Sustainable Engineering through Open Hardware and Digital Fabrication

Ingeniería Sostenible a través del Hardware Libre y Fabricación Digital

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ABSTRACT: This article explores the convergence of sustainable engineering, open hardware, and digital fabrication as a transformative approach to addressing global challenges. It examines how open hardware principles, such as modular design and accessible blueprints, enable a circular economy, reduce waste, and promote localized manufacturing, aligning with sustainable engineering goals. The integration of digital fabrication techniques, including digital twins and 3D printing, enhances resource efficiency, enables customized solutions, and supports data-driven decision-making. Real-world examples, from sustainable engineering education to plastic waste recycling, highlight the practical applications and potential of this integrated approach. By embracing these principles, future engineers can develop sustainable solutions that benefit both society and the environment. This review emphasizes the importance of aligning technological advancements with sustainability to foster a more resilient and equitable future.

RESUMEN: Este artículo explora la convergencia de la ingeniería sostenible, el hardware abierto y la fabricación digital como un enfoque transformador para abordar los desafíos globales. Examina cómo los principios del hardware abierto, como el diseño modular y los planos accesibles, permiten una economía circular, reducen los residuos y promueven la fabricación localizada, en consonancia con los objetivos de la ingeniería sostenible. La integración de técnicas de fabricación digital, incluyendo gemelos digitales e impresión 3D, mejora la eficiencia de los recursos, permite soluciones personalizadas y apoya la toma de decisiones basada en datos. Ejemplos del mundo real, desde la educación en ingeniería sostenible hasta el reciclaje de residuos plásticos, destacan las aplicaciones prácticas y el potencial de este enfoque integrado. Al adoptar estos principios, los futuros ingenieros pueden desarrollar soluciones sostenibles que beneficien tanto a la sociedad como al medio ambiente. Esta revisión destaca la importancia de alinear los avances tecnológicos con la sostenibilidad para fomentar un futuro más resiliente y equitativo.

1. Introduction

Open hardware enables sustainable engineering by fostering longevity, resource efficiency, transparency, and social equity through modular design, repairability, and access to blueprints, thereby promoting a circular economy, reducing waste, and supporting localized manufacturing (Kucuksayrac, 2023; Pohl et al., 2021; Soomro et al., 2021). By democratizing knowledge and encouraging collaborative creation, open hardware ensures designs remain accessible and adaptable, mitigating obsolescence and promoting sustainable consumption, while also enabling innovative uses of waste materials and fostering equitable access to technology (Kılınç & Kılınç, 2024; Nagatomo, 2024).

Digital fabrication enhances sustainable engineering by providing tools and methods that promote circular economy principles, improve resource efficiency, and reduce environmental impact (Ali et al., 2025; Erzen et al., 2025). Digital technologies, such as digital twins, 3D printing, IoT sensors, and simulation software, enable more accurate information management, customized solutions, optimized production processes, and data-driven decision-making, which are essential for achieving sustainability goals and preparing future engineers for digitally-driven industries (El-Nwasany et al., 2024; Lolin, 2024; Yan et al., 2025).

2. Sustainable Engineering

Sustainable engineering is a field that integrates sustainability principles into engineering practices to address global challenges such as climate change and socio-economic impacts. It emphasizes the development of proactive, informed, and responsible engineering designers who can contribute to the United Nations' Sustainable Development Goals (SDGs). Sustainable engineering education, such as the Sustainable Design program at Aalborg University, aims to equip students with the knowledge, skills, and attitudes necessary to tackle sustainability issues through innovative and systemic approaches. This involves not only technical competences but also a deep understanding of the broader socio-economic and environmental contexts in which engineering solutions are implemented. The integration of sustainability into engineering education is crucial for fostering a holistic and transformative approach to engineering that supports the transition to a low-carbon economy and society (Guerra et al., 2025).

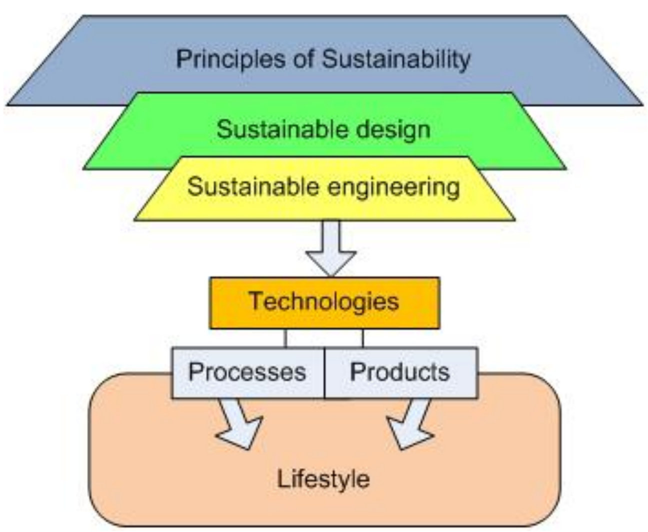

Figure 1 Sustainable engineering and lifestyle (Glavič, 2022)

Design for Disassembly (DfD) is a design approach aimed at facilitating the disassembly of products or structures at the end of their useful life to enable the reuse, recycling, or recovery of components and materials, thereby diverting them from the waste stream (Ostapska et al., 2024). This approach is rooted in the principles of sustainability and circular economy, emphasizing the reduction of waste and the efficient use of resources.

The connection between DfD and sustainable engineering lies in their shared goals of minimizing environmental impact and promoting sustainability. Sustainable engineering integrates principles of sustainability into engineering practices to address global challenges, such as climate change and socio-economic impacts (Guerra et al., 2025). By incorporating DfD principles, sustainable engineering can enhance the lifecycle management of products and structures, ensuring that they can be efficiently disassembled and their components reused or recycled. This not only reduces waste but also conserves resources and energy, contributing to a more sustainable and circular economy. Thus, DfD serves as a practical application of sustainable engineering principles, fostering a holistic approach to design that considers the entire lifecycle of products and structures.

A recent work examined students' views on sustainable engineering design (Guerra et al., 2025). This study highlights the importance of knowing sustainable development goals and having courses related to them in order to have strong sustainable engineering design skills.

Other example of sustainable engineering is related to recycling plastic waste in porous asphalt pavement (Hao et al., 2024). This example aims to alleviate the plastic waste crisis and to create a circular economy for plastics. The study explores recycling plastic waste (LDPE, HDPE, PP) in porous asphalt pavement via the wet process, evaluating its engineering, environmental, and economic impacts. Results show enhanced rutting and stripping resistance, though excessive plastic reduces abrasion resistance. Environmental leaching tests confirmed no significant pollution risks. Economically, incorporating plastics lowers costs, with 10% HDPE/PP being optimal. The research highlights porous asphalt as a sustainable solution for plastic waste, promoting a circular economy while maintaining pavement performance. Limitations include unaged mixtures and variable air voids, suggesting need for further investigation into long-term effects and real-world applications.

A recent review article by (Ostapska et al., 2024) examines DfD in the Architecture, Engineering, and Construction (AEC) industry, analyzing 470 publications and 151 built structures. They highlight timber as the dominant material (75% of cases), with small-scale projects (<300 m^2) comprising 50% of examples. DfD enhances circularity by enabling reuse and reducing waste, though barriers like cost, lack of standards, and technological gaps persist. The study underscores the need for integrated frameworks, Building Information Modelling (BIM) tools, and reversible connections to advance sustainable engineering. DfD aligns with circular economy goals, offering a pathway to minimize environmental impact in construction.

Another recent study presents a Field-Programmable Gate Array (FPGA) based tool designed to enhance the teaching of hybrid object recognition systems in computer engineering courses. It emphasizes a modular approach, combining software models and hardware architectures to improve efficiency and flexibility in system design. The tool supports project-based learning (PBL), fostering practical skills and knowledge construction. While the focus is on computer vision and object recognition, the methodology aligns with sustainable engineering principles by promoting reusable modules, reducing computational costs, and encouraging innovative solutions. The empirical evaluation highlights improved student engagement and performance, preparing future engineers to address real-world challenges sustainably (Guzmán-Ramírez et al., 2024).

3. Open Hardware

Open hardware is also known as open-source hardware (OSH, OSHW) or libre hardware. Depending on the context, related terms sometimes are used by other authors such as open source electronics, open source consumer electronics products, open source design, open-source sensors, open source actuators open source laboratory equipment, open source medical devices, open-source devices and/or open-source equipment. I prefer open hardware for its simplicity and generality. Open hardware refers to physical artifacts of technology designed and offered in the same manner as free and open-source software (FOSS). This means that the design specifications, schematics, and other necessary information are made publicly available, allowing anyone to study, modify, distribute, make, and sell the design or hardware based on that design (Dunn et al., 2023). Open hardware emphasizes the principles of openness and collaboration, enabling users to customize, adapt, and improve upon existing designs. This approach fosters innovation and community-driven development, similar to the open-source software movement. The open hardware movement encourages the sharing of knowledge and resources, which can lead to more accessible and affordable technology solutions (Phan & Ngo, 2023). Overall, open hardware represents a paradigm shift towards more transparent, collaborative, and user-centric development of physical technology, aligning with the broader goals of the open-source movement.

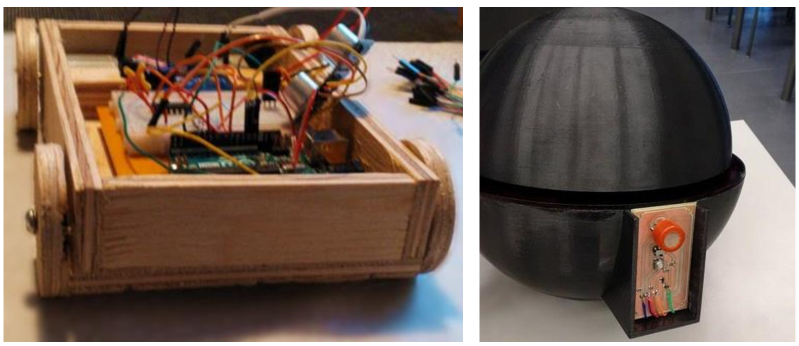

Figure 2 Two examples of open hardware devices (Georgiev & Nanjappan, 2023)

Open hardware allows engineers to adapt the device the best way and according to the characteristics of the application. Moreover, the use of open components makes the system readily and easily expandable from the hardware and software point of view. Hence, open hardware offers an efficient and sustainable way to achieve the desired results with the level of customization required (Triozzi et al., 2023).

Unlike open source software, reproducing an open hardware device has the manufacturing cost associated. Additionally, open hardware designs has not profoundly changed how and where hardware is manufactured (Dunn et al., 2023). Anyway, it is a step towards creating our own devices. Still, much has to be done to have open hardware building blocks (e.g. microcontrollers, electric motors, sensors, etc.) fully manufactured in a geographically close location.

A recent open hardware example is a photovoltaic system monitoring using an Arduino Uno microcontroller and low-cost sensors. The system integrates standard sensors (LDR, DHT22, voltage/current modules) with Arduino's open-source platform, enabling real-time data logging through Microsoft Excel. This setup demonstrates key open hardware principles: using widely available, affordable components; allowing user customization of both hardware and software; and providing a transparent framework that others can replicate or adapt. By combining open-source hardware with common software tools, the design offers a practical alternative to proprietary monitoring systems while maintaining functionality for performance tracking and optimization in renewable energy applications (Akhtar & Iqbal, 2024).

Another open hardware example is the integrated approach to assess Smart Passive Bioventing (S-PBv) as a sustainable remediation strategy for sites polluted by persistent organic pollutants. S-PBv leverages natural atmospheric pressure fluctuations to facilitate air entry into the subsoil, promoting microbial degradation of contaminants while minimizing economic costs and volatilization risks. The study outlines a pilot test in Taranto, Italy, using intelligent sensors based on open-source hardware and software to monitor environmental parameters. Results highlight S-PBv's eco-sustainability, cost-effectiveness, and applicability, particularly for medium-weight organic contaminants, offering a promising alternative to conventional bioremediation methods. The technology demonstrates potential for broader field applications with optimized data management and minimal maintenance (Triozzi et al., 2023).

Yet another example of open hardware is the Jubilee project. It is an Open Source Hardware machine designed for distributed manufacturing, where users self-produce and customize the device using off-the-shelf and digitally fabricated parts. Through analysis of 170+ builds, interviews, and community interactions on Discord and GitHub, the study highlights how a supportive online community, real-time collaboration, and iterative design improvements contributed to the project's success. Key findings include the viability of self-production for niche hardware, the importance of community engagement, and the role of customization in driving innovation. The study offers recommendations for fostering similar Open Source Hardware initiatives (Dunn et al., 2023).

The last example used in this article to showcase the use of open hardware is an FPGA-based digital PID controller to enhance the performance of mechanical ventilators, addressing challenges like low speed and jitter in traditional microprocessor-based systems. The design integrates a pulse generator, quadrature decoder, and UART communication for real-time control, achieving a cycle time of approximately 20ns. The study validates the approach through hardware implementation, demonstrating improved accuracy and responsiveness. Results show efficient resource utilization and superior performance compared to conventional methods. The proposed solution offers a reliable, high-speed alternative for non-invasive ventilators, particularly beneficial in emergency and pandemic scenarios, while maintaining cost-effectiveness and scalability (Phan & Ngo, 2023).

2.1. Open Hardware Licenses

As with open-source software (OSS), there are licenses accompanying each open hardware design. Or at least, there should be an attached license. This is not always the case because some open designs do not mention the applicable license. **Table 1** shows a list of open hardware licenses and their release year. The table includes Tucson Amateur Packet Radio Open Hardware License (Tucson Amateur Packet Radio, 2025), CERN Open Hardware License (CERN, 2025) and Solderpad Hardware License (FOOSi Foundation, 2025).

Table 1 Open Hardware Licenses

Short Name	Long Name	Based on	Year
TAPR OHL v1.0	Tucson Amateur Packet Radio Open Hardware License v1.0	GNU GPL	2007
CERN OHL v1.0	CERN Open Harware License v1.0	N/A	2011
SHL v0.50	Solderpad Hardware License v0.50	Apache License 2.0	N/A Estimated 2012
SHL v0.51	Solderpad Hardware License v0.51	SHL v0.50	2012
CERN OHL v1.2	CERN Open Harware License v1.2	CERN OHL v1.0	2013
SHL v2.0	Solderpad Hardware License v2.0	SHL v0.51	2018
CERN OHL v2.0	CERN Open Harware License v2.0	CERN OHL v1.2	2020
SHL v2.1	Solderpad Hardware License v2.1	SHL v2.0	2020

4. Digital Fabrication

Digital fabrication, also known as digital manufacturing, is a subset of advanced manufacturing methods. Digital fabrication includes additive manufacturing and 3D printing. Digital manufacturing can be classified as direct digital manufacturing or indirect digital manufacturing. Direct digital manufacturing is the creation of the desired part directly by the digital manufacturing device e.g. when a 3D printer prints a component. Indirect digital manufacturing is the creation of a mold by the digital manufacturing device and then using that mold to create the desired part or component e.g. when a reusable 3D printed mold is used to fabricate hydraulic actuators. Digital manufacturing has received high reception and adoption in the society (Saldarriaga et al., 2024).

Digital fabrication has core attributes such as mass customization, reduced time between design and production, precise and efficient robot manufacturing and a broad range of aesthetic and functional possibilities. Digital manufacturing has altered the status quo of the participants in the design and manufacturing process, in the sense that anyone can design and fabricate a piece e.g. a piece of furniture. Digital fabrication has gained increased attention and has been accompanied by supporting events such as the RepRap project and the launch of the Make magazine. Digital fabrication technology has gained greater adoption due to decreased cost in equipment and a variety of software including open-source software. All this has led to what is known as the Maker Movement: social, technological and commercial efforts around digital fabrication. Additionally, digital manufacturing has been supported by Human-Computer Interaction researchers in order to develop intuitive and easy to use tools and techniques (Hirsch et al., 2024).

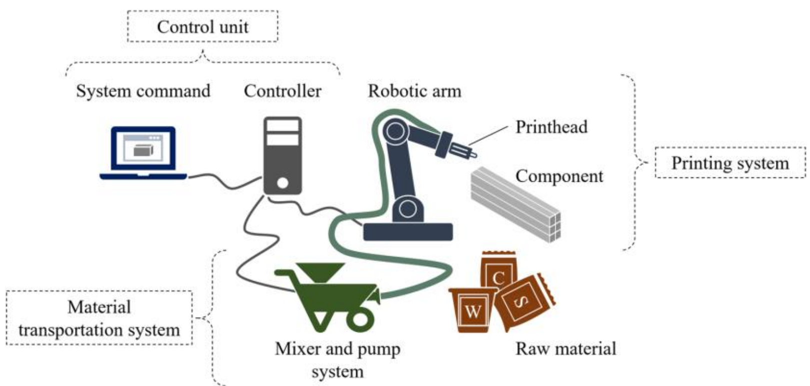

Figure 3 Example of digital fabrication: robot concrete printer (Peralta Abadia et al., 2023)

Digital fabrication is linked to other concepts such as Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfDe). DfMA is a design methodology that focuses on simplicity of the design to make the manufacturing as simple and as fast as possible. Although digital fabrication is linked to DfMA, there is a lack of integration between both. DfMA and DfDe enhance efficiency, reduce waste, and promote sustainability by optimizing manufacturing and end-of-life stages. Additionally, there is potential of combining DfMA and DfDe to advance circular economy practices (Roxas et al., 2023).

Digital manufacturing is an effort to automate and digitalize industry in the context of Industry 4.0. One example is additive manufacturing using concrete also known as concrete printing. A standard concerning this topic is the ISO/ASTM 52950 titled Additive Manufacturing. Additive manufacturing (AM), is transforming construction by automating processes and enabling the layer-by-layer fabrication of structures. AM methods, such as material extrusion and particle-bed binding, are increasingly applied to concrete printing, offering benefits like reduced construction time, cost, and environmental impact. However, challenges persist in data modeling, especially for cementitious materials with time-dependent properties. Semantic modeling approaches, like Printing Information Modeling (PIM), aim to standardize process, material, and geometry data to improve interoperability and reduce trial-and-error in concrete printing. Integrating AM with BIM further enhances digital workflows, supporting automation and innovation in sustainable construction (Peralta Abadia et al., 2023).

5. The link between Sustainable Engineering and Open Hardware

Sustainable engineering and sustainable design are intrinsically linked to open hardware through principles of longevity, resource efficiency, and transparency. (Pohl et al., 2021) emphasize that open hardware, characterized by modular design and repairability, extends the lifespan of devices, reducing environmental impacts associated with production and disposal. By enabling access to blueprints and spare parts, open hardware fosters a circular economy, aligning with sustainable engineering goals of minimizing waste and conserving resources. Similarly, (Kucuksayrac, 2023) highlights how open design in digital prototyping promotes sustainability by encouraging collaborative creation and localized manufacturing, which reduces transportation emissions and supports economic sustainability. Both articles underscore that open hardware democratizes knowledge, ensuring that designs remain accessible and adaptable, thus mitigating obsolescence and promoting sustainable consumption patterns.

The integration of open hardware in sustainable engineering is further reinforced by its emphasis on transparency and social equity. (Soomro et al., 2021) argue that digital fabrication tools in educational settings, when combined with open-source principles, enhance sustainability by enabling reuse, recycling, and reduced energy consumption. Their framework demonstrates how open hardware aligns with environmental and social sustainability indicators, such as local manufacturing and inclusive design. (Pohl et al., 2021) also stress the importance of transparent supply chains and fair labor practices in open hardware production, linking it to social sustainability. Together, these articles illustrate that open hardware not only addresses technical and environmental challenges but also fosters equitable access to technology, making it a cornerstone of sustainable engineering and design practices.

Sustainable engineering and sustainable design are increasingly linked to open hardware through the principles of circular economy and the utilization of Industry 4.0 technologies. (Nagatomo, 2024) illustrates this by examining the use of open-source resources, such as the Precious Plastic Universe (PPU) database, and additive manufacturing to transform single-use plastic waste into reusable materials. This approach not only addresses environmental concerns but also promotes quality education and responsible consumption, aligning with SDGs 4, 12 and 13. Similarly, (Kılınç & Kılınç, 2024) highlights the potential of 3D food printing (3DFP) as a cutting-edge technology that can reduce food waste and enable the creation of customized, nutritious food. Both articles emphasize the role of innovative technologies in achieving sustainability goals.

Open hardware facilitates sustainable practices by enabling experimentation, innovation, and efficient resource utilization. (Nagatomo, 2024) demonstrates that access to open-source designs and technologies empowers students to innovate within the constraints of recycled materials, fostering a deeper understanding of sustainability and responsible design. (Kılınç & Kılınç, 2024) note that digital advanced technologies like 3D printing are increasingly being applied in smart farms and smart food factories to improve food system outcomes. This convergence of sustainable engineering, sustainable design, and open hardware supports the development of circular systems where waste is reimagined as a valuable resource, promoting reuse and remanufacturing rather than disposal.

6. The link between Sustainable Engineering and Digital Fabrication

(Ali et al., 2025) highlight the critical role of digital twins (DTs) in advancing the circular economy (CE) and achieving SDGs. The authors emphasize that accurate information, facilitated by digital tools like DTs, is essential for the effective circulation and longevity of materials and products. They conceptualize DT as a cornerstone for the CE paradigm, positively influencing sustainability by supporting recyclability, reusability, and reducibility processes. The study reviews the evolution, taxonomy, and challenges of DT deployment, underscoring its potential to downsize carbon footprints and waste in various sectors.

(Yan et al., 2025) focus on integrating digital skills into chemical engineering education to prepare students for digitally-driven industries. Their research emphasizes the incorporation of new technologies and methods into the teaching process. They showcase how digital skills, assessed through Python-based process modeling assignments and IoT-enabled equipment training, demonstrate a commitment to meeting the demands of modern industries while considering sustainability factors. The curriculum integrates the United Nations SDGs, with courses dedicating significant content to sustainability case studies, linking digital manufacturing to broader sustainability objectives.

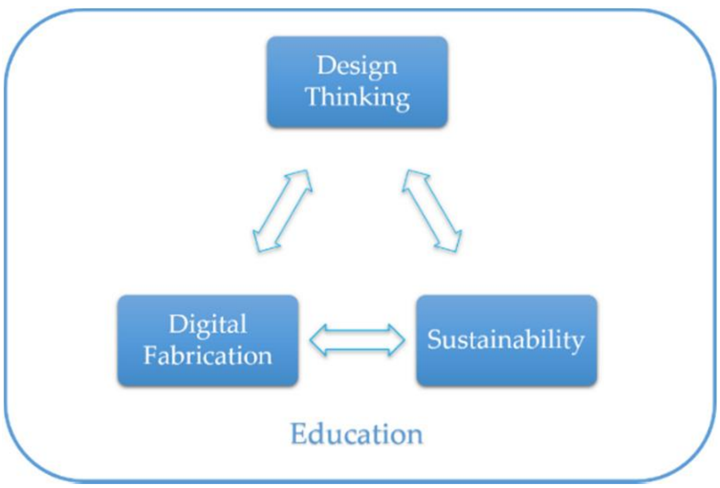

Figure 4 Relationship between Sustainability and Digital Fabrication (Soomro et al., 2021).

(Erzen et al., 2025) explore how digitalization and 3D printing are transforming the production processes of insulation materials, reducing environmental impact and optimizing performance. They note that 3D printing offers customized solutions, shaping insulation elements to meet specific building needs and preventing excess material use. This approach is aligned with circular economy principles, reducing waste and promoting sustainability in the construction sector. The review also highlights how digital analysis and simulations enhance the testing and development of insulation materials, contributing to more precise and sustainable building technologies.

(Ogundare et al., 2024) highlight the potential of integrating digital technologies into the engineering profession within developing economies to drive economic growth, innovation, and sustainable development. The report emphasizes the transformative impact of digital tools, such as simulation software and IoT sensors, on engineering processes, fostering innovation and collaboration. Furthermore, the authors stress the importance of engineers evolving into multidimensional leaders with cross-disciplinary knowledge and digital literacy to address complex challenges and contribute to sustainable development goals.

(El-Nwasany et al., 2024) argue for a new approach to technical education, "technical education 4.0", which integrates technical education with the technology developments that define the Industrial Revolution 4.0 to promote sustainable economic growth and inclusive development. This approach emphasizes the importance of aligning technical education with industry needs, particularly regarding automation and control patterns like the Internet of Things, cloud computing, and digital twins. The authors also stress the need for sustainable learning environments and methodologies that meet the needs of "Generation Z".

(Lolin, 2024) examines the effect of applied engineering practices (Lean IT and DevOps) on the operational efficiency of IT management, demonstrating that organizations adopting these practices have realized substantial improvements in operational performance. The research illustrates the importance of organizational factors, such as resource allocation and employee training, and highlights the need for combining applied engineering practices with managerial leadership and data-driven decision-making to succeed in competitive global markets. The study further illustrates how engineering practices, including automation and AI technologies, act as a strategic enabler to decrease operational complexity and accelerate innovation, contributing to sustainable growth.

7. Conclusions

This article has explored the synergistic relationship between sustainable engineering, open hardware, and digital fabrication. By leveraging open hardware principles, such as modular design and accessible blueprints, engineers can foster a circular economy, reduce waste, and promote localized manufacturing, aligning with the core tenets of sustainable engineering. Furthermore, the integration of digital fabrication techniques, including digital twins and 3D printing, enhances resource efficiency, enables customized solutions, and supports data-driven decision-making, thereby contributing to the achievement of sustainability goals.

The convergence of these approaches—sustainable engineering, open hardware, and digital fabrication—presents a powerful framework for addressing global challenges and fostering a more sustainable future. The examples discussed, ranging from sustainable engineering education and plastic waste recycling to FPGA-based tools and smart bioventing systems, highlight the practical applications and transformative potential of this integrated approach. As technology continues to evolve, embracing these principles will be crucial for equipping future engineers with the skills and knowledge necessary to design and implement sustainable solutions that benefit both society and the environment.

8. Declaration of competing interest

I declare that I have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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10. Author contributions

H.E.: ideation, literature search and article writing.

11. Data availability statement

Further data is available on request by email to the corresponding author.

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