability to analyse, evaluate, and synthesise information logically and impartially, to form justified conclusions and practical solutions. In the face of global challenges, this competence is indispensable for navigating the enormous flow of information and misinformation. Critical thinking allows individuals to identify cognitive distortions, question established assumptions, and reach reasoned conclusions, rather than accepting information uncritically. The lack of such an ability significantly hinders understanding of the deep structural causes behind phenomena such as environmental degradation or socioeconomic polarisation [17,34].

The connection with systems thinking is also of great importance. While critical thinking helps to analyse individual elements, systems thinking provides the overall framework and context. It allows the problem solver to perceive the situation as part of a larger, interconnected system, creating conditions for anticipating possible side effects of the decisions made. In this way, strategies can be developed that not only address the specific problem but also contribute to improving the overall functioning of the system [16,19].

Unlike the reductionist approach, which considers problems in isolation, systems thinking focuses on understanding the interrelationships and dependencies between the different components of a complex system. Global crises are not isolated events, but rather the result of complex interactions among economic, social, and environmental factors. Systems thinking allows individuals to identify these interrelationships, anticipate the potential side effects of a given decision, and develop more sustainable strategies. It is essential for developing holistic solutions that consider the whole picture, not just its parts [16].

It is clear that critical and systems thinking represent two complementary yet distinct cognitive approaches to solving problems, differing in their emphasis and scope. Critical thinking is primarily associated with processes of analysis and evaluation. It involves a thorough examination of information, statements, or arguments to assess their credibility, logical consistency, and validity [19]. In this context, the critical thinker asks questions such as: How accurate is this statement? What evidence supports it? Are there hidden premises? Such an approach focuses on the details and internal structure of the problem or information under consideration. This makes it easier to identify and eliminate false information (e.g., disinformation), creating conditions for forming reasoned and reliable conclusions based on the available facts [34].

Systems thinking, on the other hand, is based on synthesis and understanding of interrelationships. Its goal is to clarify how individual elements of a system interact with each other and how these interactions shape the overall behaviour of the system [16]. For the systems thinker, the connections, dependencies, and dynamics of feedback loops are more important than the isolated components themselves. Applying systems thinking involves asking questions such as: How does this problem fit into the broader context? How will a change in one element affect the others? What unintended consequences might arise? This approach makes it possible to adequately understand and address complex, multifaceted challenges, such as environmental crises, which cannot be considered in isolation from their multiple interdependencies.

The primary difference between the two skills is as follows: critical thinking focuses on the content and characteristics of individual elements, whereas systems thinking emphasises the connections and interdependencies between them. In other words, critical thinking focuses on the particular tree to assess its condition and validity, while systems thinking examines the broader ecosystem to understand how the individual tree fits into it. Therefore, effectively addressing contemporary challenges requires the combined applica-

tion of both skills: critical thinking as a tool for checking the credibility of information, and systems thinking as a means of understanding context and complex interrelationships.

Alongside these cognitive competencies, teamwork and collaboration are indispensable skills for achieving meaningful change. None of the global crises we face today can be solved by a single individual or organisation alone. Effective collaboration thus implies not only the ability to exchange ideas and actively listen to different perspectives, but also the willingness to work towards common goals. This skill extends beyond interpersonal interaction to encompass intercultural understanding and interdisciplinary cooperation. Successfully addressing complex problems such as climate change, therefore, requires the combined efforts of scientists, engineers, politicians, economists, and citizens worldwide, which emphasises the fundamental role of collaboration [18].

One of the primary weaknesses of modern educational systems is the persistent dominance of practices that prioritise rote memorisation and individual competition. Traditional teaching methods—such as lecture-based instruction and standardised testing—limit students' ability to develop critical thinking skills by emphasising passive absorption of information rather than active analysis, interpretation, and application [21]. Furthermore, the lack of project-based activities that require teamwork and knowledge integration from different disciplines hinders the development of collaborative and systems thinking skills. The result is a generation that may possess information but lacks the necessary competencies to address complex and multifaceted real-world problems.

In summary, it must be emphasised that the key skills—critical thinking, systems thinking, and teamwork—are not merely desirable competencies but are necessary to address contemporary global challenges. Therefore, their targeted development should be viewed not as a secondary aspect, but as a fundamental task of any educational system seeking to prepare future generations for the uncertainties and complexities of tomorrow. Rethinking education to focus on the development and integration of these skills should thus be perceived as a strategic step towards creating a more sustainable, inclusive, and just future.

2.4. IoT as a Tool for Sustainability Problem-Solving

IoT is a transformative technology with a significant impact on several sectors, including healthcare, agriculture, industry, and education. At its core, the Internet of Things (IoT) is a network of interconnected devices equipped with sensors and software that collect, transmit, and exchange data. In the educational context, this enables the creation of innovative learning environments—dynamic ecosystems that collect and analyse information from users and the environment in real-time through IoT-based devices and systems [7].

In a narrower definition, IoT can be viewed as a form of communication between devices that identify and activate each other through connectivity. Information received from one object can be stored, monitored, or shared with another, thus creating an interactive network of smart objects. The conceptual framework of IoT consists of three main components [35]:

- Things: Objects, sensors, and actuators;
- The Internet: The infrastructure that provides the connection between them;
- Semantics: The intelligent processing and interpretation of the collected data.

The application of IoT is multi-layered and widespread. As Aydın and Göktaş [35] note, the technology is already finding applications in healthcare, logistics, innovative city development, agriculture, and industrial processes. In education, IoT proves to be a particularly valuable tool, enabling access to learning materials from anywhere, supporting computer science classes, facilitating remote interaction, and providing opportunities for data collection and analysis through the use of sensors. Consequently, smart classrooms,

campuses, and laboratories can be built that function as real-time feedback systems, thus increasing the effectiveness of the learning process.

The integration of IoT in education is also leading to a profound transformation of personalised online learning, creating adaptive and context-aware environments. These environments utilise real-time data generated by devices and sensors to tailor the content, methods, and pace of learning to the individual needs, learning styles, and preferences of learners. In this way, IoT contributes to the construction of student-centred educational ecosystems powered by continuous data exchange and intelligent analysis [7].

The contribution of IoT sensor technologies to enhancing contextual awareness is particularly significant. The use of accelerometers, GPS (Global Positioning System), and ambient light sensors enables the collection of information about movement, location, and environment, which is used to adapt educational content to current conditions and individual learner needs. More advanced applications include NFC (Near Field Communication) readers and tags that facilitate interaction between students and robots, creating more immersive and interactive learning experiences. Prototypes built on platforms such as the Arduino Uno R3 and Grove demonstrate IoT's potential by monitoring classroom parameters—including temperature, humidity, and air quality—and transmitting the data for subsequent online analysis [7,35].

Furthermore, multi-touch technologies, biometric scanners, and interactive dashboards enhance student engagement and support a more interactive learning environment. RFID (Radio Frequency Identification) systems facilitate attendance management and logistical aspects, such as on-campus parking. More broadly, IoT devices can be used not only to monitor academic resources but also to track the psychosocial well-being of learners, making them a key tool for modernising and optimising educational processes [7,35].

Through the use of sensors and smart devices, students engage with real and tangible challenges, allowing them to explore, analyse, and propose solutions supported by empirical evidence [4]. Therefore, the integration of IoT within ESD transforms the traditional problem-solving process (discussed in Section 2.3) into a dynamic, data-driven practice. This cycle (Figure 1) can be conceptualised in several sequential stages:

1. Problem Definition

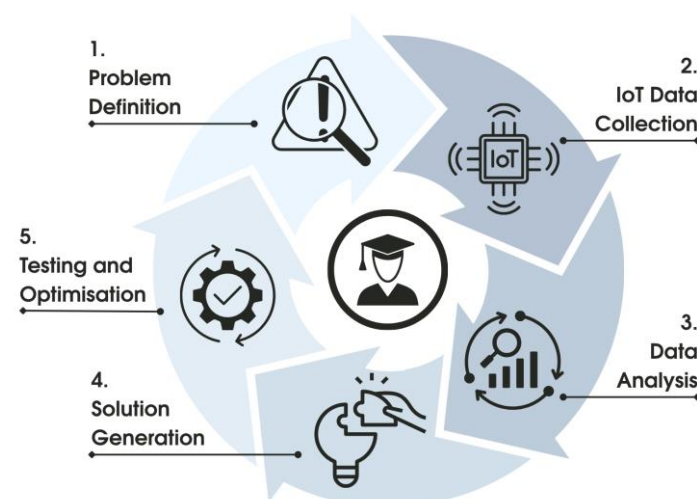


Figure 1. IoT-enabled problem-solving process in the ESD context. Source: Authors' development.

The first stage involves identifying and formulating a local sustainability problem. For the process to be effective, the problem must be both relevant and meaningful to students. Rather than addressing abstract global phenomena such as climate change, attention focuses on specific challenges in the immediate environment—for example, air

quality in the classroom, noise levels in the school playground, or water consumption in the school garden [36]. At this stage, research questions and hypotheses are formulated to structure the subsequent work.

2. IoT Data Collection

After defining the problem, students use IoT devices to collect quantitative data from the real environment. This typically includes sensors measuring temperature, humidity, CO₂ concentration, water pH, light, or noise levels [37]. The data is transmitted wirelessly to central databases or cloud platforms, where it is stored and prepared for analysis. It is at this stage that a theoretical problem is transformed into a data-driven one, allowing students to work with objective and reliable information instead of assumptions [5].

3. Data Analysis

In the third phase, students analyse and interpret the collected data using visualisation software tools, such as graphs and charts. They look for patterns and draw conclusions that connect the data to the real-world context. For example, increasing CO₂ levels at certain times of the day may be associated with worsening air quality [4]. This crucial step develops critical thinking and logical reasoning, as students are required to identify cause-and-effect relationships and underlying factors [28,37].

4. Solution Generation

Based on the data analysis, students formulate innovative solutions. Unlike hypothetical ideas, these proposals are supported by concrete empirical evidence, making them more realistic and applicable. For example, if excessive water consumption is detected, an automated irrigation system with IoT sensors can be proposed, activated only when the humidity drops below a certain level [4,36]. This stage stimulates creativity and systems thinking, requiring students to consider the problem in its entirety and develop solutions that are both technologically and environmentally sustainable.

5. Testing and Optimisation

The final step involves prototyping and empirical testing of the developed solution. Students implement the proposed system and measure its effectiveness using IoT sensors. For example, they can track whether the automated irrigation system has led to a reduction in water consumption. If the results do not meet expectations, adjustments and optimisation are undertaken, aligning with the engineering approach and the principles of experiential learning. This iterative process builds resilience and adaptability—other key skills for dealing with the complex challenges of modern times [37].

Therefore, by its very nature, problem-solving is not an isolated competence, but an integrative capacity. It combines, but is not limited to, the analytical dimensions of critical thinking with the holistic perspective of systems thinking, as well as the communicative and social aspects of collaboration. It is this synergy of skills that enables the effective handling of complex and multidimensional challenges, making it a key driver of innovation and sustainable societal development.

Furthermore, the integration of technologies such as IoT into ESD enables students to collect, visualise, and analyse real-time data related to their environment—for example, measuring water or electricity consumption in the school building. This transforms abstract concepts of resource conservation into concrete, measurable results that serve as the basis for informed problem-solving. Such projects demonstrate how technology can catalyse behavioural change and the formation of environmentally friendly habits.

3. Methodology

3.1. Research Methodology

This study employs a qualitative research approach, aimed at gaining a deeper understanding of the role of the Internet of Things (IoT) and Project-Based Learning (PBL) in developing problem-solving skills within the context of Education for Sustainable Development (ESD). The study is designed to combine a systematic review of the scientific literature, an analysis of empirical cases, and the development of a conceptual model.

The main research question guiding the study is: How can the integration of IoT technologies and PBL support the development of problem-solving skills within ESD?

3.2. Mixed-Methods Design

A mixed design was applied, combining:

- Systematic literature review—aimed at identifying the main trends, challenges and gaps in research on IoT in education;
- Case study analysis—focused on empirical examples from practice that demonstrate how IoT is applied in a real educational environment;
- Development of a conceptual model (EcoHabits)—synthesised based on the previous two stages and designed to address the identified gaps by proposing an innovative pedagogical framework.

3.3. Data Collection

Systematic literature review (SLR) procedure

- Search strategy and scope

The search was systematically executed across two leading multidisciplinary bibliographic databases: Scopus and Web of Science (WoS). These databases were selected as they primarily index peer-reviewed scientific publications and offer standardised tools for precise, auditable search queries, thereby guaranteeing the high quality of the literature included.

Google Scholar was intentionally excluded from the primary systematic search process. This decision was based on the platform's technical limitations, specifically the difficulties in consistently tracking and exporting large volumes of data for comprehensive analysis, as well as the lack of standardised, replicable filtering tools essential for the SLR methodology. Relying solely on Scopus and WoS further ensures a focus on indexed, peer-reviewed literature, strengthening the validity of the data synthesis.

The temporal scope of the search was strictly defined, covering publications from January 2005 through March 2025, reflecting the period relevant to the increased adoption and research interest in IoT within educational contexts.

The search was conducted using five distinct combinations of keywords (strings) related to the core concepts of the study, applied to the Title, Abstract, and Keywords fields:

- “IoT applications in schools” AND “project-based learning”
- “IoT” AND “sustainability education”
- “IoT” AND “sustainability education” AND “problem-solving”
- “Internet of Things in education” AND “project-based learning”
- “Internet of Things in education” AND “problem-solving skills”
- Inclusion criteria:
 - Publications must be peer-reviewed articles or conference proceedings (meta-analyses were considered but often fulfilled the previous criteria);
 - Publications must be available in English;

- Content must directly address the application or role of IoT and/or PBL in the context of ESD or the development of problem-solving skills in formal educational settings (K-12 or higher education);
- Publications must fall within the defined time range (2005–2025).
- Exclusion criteria:
 - Grey literature (e.g., dissertations, books, technical manuals) unless specifically cited as an institutional report for a case study;
 - Articles focused purely on the technical aspects of IoT hardware/software without pedagogical application;
 - Publications outside the defined time range.
- Screening process and PRISMA flow

The screening process documented the flow of information according to the key stages of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. The initial cumulative search across all five strings in Scopus and WoS yielded a total of 480 records. During the initial processing phase:

- Six (6) retracted publications were immediately excluded to maintain the integrity of the review.
- The remaining records were imported into the citation management software Zotero (Version 7.0.27), which was used to identify and merge all duplicate entries automatically.

This process resulted in a pool of 266 unique records that proceeded to the next stage of screening. After screening titles and abstracts, 141 records were excluded due to a lack of relevance to the educational context or specific research concepts (IoT, PBL, ESD). The full text of the remaining 125 articles was assessed for eligibility, of which 83 were subsequently excluded (e.g., due to weak methodology, insufficient focus on Education for Sustainable Development, or absence of primary data). A final number of 42 articles were included in the systematic review for thematic analysis. The PRISMA flow diagram (Figure 2) detailing the screening process was generated using the PRISMA2020 R package and Shiny app [38].

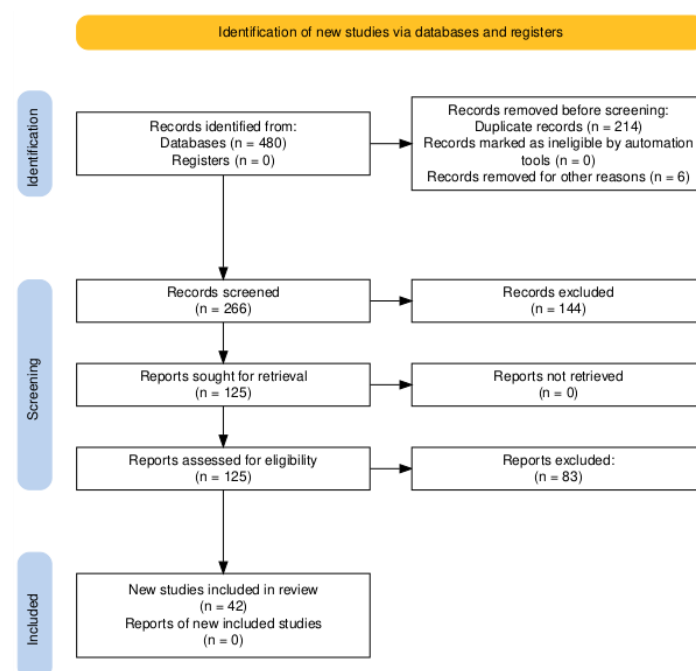


Figure 2. PRISMA Flow Diagram detailing the identification, screening, and inclusion of records for the systematic literature review. Generated using the PRISMA2020 Shiny application [38].

Note: Additional sources, such as institutional reports and books, were used exclusively for the Case study analysis and the development of the conceptual model (*EcoHabits*) and are not accounted for in the PRISMA flow chart.

Case Studies

Examples of IoT implementation in diverse educational contexts, published in scientific articles or described in institutional reports, were selected. These cases were chosen based on two primary criteria: (1) relevance to identified gaps from the literature review (Stage 1), and (2) potential to illustrate successful integration of IoT, PBL, and ESD.

3.4. Data Analysis

The literature review was analysed through thematic coding, which allowed for the derivation of the main categories: pedagogical benefits, technological challenges, and integration with ESD and PBL. To ensure full methodological transparency and address the need for a documented source of the analysed data (the secondary dataset), a comprehensive list of the 42 included articles detailing their thematic focus (derived codes) and selection status for Case Study Analysis is provided in Appendix A Table A1. The case studies were examined through comparative analysis, looking for similarities and differences in the application of IoT solutions, the impact on students' skills and the role of institutional support. As a result, the *EcoHabits* model was constructed as a conceptual framework by synthesising the findings from the previous two stages. Although it lacks empirical validation within the framework of this study, it is intended as a basis for future pilot projects and experimental studies.

3.5. Limitations of the Study and Ethical Considerations

It is worth noting that the study does not include empirical testing of the proposed concept. The results are based on secondary data and conceptual modelling. However, the methodology provides a clear framework for future research, including the piloting of *EcoHabits* in university and school contexts.

The study uses only publicly available sources and published case studies. All data has been processed in accordance with academic citation standards and without compromising personal or institutional information.

4. Results

This section presents the research results, organised in accordance with the chosen methodological framework. As outlined previously, the study combines a SLR, an analysis of real-world case studies, and the development of a conceptual model. The aim is thus not only to describe the current state of IoT use in education, but also to outline potential directions for future development.

The results of the SLR serve as the basis for identifying key concepts, definitions, and challenges related to the application of IoT in the educational context. This theoretical layer outlines the general framework and provides the analytical categories through which the case studies are interpreted. This approach ensures consistency between the different data sources and guarantees higher reliability of the conclusions drawn.

The next step is the presentation of the case studies, which provide an empirical perspective on the real challenges and benefits of integrating IoT into educational practice. Analysis of specific examples reveals not only the technological aspects but also the pedagogical and organisational dimensions of the process. This facilitates a deeper understanding of the mechanisms by which IoT can transform the educational environment.

Based on these two analytical layers—theoretical and empirical—the *EcoHabits* conceptual model was developed. It represents a synthetic result of the research conducted and

responds to the identified gaps in existing IoT applications. Thus, the Results section not only describes the existing knowledge and practice, but also contributes its own proposal, which can serve as a basis for future research and practical implementation in educational and sustainable development contexts.

4.1. Domotic School Garden: Integrating IoT and PBL in School Education

The Domotic School Garden project is an innovative educational initiative funded by the Erasmus+ programme aimed at developing and implementing smart school gardens. The central concept is based on integrating IoT into the learning process through PBL. Students actively participate in the development of low-cost sensor systems for monitoring parameters such as soil and air humidity and temperature, in order to optimise irrigation and sustainable resource management. This initiative directly addresses key aspects of SDGs 6 (clean water and sanitation) and 12 (responsible consumption and production) [39–45].

The project is implemented across several European countries, including Spain, Bulgaria, Italy, and Greece. The coordinator is the Miguel Hernández University (UMH) in Spain, with partners including primary schools and educational institutions from Chirpan (Bulgaria), San Giustino (Italy), and Xanthi (Greece). Each institution applies the common framework by building a school garden, combining IoT technologies with a STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach. The results encompass not only technological infrastructure (sensors, control systems, solar power), but also pedagogical materials for integrating science, technology, and sustainable development into the learning process [42,46].

The scientific significance of the Domotic School Garden lies in its transdisciplinary nature. The project combines engineering solutions, agroecological practices, and pedagogical innovations, placing students in the role of citizen scientists. This approach not only enhances the digital and environmental competencies of young people but also fosters the development of responsible attitudes towards the sustainable management of natural resources. Consequently, the Domotic School Garden is considered a model for implementing IoT-based educational practices in primary and secondary education, combining technological development with the achievement of social and environmental goals [42,44].

The project is a classic example of PBL that integrates IoT to solve a sustainability problem. The main challenge addressed is the inefficient management of water resources in green spaces. Traditional scheduled irrigation often leads to unnecessary water wastage if the soil is still wet, or insufficient irrigation if it is too dry. This problem directly relates to SDG 6 (ensure access to clean water and sanitation), emphasising the need for efficient and responsible water use [8].

The project transforms students from passive observers into active citizen scientists who collect and analyse data to find a lasting solution [36]. The cycle begins with problem identification and subsequent data collection from the real environment. Students install various IoT sensors in the garden's soil. Soil moisture sensors measure water content, while temperature (air and soil) and light intensity sensors collect supplementary environmental information. The data is transmitted wirelessly in real-time to a microcontroller (e.g., Arduino or Raspberry Pi) and then uploaded to a cloud platform for storage and visualisation [37]. This process enables students to gather objective, quantitative information about the garden's condition and identify periods of excessive moisture or drought.

The next step is data analysis. Students use software tools (e.g., spreadsheets or specialised platforms) to examine the collected information. They look for patterns, such as identifying that plants begin to dry out when soil moisture drops below 30%, or that watering on sunny days leads to faster water evaporation. This analysis provides them

with concrete evidence of inefficient watering. Based on this data, students proceed to generate a solution: designing an intelligent irrigation system. The system consists of a microcontroller connected to the sensors and a water pump or solenoid valve.

In the final stage, students build and test their prototype. They programme the microcontroller to activate the water pump automatically only when the data from the soil moisture sensor falls below a defined threshold. Once the system is operational, they continue to collect data to measure its efficiency. This allows them to determine the amount of water saved, making their contribution to sustainability tangible and measurable. This iterative process promotes not only problem-solving skills but also systems thinking and critical analysis, teaching them to adapt and optimise their solutions based on real-world outcomes [26,36]. The project ultimately transforms the abstract concept of water conservation into a concrete, technological, and educational experience.

4.2. Integrating PBL and IoT into Air Quality Initiatives

The relationship between educational practices and sustainable development finds practical application in several projects focused on monitoring and improving air quality. Projects such as air:bit, SchoolAIR, Clean Air, and Know the Air demonstrate how different contexts—schools, universities, or communities—can be united through PBL, citizen science, and IoT technologies to achieve key SDGs [47–50].

The air:bit project (Norway) represents an innovative PBL model where students build their own air quality measurement kits. By integrating electronics, programming, and data analysis, they collect empirical information about pollutants in their environment. air:bit thus not only develops STEAM competencies but also stimulates critical thinking and awareness of environmental challenges. The project directly aligns with SDG 4 (Quality Education), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), as it enables students to connect local measurements with global environmental processes [46–50].

The SchoolAIR project (Portugal) offers a more structured and technologically sophisticated framework for monitoring indoor air quality in classrooms. The use of advanced IoT architectures, including Edge and Fog Nodes, enables the integrated analysis of CO₂ and delicate particulate matter in real-time. Its pedagogical value lies in creating an opportunity to combine engineering disciplines and health sciences in a university environment. SchoolAIR supports SDG 3 (Good Health and Well-being) and SDG 9 (Industry, Innovation, and Infrastructure) by demonstrating how technologies can help reduce health risks and optimise the educational environment [47–49].

The British Council's Bulgarian Clean Air project focuses on education and public awareness. Although it does not directly involve IoT technologies, it represents a strong example of PBL, utilising tools, tasks, and experiments designed for students and their families. The project encourages students to actively participate in investigating local sources of pollution and formulating community solutions. Clean Air supports SDG 4 (Quality Education), SDG 11 (Sustainable Cities and Communities), and SDG 17 (Partnerships for the Goals) by bringing together schools, families, and the scientific community [46–48].

The Know the Air (Bulgaria) initiative is built on an IoT infrastructure for real-time air quality monitoring. Although initially focused on raising public awareness, it has strong potential for integration into curricula and citizen science initiatives. By accessing data from monitoring stations, students and citizens can become aware of spatial variations in pollution and take action to change (Table 1).

Table 1. Comparative analysis of IoT projects in terms of methodology (PBL/IoT) and contribution to the SDGs.

Project	Location	PBL Element	IoT Element	Main Context	Key Highlights	Supported SDGs
air:bit	Norway	Yes	Yes	High School	Students build and programme sensors to measure PM and CO ₂ ; analyse local data; STEAM skills	SDG 4: Quality Education; SDG 11: Sustainable Cities and Communities; SDG 13: Climate Action
SchoolAIR	Portugal	Partially	Yes	University Environment	IoT architecture (Edge/Fog nodes), indoor air quality monitoring (CO ₂ , PM _{2.5}); cloud analytics	SDG 3: Good Health and Well-being; SDG 9: Industry, Innovation and Infrastructure
Clean air	Bulgaria	Yes	No	School and Family Environment	Project and experiment toolkit; encourages pollution research and school-family collaboration	SDG 4: Quality Education; SDG 11: Sustainable Cities and Communities; SDG 17: Partnerships for the Goals
Know the Air	Bulgaria	Limited	Yes	Public Spaces	Network of monitoring stations; real-world air data; potential for integration into citizen science and education	SDG 3: Good Health and Well-being; SDG 11: Sustainable Cities and Communities; SDG 13: Climate Action

Furthermore, the Adopt Station initiative of the Know the Air project offers a unique model of social and educational engagement. Within this model, socially responsible companies finance the installation of permanent IoT air quality monitoring stations in schools, kindergartens, parks, and neighbourhoods. This form of donation combines civic engagement with the creation of an open infrastructure that provides public access to real-time data. This opens up a space for learning through action, encompassing environmental, technical, and societal aspects [50]. The social benefit is two-fold:

- Vulnerable groups (e.g., children, adolescents, and adults) gain access to information necessary for a healthy environment; and,
- Donors (including businesses and institutions) become facilitators of sustainable solutions, demonstrating their Corporate Social Responsibility (CSR).

Thus, Adopt Station establishes a connection between various stakeholders in the sustainability ecosystem—including schools, parents, companies, and government institutions—and encourages them to respond to problems based on concrete data.

The educational dimension of the initiative is highlighted by the active participation of students, teachers, and community groups. They can utilise the data from the stations in interdisciplinary learning projects related to ecology, civic education, science, and technology. The data enable the formulation of scientific questions (e.g., How do weather and traffic affect air quality?), conducting measurements, analysis, and multiparameter interpretations. This leads to the development of critical thinking and civic science literacy—essential aspects of modern education. The project contributes to SDG 3, SDG 4, SDG 13, and SDG 17 by linking scientific measurements with social engagement and motivating partnerships between different types of organisations [46–50].

The reviewed initiatives clearly demonstrate how the integration of PBL with IoT technologies creates learning scenarios with high social and environmental relevance. Although these examples successfully illustrate the application of IoT for environmental

monitoring, they overlook the direct connection to personal behavioural change. This critical gap is what the following conceptual model aims to address.

Based on these synthesised findings, the present study moves from theoretical synthesis to a conceptual contribution. The next step involves developing a theoretical framework specifically designed to address the identified gaps, thereby establishing a clear distinction between empirically synthesised knowledge and an innovative, yet untested, theoretical model. Therefore, the *EcoHabits* model is constructed as a conceptual (hypothetical) framework derived directly from the thematic analysis, representing a new theoretical contribution that requires future empirical validation.

4.3. *EcoHabits* Conceptual Model: Connecting Individual Behaviour with Collective Contribution to Sustainability

The *EcoHabits* model is based on integrating PBL and IoT to explore the relationship between individual behaviour and collective contributions to sustainable development. Students actively participate in developing and implementing IoT solutions for monitoring key indicators related to healthy lifestyles and sustainable habits, such as physical activity, water and energy consumption, exposure to polluted air, and passive smoking. This shifts the learning process beyond abstract discussions, focusing instead on real, measurable factors that directly impact personal and societal well-being. The project is structured around practical work:

- Students design and assemble sensor nodes (e.g., using ESP8266/ESP32 microcontrollers and sensors for motion, air quality, humidity, or resource consumption).
- They integrate these nodes into cloud platforms (such as MQTT, Node-RED, and Grafana).
- They develop dashboards for data visualisation and analysis.

Through these tools, learners can track their habits, identify problematic trends (e.g., insufficient physical activity or prolonged exposure to unhealthy environments), and suggest interventions—both technological and behavioural. PBL thus becomes a method for systematic learning through experimentation, with IoT providing the reliable empirical basis for analysis.

The project's significance lies in its profound transdisciplinary nature. Students acquire knowledge and skills in electronics, programming, and data analysis, while simultaneously developing competencies related to health, sustainability, and civic responsibility. The approach unites STEM disciplines with social and behavioural sciences, enabling young people to understand and perceive the impact of their habits on the broader ecosystem. As a result, *EcoHabits* simultaneously supports the development of digital competencies and cultivates environmental and social awareness, clearly demonstrating the connection between individual behaviour and global SDGs.

Crucially, while most IoT applications in education focus on monitoring static environmental parameters (e.g., air, water, soil), the current model offers an innovative framework that links individual human behaviour directly to global sustainability goals. The *EcoHabits* model is a hypothetical system that uses wearable technologies to track sustainability-related activities, transforming them into an educational and motivational tool. The primary goal is to transform abstract concepts of sustainability into concrete, measurable, and rewarding actions that encourage lasting habit formation.

The *EcoHabits* mechanism is based on three main steps: data collection, transformation of data into educational indicators and visualisation of collective contributions:

- Data collection phase: Students use wearable IoT devices (e.g., fitness trackers) that collect anonymised data about their physical activity, such as the number of steps taken or the distance travelled by bike. The model can also integrate data from IoT

air quality sensors that capture concentrations of delicate particulate matter (PM_{2.5}), volatile organic compounds (VOCs), or carbon monoxide. This permits recording whether the student is exposed to tobacco smoke—directly or as a passive smoker—and transforming this exposure into an indicator of health risk factors. The devices track metrics such as those shown in Table 2.

Table 2. Example metrics to track. Source: Authors’ development.

Indicator	Definition
Number of steps taken	Walking in the schoolyard, on the stairs or on the way to school is reported, which is directly linked to a reduction in the use of cars or elevators.
Distance cycled	Accurate information is provided on the mileage that replaces a motor vehicle trip.
Exposure to air pollution/ tobacco smoke	Time spent in environments with high levels of PM _{2.5} or VOCs, as recorded by sensors; values can be used as an indicator of passive smoking and adverse health environments.
Other data	Depending on the device, data on the number of floors climbed can also be collected, which is also linked to energy savings.

- **Data-to-Indicator phase:** In this phase, the raw data collected by wearable devices is transformed into concrete educational indicators (Table 3). This transformation is facilitated by a mobile application that acts as an intermediary layer. For example, the distance travelled by bicycle can be converted into carbon emissions saved, and the number of stairs climbed can be converted into electricity saved by forgoing the use of the elevator. The goal is to convert abstract actions into measurable environmental benefits.

Table 3. Example indicators for measurable benefits. Source: Authors’ development.

Indicator	Definition
Carbon emissions saved	The distance travelled by bicycle is calculated and converted into carbon emissions saved using a standard equivalence formula. In this way, a simple bicycle ride becomes a tangible contribution to reducing the environmental footprint.
Electricity saved	The number of steps climbed can be converted into electricity saved, expressed in kilowatt hours, by not using the elevator.
Reduced exposure to tobacco smoke	The time spent in environments with recorded high concentrations of PM _{2.5} or VOC is converted into an educational indicator of health risk factors. Lower exposure indicates an improvement in the air quality to which the student is exposed and a reduction in the risk of diseases related to smoking, both active and passive.

- **Visualisation phase:** Aggregated data from the entire school community is visualised in real-time on a public dashboard or within a dedicated section of the application (Figure 3). This dashboard displays the total collective contribution of all students, including the total amount of emissions saved for the month and the total number of kilometres travelled.

The final step—visualisation of the aggregated data—is the motivating element of the model. The anonymised and processed data from the entire school community or participating student group is displayed publicly on a real-time dashboard or within the application. The visualisation serves three key functions:

- Overall Contribution:** Students can view the total amount of carbon emissions saved or the total kilometres cycled by the entire school community for the month.

- b Achievements and goals: The dashboard can track the achievement of specific objectives—for instance, unlocking a virtual or real achievement when the community saves 100 kg of carbon emissions.
- c Interaction and competition: Healthy competition between classes can be encouraged by highlighting the contributions of each group, thereby fostering collective responsibility and commitment.

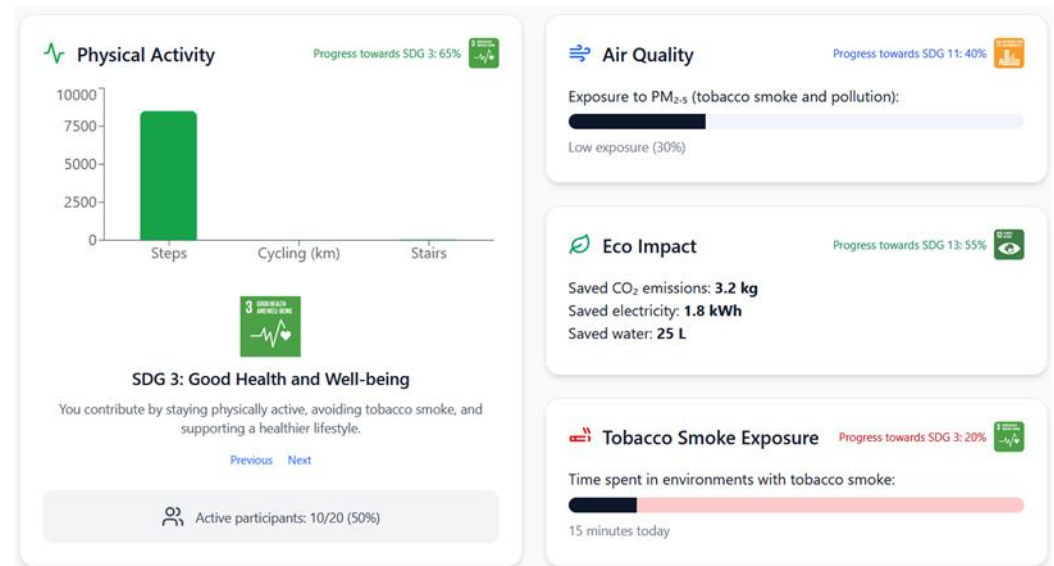


Figure 3. *EcoHabits* Dashboard: Collective data on physical activity, environment and tobacco smoke exposure. Source: Authors' development.

This visualisation transforms individual habits into a collective mission, fostering a sense of community and a shared contribution to global sustainability goals. In this sense, the *EcoHabits* conceptual model aims to demonstrate how IoT can be utilised as a tool for social transformation and the fostering of a sustainable culture.

As illustrated in Figure 3, the *EcoHabits* conceptual model is designed to include a component for detecting smoking and passive smoke exposure through wearable devices and stationary air quality sensors. A smartwatch can detect gestures (rhythmic hand-to-mouth movements), changes in heart rate, or stress markers associated with smoking. Concurrently, stationary PM_{2.5}/VOC/CO₂ sensors can detect the presence of smoke in the environment. The combination of these data will allow for a more precise understanding of exposure and health impacts, leading to more effective interventions.

However, it is essential to note that while research and technology suggest that some functionality for detecting smoking or tobacco smoke exposure can be implemented via wearable devices, such an approach faces several limitations:

Gesture detection—wearable component (smartwatch or fitness tracker): for gesture detection of active smoking + heart rate/variability, stress markers, etc. The accelerometer in a smartwatch can recognise gestures typical of smoking (e.g., hand-to-mouth movement) with relatively high accuracy (85–95%) [51]. A similar approach is used in another study, where heart rate and movement are also analysed to detect smoking [52].

Ambient air quality sensors (classroom, school, home)—PM_{2.5}, VOC, CO₂—to capture pollution, which can be an indicator of a smoky environment. Many indoor (i.e., non-wearable) IoT devices utilise sensors (such as PM_{2.5}, VOC, and CO) that can detect airborne particles and pollutants, including those generated by smoking or vaping. For example, the Netvox RA02G is a sensor that can detect cigarette smoke/vape/outdoor smoke via a PM_{2.5} indicator.

A combined approach, i.e., combining data: active smoking + high particle environment = higher risk and increased exposure to second-hand smoke. In general, smartwatches currently do not have sensors that specifically measure a chemical marker of tobacco smoke (e.g., nicotine), but instead use indirect markers—such as gestures, movement, and heart rate changes—to determine whether a person smokes. For passive smoking (i.e., exposure to smoke in the air), air quality sensors (especially those detecting PM_{2.5} particles or VOCs) are more suitable detectors. They cannot determine whether the particles are coming from tobacco smoke. Still, they can indicate that the air is polluted at levels above usual, which may correspond to passive smoking.

Although the use of wearable devices and air quality sensors to detect active and passive smoking poses several challenges, these limitations should not be viewed solely as obstacles. On the contrary, they can be interpreted as opportunities to deepen research, stimulate student creativity, and expand the scope of IoT technologies.

The limitations inherent in gesture detection using accelerometers, for example, highlight the necessity for developing algorithms capable of distinguishing similar movements, such as eating or drinking. This creates a challenging but extremely fruitful environment for learning about data analysis, machine learning, and human behaviour modelling. In this way, the technological barrier itself becomes a catalyst for the development of new skills and a deeper understanding of real-world complexity.

Similarly, the difficulty in accurately identifying passive smoking using air quality sensors creates an opportunity for interdisciplinary research. It encourages learners to seek integrative solutions that combine physical measurements with contextual information, such as location, time, and social factors. Thus, the limitations of technology actively support the development of systems thinking, as they necessitate an understanding of the problem in its entirety and its interconnectedness. Therefore, rather than being seen as barriers, the challenges of mobile tobacco detection can be interpreted as a motivating factor for fostering innovation and transforming the educational process. They convert the study of IoT technologies into a dynamic and open process where the imperfections of existing solutions serve as a starting point for creating new knowledge and critical reflection on sustainability.

A key feature of the *EcoHabits* conceptual model is that its development and application are assigned to students, who represent a vulnerable social group, both highly affected by health risk factors and highly open to innovation. This approach offers a significant advantage over traditional, restrictive methods (e.g., bans on smoking in public spaces). Such regulations often create the illusion of control without addressing the root causes of behaviour, frequently encouraging the circumvention of restrictions rather than fostering lasting healthy habits.

In contrast, engaging students in the process of identifying and analysing health and sustainability issues encourages the development of solutions that stem from the users of the system themselves. In this way, the problem is viewed from the inside—through the lens of the people actually at risk—rather than through externally imposed restrictions. Consequently, proposals for interventions and technological applications are more realistic, more sustainable, and possess greater potential for social impact.

5. Discussion

The *EcoHabits* project demonstrates high relevance within the context of ESD, as it directly addresses two of the most serious global public health challenges: the growing levels of obesity and the continuing threat of tobacco smoking, particularly amongst young people. These issues are inextricably linked to cultivating a culture of sustainability and responsible behaviour. In the school environment, it is evident how the unhealthy

habits formed by adolescents today will inevitably affect both their future health and the sustainable development of society as a whole.

Global obesity rates have been increasing at an alarming rate in recent decades. According to data from the World Health Organisation (WHO), in 2022, more than 2.5 billion adults (18 years and older) were overweight, including 890 million with established obesity. This represents an increase from 7% in 1990 to 16% in 2022. The problem is not limited to adults—over 390 million children and adolescents aged 5–19 years are also overweight, with 160 million of them diagnosed as obese. This represents an increase from 2% in 1990 to 8% in 2022. Projections for 2050 indicate that without effective interventions, more than half of adults and one third of children and young people worldwide will be overweight or obese [53,54]. The primary factors driving this increase include excessive consumption of ultra-processed foods, as well as reduced physical activity associated with modern lifestyles and increased screen time.

The problem of smoking among young people remains a serious global concern, despite the apparent decline in traditional cigarette use in some countries. In the United States, for example, while the percentage of students who smoke cigarettes decreased to 1.4% in 2024, more than two million young people continue to use tobacco products. E-cigarette use also saw a decline, from 2.13 million (7.7%) in 2023 to 1.63 million (5.9%) in 2024 [55]. Globally, however, the situation varies significantly between regions, with some countries experiencing alarming increases amongst youth. The WHO emphasises the crucial need for continued educational campaigns, regulation of tobacco sales, and increased public awareness of the health risks to prevent young people from becoming addicted to tobacco [54].

Obesity and smoking are not merely medical issues, but profound socio-economic problems. According to the Organisation for Economic Co-operation and Development (OECD), these issues lead to significant productivity losses and enormous healthcare costs worldwide. Investments in prevention and early education for a healthy lifestyle, which promote physical activity and proper nutrition, yield high returns to society [56]. Furthermore, measures to limit obesity and smoking necessitate integrated strategies that combine education, regulation of the marketing and sale of harmful products, and the promotion of healthy eating habits and physical activity. Only through a systemic approach is it possible to reduce adverse health consequences and ensure sustainable improvements in public health. The *EcoHabits* model, therefore, aims to have a direct impact on several key SDGs:

- **SDG 3: Good health and well-being.** By monitoring factors related to health and well-being—such as physical activity, air quality, and exposure to tobacco smoke—the project directly addresses critical issues plaguing modern health systems. For example, *EcoHabits* translates physical activity (e.g., steps, walking, and cycling) into concrete indicators of progress and rewards. This supports the formation of healthy habits in an environment where adolescent overweight is above the EU average, and smoking is a key risk factor for various oncological, respiratory, and cardiovascular diseases.
- **SDG 4: Quality education (link to the learning process, increasing competencies):** The built-in educational elements (explanations, challenges, and group goals) address identified deficits in knowledge and behaviour amongst young people (e.g., low fruit/vegetable consumption or skipping breakfast) by linking theory directly to everyday choices. The integration of technological tools, STEM knowledge, and social engagement offers learning through practice, effectively developing critical thinking and preparing youth for active participation in sustainable development.
- **SDG 12: Responsible consumption and production:** The system can also measure other sustainable habits, such as the use of water bottle filling stations (via geolocation),

which directly reduces plastic waste consumption. This demonstrates how data can be used to promote resource efficiency and sustainable consumption patterns, turning individual action into a quantifiable contribution to waste reduction.

- **SDG 11: Sustainable cities and climate:** By engaging students in reflecting on their own behaviour within the context of the school and urban environment, *EcoHabits* increases their sensitivity to local environmental and social conditions. Encouraging active mobility (walking and cycling) instead of motorised transport allows the model to convert individual kilometres into saved CO₂ emissions and visualise the collective contribution of the school community, directly supporting local climate goals. This active mobility focus also aligns with EU/OECD recommendations as part of broader anti-obesity policies.
- **SDG 13: Climate action:** By converting physical activity into the equivalent of carbon emissions saved, the *EcoHabits* model makes the students' contribution to combating climate change tangible and measurable. This mechanism transforms abstract climate concepts into quantifiable individual actions, thereby strengthening environmental literacy and personal accountability.

EcoHabits also creates connections with other goals. Tracking habits related to resource consumption (e.g., water and energy) can be indirectly linked to SDG 6 and SDG 7, as students are encouraged to propose IoT-based solutions to optimise resource use. Overall, the project highlights the critical importance of sustainable practices in everyday life and successfully links environmental sustainability with education for responsible consumption.

In summary, the analysed case studies—the Domotic School Garden, air quality monitoring projects, and the *EcoHabits* conceptual model—illustrate three distinct yet complementary levels of IoT integration in ESD (Table 4). While all examples utilise PBL and data collection technologies, they differ significantly in their primary focus, student engagement model, and the ultimate goal of the educational intervention.

Level 1: Resource management (Domotic School Garden). This level focuses on optimising and managing resources within a closed, controlled environment. Students act as engineers and system integrators who create an automated solution (smart irrigation) to a specific, local problem (water waste).

Level 2: Environmental monitoring and citizen science (Air Quality Projects). The focus shifts from control to observation and awareness-raising. Students assume the role of citizen scientists, collecting, analysing, and sharing data on a broader societal problem, thereby contributing to collective knowledge and potentially influencing policy change.

Level 3: Personalised feedback and behavioural change (*EcoHabits* Model). This most innovative level focuses on individual behavioural change. Unlike the other two approaches, which examine external systems, *EcoHabits* looks inward, utilising IoT to measure personal habits (physical activity, exposure to tobacco smoke) and transform them into measurable contributions to sustainability. This approach is unique in its capacity to directly connect personal choices to global goals, making sustainability a personal and motivating experience.

Three key conclusions can be drawn from the comparison of the three levels of IoT integration:

Contextual effectiveness: There is no single universal “best approach”; the effectiveness of each model is dependent on the specific educational goals. For developing STEM skills and systems thinking, a resource management model (e.g., the Domotic School Garden) is highly suitable. For increasing civic engagement and data-driven work, air monitoring projects offer a more effective framework.

Table 4. Comparative analysis between the models considered. Source: Authors’ development.

Criterion	Domotic School Garden	Air Quality Projects (air:bit, SchoolAIR, etc.)	Conceptual Model <i>EcoHabits</i>
Main pedagogical focus	Resource Management and System Optimisation. Students learn how to effectively manage natural resources (water) in a controlled environment by designing and implementing an automated system.	Environmental monitoring and citizen science. The main goal is to raise awareness of a local ecological problem (air pollution) by collecting and sharing data.	Personal behaviour changes and health culture. The focus is on building sustainable personal habits by linking individual actions with collective contributions to health and sustainability.
Role of IoT technology	Control and Automation Tool. IoT sensors and actuators are used to create a closed-loop system that automatically controls irrigation based on real-world data.	A tool for monitoring and collecting data. IoT is used to build a network of sensors that collect environmental data in real time, which is then visualised and shared publicly.	Monitoring and data collection tool. IoT is used to build a network of sensors that collect environmental data in real time, which is then visualised and shared publicly.
Engagement model	The Student Engineer. Students are active creators of an end-to-end technological solution—from assembling the hardware to programming the logic.	The Student-citizen scientist. Students participate in collecting and analysing data, contributing to a larger database and helping to inform the community.	The Student-agent of change. Students are both the object and subject of the research, using their personal data to improve their habits and observe the collective effect of these changes.
Key outcomes and skills	Development of systems thinking and engineering skills (STEM). Students understand how individual components (sensors, soil, water, software) interact in a complete system.	Development of data analysis skills and civic engagement. Students learn to interpret data, understand its connection to public problems and communicate their results.	Development of self-reflection, health literacy and understanding of the “personal-global” connection. Awareness of how daily choices affect larger systems is encouraged.
Scale and impact	Local and controlled. The impact is limited to the specific school garden, but the solution is comprehensive and complete.	Community and informational. The impact is broader, as the data is public and can inform the community as a whole, but does not necessarily lead to a direct solution to the problem.	Individual and collective behavioural Impact is at the level of personal change, which, aggregated, leads to a measurable collective effect (e.g., saved CO ₂ emissions).

Evolution of IoT application: The analysis reveals a crucial evolution in IoT application—moving from controlling external systems to influencing internal, human ones. *EcoHabits* represents the next step in this evolution, successfully filling the gap identified in this manuscript: the direct connection between collected data and changes in personal behaviour. While the most challenging to implement, this approach is potentially the most impactful, given that sustainability is inherently related to shifting human habits.

Comprehensive spiral progression: Combining the three approaches creates the most comprehensive sustainability education programme. Students can begin with small-scale resource management (Level 1), progress to monitoring larger community issues (Level 2), and ultimately apply these lessons to their own daily lives (Level 3). Such a spiral progres-

sion would allow learners to develop the full range of competencies required to become active and responsible citizens.

The preceding analysis clearly indicates that IoT-enhanced PBL projects in the field of ESD are not only capable of providing local solutions to specific problems (e.g., polluted air, inefficient irrigation, or energy consumption) but also act as a multiplier for achieving the SDGs. They effectively transform schools into laboratories for sustainability, where students transition from passive consumers of knowledge to active creators of innovations with real social and environmental impact.

The project cycle typically begins with defining the problem, necessitating the development of critical thinking. Students formulate questions such as, “How clean is the air in our classroom?” or “How does the traffic around the school affect the air quality?” To address these questions, they proceed to data collection via IoT. Students build their own, low-cost air monitoring devices using microcontrollers (e.g., Arduino) and various sensors. These sensors measure levels of CO₂, volatile organic compounds (VOCs), and particulate matter (PM_{2.5} and PM₁₀). The devices are strategically placed in various locations—classrooms, the gym, hallways, and near the road—to collect real-time data transmitted wirelessly to a centralised database.

Once the data is collected, students commence their analysis. They use graphs to visualise the sensor readings and identify patterns. They may observe that CO₂ levels increase significantly during school hours, for instance, indicating inadequate ventilation. Alternatively, they might notice that particulate matter concentrations are higher near busy streets. This analytical process actively develops critical thinking and logical reasoning skills, as students must correlate the data with human activities and understand complex cause-and-effect relationships [39].

Based on their analysis, students proceed to generating solutions and enter the creative phase. They can propose various measures to improve air quality, such as installing an innovative ventilation system that automatically activates when CO₂ levels are high; planting certain types of plants in the classroom known for their purifying properties; and organising campaigns to promote the use of bicycles, which reduces traffic around the school. These proposals are supported by real data, which makes them more convincing and compelling [4,37]. The final step is to test and optimise the proposed solutions. If students have installed an innovative ventilation system, they can continue to monitor data from IoT sensors to assess its effectiveness. This iterative process encourages systems thinking and teamwork skills, as students must collaborate, evaluate their results, and make adjustments for improvement. Ultimately, the project transforms students into active participants in solving a significant societal problem, instilling in them a sense of responsibility and confidence in their own abilities to contribute to a sustainable future.

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These proposals are supported by empirical data, rendering them more convincing and compelling [4,37]. The final step involves testing and optimising the proposed solutions. If students have installed, for instance, an innovative ventilation system, they continue to monitor data from IoT sensors to assess its effectiveness. This iterative process encourages systems thinking and teamwork skills, as students must collaborate, evaluate their results, and make adjustments for improvement. Ultimately, the project transforms students into

active participants in solving a significant societal problem, instilling in them a sense of responsibility and confidence in their own ability to contribute to a sustainable future.

In summary, approaches that integrate PBL, IoT, and ESD not only make significant progress towards the SDGs, but also promote several other key skills, including:

- **Critical thinking:** When PBL, IoT, and ESD are integrated, this capacity is developed in a particularly effective manner. These combined approaches transform students from passive recipients of knowledge into active researchers engaging with real-world challenges [57]. Through PBL, students are positioned at the centre of the learning process (Figure 1), working on authentic problems relevant to their lives. The integration of IoT provides them with real-time data, which is essential for informed analysis and decision-making.
For instance, instead of merely reading about climate change, students can use sensors to monitor air quality in their city or school. This enables them to collect, process, and interpret raw data—a key prerequisite for critical thinking. They must then ask crucial questions such as, “Why does the data show this?” and “What can be done to improve the situation?” thereby building analysis and synthesis skills. In the context of ESD, which aims to integrate sustainability principles into curricula, the PBL-IoT combination is potent, requiring students to make decisions that appropriately balance the environmental, social, and economic aspects of problems [58].
- **Systems thinking:** When students work on projects such as the School Garden or Air Quality, they must recognise that the problem is not simply dry soil or polluted air, but a complex system of interacting factors. They observe that air temperature, light intensity, and soil moisture, for instance, are all interconnected. Crucially, the project compels them to adopt a holistic perspective (systems thinking): understanding how human activity (e.g., waste disposal), natural processes (rain and sunlight), and technological solutions (sensors and pumps) mutually interact [10].
- **Creativity:** The ability to generate new and original ideas is a direct result of working on authentic and open-ended problems. In traditional education, students often seek the single “right answer.” In the approach considered here, however, they are confronted with complex challenges lacking ready-made solutions. Questions such as, “How can we most effectively reduce water consumption?” or, “How can we improve the air quality in the classroom?” necessitate innovative and out-of-the-box thinking [26,27]. Students must think creatively to develop their own prototypes and solutions based on the data they have collected. This iterative process of design and experimentation actively fosters creativity and self-confidence in generating novel solutions [13].
- **Teamwork:** Working on PBL projects inherently involves a collective effort that actively fosters strong teamwork, communication, and collaboration skills [12,29]. Within a project, students must assign roles, discuss ideas, resolve conflicts, and collaborate to achieve a common goal. For example, one student might be responsible for setting up the sensors, another for programming the microcontroller, and a third for analysing the data. This collective process teaches them how to communicate effectively, respect diverse viewpoints, and reach consensus. These social skills are crucial for successfully tackling real-world problems, which frequently require collaboration and cannot be solved by a single individual [30,59].

Despite the significant benefits identified, the integration of PBL with IoT in ESD faces several challenges that necessitate careful consideration and strategic planning. Two of the most substantial obstacles are the need for community and expert collaboration and the requirement for adequate teacher training.

The true potential of the approach is unleashed when projects extend beyond the classroom walls and connect with real problems in the local community. To collect authentic data on issues such as air quality or waste management, students must interact with external actors. This necessitates collaboration with regional institutions, including municipal administrations, environmental organisations, local businesses, and individual experts who provide valuable information, mentorship, and resources. Such partnerships are essential and are explicitly enshrined in SDG 17: Partnerships for the Goals [8], recognising that complex problems demand collective efforts.

Whilst collaboration is vital, it simultaneously poses significant challenges. Schools frequently lack established channels or sufficient time to initiate and maintain these partnerships. The process of securing suitable experts willing to dedicate their time to working with students can be complex [60]. Furthermore, logistical and administrative barriers—such as coordinating schedules, obtaining permits, and securing financial resources for external activities—can hinder even the best-conceived projects.

Overcoming the challenges of external collaboration necessitates focused efforts at both the school and regional levels. Establishing formal collaborative programmes between schools and local organisations, alongside building online platforms to facilitate connections between educators and experts, can significantly mitigate these difficulties. School leaders, in particular, must foster a culture of openness to the community and provide the necessary resources for teachers to build these key partnerships.

Another critical challenge is the requirement for teachers to possess both the pedagogical and technological skills necessary to effectively facilitate PBL with IoT. The educator's role is shifting dramatically: from a provider of information, they are becoming a facilitator, mentor, and navigator [61]. This paradigm demands that they hold basic knowledge of electronics (working with sensors and microcontrollers), programming, and data analysis [4]. However, most current teacher training curricula do not incorporate such courses, leaving a large proportion of the teaching staff profoundly unprepared for these new educational demands.

This lack of preparation inevitably leads to resistance towards the introduction of new methods. Educators may feel uncertain or overwhelmed by technological complexity, which ultimately hinders the seamless integration of IoT into the learning process. The problem is compounded by the fact that the professional development offered is often superficial, focusing primarily on technology itself rather than its pedagogical integration and how it can effectively facilitate student learning [62]. Addressing this challenge necessitates systemic change.

Targeted and sustainable professional development programmes must be created to train teachers not only in technical skills (e.g., how to connect sensors and write code) but critically, in the methodology of facilitating PBL. Encouraging collaboration amongst educators and establishing communities of practice can significantly help reduce technological anxiety and build professional confidence.

Ultimately, sustained investment in teacher education is key to successfully implementing innovative approaches that will prepare future generations to address the complex issues of sustainability.

5.1. Limitations of the Study

The present study, while offering a thorough theoretical and practical overview, has several limitations that should be considered when interpreting the results. First, the methodological framework is primarily based on qualitative analysis, including a systematic literature review and case studies. The main contribution—the *EcoHabits* conceptual model—is a theoretical construct that, at the time of writing, has not undergone an empirical

validation process. Therefore, the conclusions drawn regarding its potential effectiveness are based on theoretical synthesis and logical argumentation, rather than on experimental data from a real environment. Future research should focus on the pilot implementation and testing of the model to assess its actual impact on students' behaviour and competencies.

Second, although the analysed case studies (e.g., Domotic School Garden, air:bit) demonstrate successful practices, their applicability may be context-dependent. The study does not provide an in-depth comparative analysis of the effectiveness of the presented approaches across different socio-economic and cultural environments, particularly in educational institutions with limited resources. Therefore, generalisation of the conclusions must be made with caution. Future studies are needed to investigate the adaptability of these models and identify critical factors for their successful implementation in a broader range of schools.

Third, the paper identifies key challenges to implementing PBL with IoT, including the need for adequate teacher preparation and the development of partnerships with the community and experts. Although these barriers are outlined, the study does not propose or empirically test specific methodological solutions to overcome them. The development and evaluation of targeted teacher professional development programmes, as well as the creation of sustainable models for collaboration, remain beyond the scope of the present analysis and represent an important direction for future work.

Finally, the paper acknowledges but does not delve into a detailed critical analysis of the potential ethical, infrastructural, and equity challenges associated with scaling IoT implementation. The practical feasibility of widely deploying and maintaining IoT infrastructure across diverse school environments, especially those with limited financial resources, remains a significant limitation. Furthermore, the use of sensor data in educational contexts raises critical privacy and ethical concerns regarding the continuous monitoring of student behaviour and data ownership. While the conceptual model emphasises the potential benefits, it lacks detailed solutions for ensuring data security and obtaining informed consent in a classroom setting. Future research is therefore essential to develop robust protocols that guarantee the ethical application of IoT in education, mitigating potential inequalities in access to technology and protecting the privacy of learners.

5.2. Applicability and Practical Contribution

The results of this study demonstrate significant practical applicability for several key stakeholder groups in the education ecosystem. For educators and content developers, the paper provides a clear theoretical foundation and practical guidance for integrating IoT projects into curricula. The presented problem-solving cycle—from defining a challenge and collecting data, through analysis, to generating solutions—can serve as a universal pedagogical model. Concrete examples, such as the creation of smart school gardens or air quality monitoring systems, offer ready-made scenarios that can be adapted to various contexts, effectively transforming abstract SDGs into engaging and practical learning activities.

For education policymakers and school leaders, the study provides an evidence base for the necessity of strategic investments in technology and teacher professional development. The analysis clearly shows that the integration of PBL and IoT is not merely a technological modernisation, but an effective tool for developing key competencies—including critical and systems thinking, creativity, and teamwork. These conclusions can support decisions to revise curricula, establish STEM laboratories, and promote inter-institutional partnerships, all of which are fundamental to modern Education for Sustainable Development.

5.3. The EcoHabits Conceptual Model: Theoretical Contribution

The study provides innovative perspectives for educational technology developers and social innovators. The *EcoHabits* conceptual model illustrates how wearable IoT devices can be utilised to promote healthy and sustainable habits by connecting individual behaviour with collective contributions towards achieving global goals. This framework can serve as inspiration for creating new mobile applications, gamified platforms, and educational tools that transform data collection into a motivating and socially engaging process. In this way, the work not only analyses existing practices but also outlines clear pathways for future innovations at the intersection of technology, education, and sustainable development.

The *EcoHabits* model was created in response to identified gaps in existing IoT applications, particularly regarding the direct link between individual behaviour and collective contributions to sustainability. The model is presented not as an empirically tested system, but as a conceptual framework that offers future directions for research and practical applications in the field of educational technology. The inclusion of the hypothetical *EcoHabits* model in the article offers three main benefits that demonstrate its scientific and practical value:

Originality and innovation: The model presents an innovative framework that diverges from traditional IoT applications in education, which typically focus on static environmental parameters. Instead, *EcoHabits* connects individual human behaviour with collective contributions to sustainability. This demonstrates original thinking and provides an innovative solution that expands the scope of IoT technology in an educational context.

Connecting theory to practice: The model clearly connects theoretical principles of IoT with practical application, transforming abstract concepts of sustainability into concrete, measurable, and motivating actions. It demonstrates the conceptual viability of the idea by showing how technology can be utilised to form lasting environmental habits and create a genuine educational tool.

Basis for future research: The presented model serves as a framework for future empirical studies. It can serve as a starting point for other scholars to test, validate, and further develop ideas related to the application of IoT in education and behavioural sciences. In this way, the article not only analyses the existing situation but also provides directions for the future development of the topic.

5.4. Future Research Directions and Empirical Validation

Although the *EcoHabits* model is theoretically promising, its practical utility fundamentally depends on rigorous empirical validation. Therefore, future research must focus not only on empirically testing the effectiveness of the *EcoHabits* model in real-world environments but also on developing the ethical and infrastructural protocols necessary for its scalable deployment. This includes investigating solutions for data privacy when using wearable devices and establishing strategies to mitigate inequalities in access to technology across diverse educational settings.

In addition, to further advance the efficacy of IoT solutions in ESD, future research directions should explore interdisciplinary transfers of technological concepts. For instance, the development of more sophisticated sustainability monitoring systems within schools could significantly benefit from models observed in other domains, such as the application of digital twins for circular economy optimisation [63] or the rigorous approach of multicriteria risk management used in agriculture [64].

Through this methodology, the article not only analyses the existing information but also contributes to the scientific community with an innovative conceptual framework that can serve as a basis for future research and development.

6. Conclusions

The strategic integration of Problem-Based Learning (PBL) with IoT technologies within the framework of Education for Sustainable Development (ESD) is confirmed by this paper as a critical catalyst for pedagogical transformation. The rigorous analysis of the literature and case studies demonstrates that this combined approach shifts students from passive recipients of knowledge to active problem-solvers equipped with essential critical and systems thinking skills. Furthermore, the conceptual contribution of this work—the *EcoHabits* model—establishes a future direction for IoT-driven education, focusing on using personal, data-related feedback to achieve measurable, long-term individual and collective behavioural change.

Despite the proven benefits of the approach considered, several key areas require further research to maximise its effectiveness and applicability: (1) Long-Term impact and behavioural change: Longitudinal studies are needed to assess the long-term implications of this model on student behaviour. For example, research should examine whether participation in IoT and sustainability-related projects leads to lasting environmental awareness and responsible behaviour in adulthood; (2) Teacher training methodology: Future research must focus on developing and testing effective professional development programmes to prepare teachers for their role as facilitators in IoT-based PBL. Research could examine which training methods—such as mentoring, sharing good practices, or specialised courses—are most successful in overcoming technological and pedagogical challenges; (3) Empirical validation of the conceptual model: Essential future research should focus on testing the effectiveness and applicability of the conceptual *EcoHabits* model. This includes exploring how wearable IoT devices and other innovative technologies can be successfully integrated within the model's structure to promote sustainable habits and achieve measurable behavioural change; (4) Evaluating outcomes in diverse educational settings: More research is needed to assess the applicability and effectiveness of this approach in various cultural and socio-economic contexts, including in schools with limited resources. These guidelines will contribute to building a more robust and evidence-based framework for integrating technology into education, ensuring that future generations are prepared to address the most pressing issues of their time.

This work confirms that the strategic integration of the IoT into PBL projects, within the framework of ESD, acts as a critical catalyst for pedagogical transformation and for achieving the SDGs. The project cycle—from defining a problem and collecting data to generating and testing solutions, facilitated by IoT—builds essential 21st-century skills in students, including critical and systems thinking, creativity, and collaboration. Such initiatives effectively transform schools into laboratories for sustainability, where education serves not only as a means of accumulating knowledge but also as an engine for social change. Although the implementation of this approach is associated with challenges, such as technical integration, the need for adequate resources, and professional training of teachers, the proposed framework offers a promising solution for preparing future generations to address the most pressing global problems.

In light of the identified challenges, future research must strategically focus on developing methodologies and tools to facilitate the easier integration of IoT technologies into existing curricula. It is essential to explore effective ways to overcome the lack of flexibility in current educational programmes and to develop a professional development model for teachers that genuinely equips them with the necessary skills to facilitate complex and interdisciplinary projects. Furthermore, using the conceptual framework of the *EcoHabits* model as a hypothesis, future research should test the effectiveness of IoT in changing individual behaviour and building environmental habits in the long term. This will contribute

to a deeper understanding of technology’s role as a tool for social transformation and will reveal its potential for broader societal impact.

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Abbreviations

The following abbreviations are used in this manuscript:

CO ₂	Carbon Dioxide
CSR	Corporate Social Responsibility
ESD	Education for Sustainable Development
EU	European Union
GPS	Global Positioning System
IoT	Internet of Things
MQTT	Message Queuing Telemetry Transport
NFC	Near Field Communication
OECD	Organisation for Economic Co-operation and Development
PBL	Project-Based Learning
PM	Particulate Matter
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RFID	Radio Frequency Identification
SDGs	Sustainable Development Goals
SLR	Systematic Literature Review
STEAM	Science, Technology, Engineering, Arts, and Mathematics
STEM	Science, Technology, Engineering and Mathematics
UMH	Miguel Hernández University
UN	United Nations
VOCs	Volatile Organic Compounds
WHO	World Health Organisation
WoS	Web of Science

Appendix A

The following table presents a comprehensive list of the 42 scientific papers that met the inclusion criteria for the Systematic Literature Review. These publications were the subject of thematic coding and critical analysis, forming the main dataset for the development of the *EcoHabits* conceptual model. The “Thematic Code” column illustrates the codes extracted from each article. The “Case Study” column identifies the subset of articles that were used for critical interpretation of the practices.

Table A1. List of the 42 scientific papers included in the final qualitative synthesis (Thematic Coding Dataset).

No.	Ref. ID	First Author/Year	Title	Thematic Code	Case Study
1	[1]	Alsaleh, N.J. (2020)	Teaching Critical Thinking Skills: Literature Review	Theoretical overview, pedagogy of critical thinking	No
2	[2]	Arora, S. et al. (2024)	Role of Problem-Solving Ability in Promoting Sustainable Development	Role of problem-solving skills for SDGs	No
3	[3]	Kaur, K. (2018)	Critical Thinking for Global Peace: A key for Sustainable Development	Critical thinking and sustainable development	No
4	[4]	Sulisworo, D. et al. (2022)	Designing IoT-based Smart Weather System to Promote Critical Thinking Skills	IoT application, critical thinking, STEM	No
5	[5]	Kurni, M. (2025)	Critical Thinking Using IoT for Learning	IoT Integration, critical thinking in education	No
6	[6]	Štuikys, V. et al. (2025)	Developing Problem-Solving Skills to Support Sustainability in STEM Education Using Generative AI Tools	PBL, problem-solving skills, resilience	No
7	[7]	Spaho, E. et al. (2025)	IoT Integration Approaches into Personalized Online Learning: Systematic Review	IoT integration in education	No
8	[11]	Schroer, A.L. et al. (2015)	Educating the Aware, Informed and Action-Oriented Sustainable Citizen	Sustainability competencies, role of the citizen	No
9	[12]	Wiek, A. et al. (2011)	Key competencies in sustainability: a reference framework for academic program development	Fundamental theory, core competencies for sustainable development	No
10	[13]	Manalo, E. et al. (2025)	The development of students' thinking skills: Perspectives from higher education instructors in Japan, Europe, and Australia	Developing thinking skills	No
11	[14]	Annan-Diab, F. et al. (2017)	Interdisciplinarity: Practical approach to advancing education for sustainability and for the Sustainable Development Goals	Interdisciplinarity, education for sustainable development (ESD), SDGs	No
12	[15]	Lange, E.A. (2024)	Learning and sustainability in dangerous times: Stephen Sterling	Sustainability theory and learning, ESD philosophy	No
13	[16]	Meadows, D. (2008)	Thinking in Systems: A Primer	Fundamental theory, systems thinking	No

Table A1. Cont.

No.	Ref. ID	First Author/Year	Title	Thematic Code	Case Study
14	[17]	Thomas, I. (2010)	Critical Thinking, Transformative Learning, Sustainable Education, and Problem-Based Learning in Universities	21st century skills, pedagogical framework	No
15	[18]	Saputra, M.D. et al. (2019)	Developing Critical-Thinking Skills through the Collaboration of Jigsaw Model with Problem-Based Learning Model	PBL, critical thinking development, methodology	No
16	[19]	Almazroui, K.M. (2022)	Project-Based Learning for 21st-Century Skills: An Overview and Case Study of Moral Education in the UAE	Project-based learning, 21st-century skills	No
17	[20]	Urbano, V.M. et al. (2025)	Sustainable development in higher education: An in-depth analysis of Times Higher Education Impact Rankings	Sustainable development, impact assessment	No
18	[21]	Maganini M. et al. (2025)	Leveraging educational partnerships to integrate education for sustainable development into university geoscience curriculum	ESD integration, partnerships	No
19	[22]	Wu, T. et al. (2025)	Enhancing students' knowledge construction and affective-domain learning objectives through computational thinking integrated into project-based learning in online learning environments	PBL, computational thinking, online learning	No
20	[23]	Jeong, H. (2025)	Supporting interest development in gifted software education through computational thinking and project-based learning	PBL, computational thinking, software education	No
21	[24]	Dewey, J. (2008)	Experience and Education	Fundamental theory, experiential learning	No
22	[25]	Valdez, J. et al. (2019)	Problem-based learning approach enhances the problem solving skills in Chemistry of high school students	PBL, problem-solving skills	No

Table A1. Cont.

No.	Ref. ID	First Author/Year	Title	Thematic Code	Case Study
23	[26]	Tursynkulova, E. et al. (2023)	The effect of problem-based learning on cognitive skills in solving geometric construction problems: A case study in Kazakhstan	PBL, cognitive skills, case study in education	No
24	[27]	Affandy, H. et al. (2024)	Integrating creative pedagogy into problem-based learning: The effects on higher order thinking skills in science education	PBL, creativity, higher-order thinking skills	No
25	[28]	Wahyu, E.S. et al. (2017)	The Effect of Problem Based Learning (PBL) Model toward Student's Critical Thinking and Problem Solving Ability in Senior High School	PBL, critical thinking, problem-solving skills	No
26	[29]	Helle, L. et al. (2006)	Project-Based Learning in Post-Secondary Education—Theory, Practice and Rubber Sling Shots	Evidence for PBL, research	No
27	[30]	Zhang, L. et al. (2023)	A study of the impact of project-based learning on student learning effects: A meta-analysis study	Meta-analysis, effects of PBL	No
28	[31]	Strobel, J. et al. (2009)	When is PBL More Effective? A Meta-synthesis of Meta-analyses Comparing PBL to Conventional Classrooms	Meta-synthesis, PBL effectiveness	No
29	[32]	Calma, A. (2025)	Students' problem-solving skills in-depth: Ready for 'real life'?	Problem-solving skills, "real life" readiness	No
30	[33]	Bafarasat, A. et al. (2025)	Planning Competencies and Transformative Pedagogy for Sustainable Development	Fundamental theory, definition of critical thinking	No
31	[34]	Golden, B. (2023)	Enabling critical thinking development in higher education through the use of a structured planning tool	Critical thinking development, tools	No
32	[35]	Aydın, A. et al. (2023)	Examining the Effects of Physical Variables in Classrooms on Students' Attention via the Internet of Things	IoT in the classroom, impact of physical variables	No

Table A1. Cont.

No.	Ref. ID	First Author/Year	Title	Thematic Code	Case Study
33	[36]	Raknim, P. et al. (2017)	Development of project-based learning (PBL) for Internet of Things	PBL development for IoT, pedagogy	No
34	[37]	Tsipianitis, D. et al. (2025)	IoT Devices and Their Impact on Learning: A Systematic Review of Technological and Educational Affordances	Impact of IoT on learning	No
35	[39]	Ghashim, I.A. et al. (2023)	Internet of Things (IoT)-Based Teaching and Learning: Modern Trends and Open Challenges	IoT trends and challenges in education	No
36	[45]	Monteiro, A. et al. (2024)	Digital technologies and school gardens: Possibilities for transformative pedagogies and sustainable development	Digital technologies, school gardens	Yes
37	[46]	Fjukstad, B. et al. (2019)	Teaching Electronics and Programming in Norwegian Schools Using the air: bit Sensor Kit	IoT project (air:bit), electronics and programming	Yes
38	[48]	Barros, N. et al. (2023)	SchoolAIR: A Citizen Science IoT Framework Using Low-Cost Sensing for Indoor Air Quality Management	IoT project (SchoolAIR), citizen science, air quality	Yes
39	[57]	Aránguiz, P. et al. (2020)	Critical Thinking Using Project-Based Learning: The Case of The Agroecological Market at the “Universitat Politècnica de València”	Critical thinking, PBL, case study	Yes
40	[58]	Zeeshan, K. et al. (2023)	Internet of Things for Sustainable Smart Education: An Overview	Internet of Things, sustainable smart education	Yes
41	[59]	Zhang, R. et al. (2023)	Research on the Quality of Collaboration in Project-Based Learning Based on Group Awareness	Teamwork, PBL, collaboration	Yes
42	[61]	Sánchez-García, R.; Reyes-de-Cózar, S. (2025)	Enhancing Project-Based Learning: A Framework for Optimizing Structural Design and Implementation—A Systematic Review with a Sustainable Focus	PBL frameworks, ESD, Methodological support	Yes

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