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Sustainability Through Open-Source Hardware: A Review on Sustainability Aspects

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Abstract

Open Source Hardware (OSH) represents a novel paradigm that fosters collaborative design and the open sharing of hardware, analogous to the principles underlying Open Source Software (OSS). This review explores the sustainability dimensions of OSH, with a focus on its potential to enhance product longevity, repairability, and resource efficiency. Our analysis reveals that while OSH is frequently emphasized for its positive environmental impacts, most studies offer qualitative assessments and lack rigorous quantitative evaluations, such as life cycle assessments (LCAs). To address this gap, a structured framework for sustainable OSH is proposed, integrating key enablers such as design principles, documentation, production practices, and licensing. This framework serves as a tool for assessing the sustainability of OSH projects, emphasizing the need for a holistic approach. The argument is made for a stronger research focus on empirical studies, particularly LCAs, to quantitatively compare the environmental footprints of OSH and proprietary hardware. Such studies are essential for validating claims regarding the sustainability of OSH and guiding future innovations towards more environmentally and economically sustainable practices.

Keywords: Open-Source Hardware (OSH); Life Cycle Assessment (LCA); Distributed Manufacturing; Sustainability

1. Introduction

Open Source Hardware (OSH) has emerged as a new driver of technology and innovation, characterized by transparency, collaboration and shared development. Unlike proprietary hardware, OSH designs are freely available for anyone to study, modify and distribute, fostering innovation and democratizing access to technology. This shift can accelerate technological progress [1] by reducing costs and improving the availability of resources like lab equipment [2]. Additionally, it can enhance sustainability across various dimensions, including promoting easy repairability [3] and supporting localized production [4].

The concept of sustainability is often described by the triple bottom line approach. In this approach, ecological, economic and social aspects are given equal consideration in decision-making [5]. It seems reasonable to assume that OSH exerts an influence on all three aspects. Environmentally, it can reduce waste and promote resource efficiency through repairable and recyclable designs. Economically, it can create competitive marketplaces by lowering barriers to entry and enabling local manufacturing and customization. On a social level, the potential exists for support of education, skill development, and equitable access to technology, thereby empowering communities on a global scale.

A systematic literature review compiles current OSH sustainability assessments, emphasizing environmental factors like product longevity and repairability. By synthesizing multiple studies, it highlights the benefits of OSH, common evaluation methods, and the necessity for more data-driven research.

The primary research contribution of this study is the implementation of a structured review, a first of its kind, about OSH and sustainability. This review offers a comprehensive overview of the current state of scientific discourse on the

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subject and the methods employed to substantiate sustainability claims. A significant contribution of this study is the identification of key enablers for sustainable OSH, which are systematically compiled in a framework.

2. Methodology

The research questions for this systematic review are formulated using the CIMO (Context, Intervention, Mechanism, Outcome) framework, which is widely used for structuring research inquiries in a systematic and comprehensive manner [6]. The CIMO framework allows for a clear delineation of the different elements that influence the outcomes of interest. For this paper two main research questions were formulated:

1. Under what conditions (C) does the use of OSH (I) lead to environmental sustainability benefits (O) in different industries?
2. How are the environmental sustainability benefits of using OSH (I) currently quantified (O)?

The research questions will be answered through a systematic literature review and coding of the identified literature to build a basic theory of the relationship between OSH and sustainability. The next section discusses the methodology in more detail.

2.1. Systematic Literature Review

We followed the PRISMA method [7]for this review, conducting searches in three databases: Scopus, Web of Science, and IEEE Xplore. Additionally, we specifically searched in the "Journal of Open Source Hardware" and performed backwards search on the reviewed papers, reported under "Citation searching". The review included articles written in English and German from 2010 to 2024, focusing exclusively on peer-reviewed articles. During the identification phase, duplicates and citations of proceedings were removed. Screening was done in two phases: first by title and keywords, then by abstract (though these phases are not reported separately). Two articles could not be retrieved, and 31 articles were excluded during full-text reading and coding because they either did not use OSH, only discussed the sustainability of businesses based on OSH, or did not mention any sustainability drivers.

The search string used for this systematic review was designed to capture a broad range of literature at the intersection of sustainability and OSH. The sustainability-related terms included "sustain*", "Circular Economy", "Resource Efficiency", "Energy Efficiency" and "Life Cycle Assessment" to encompass various aspects of environmental sustainability. For OSH, the terms "Open Source Hardware”, "Open Source Appropriate Technologies"," "Free and Open Source Hardware", "Open Hardware", "Open Design", "Open Design Hardware", "Libre Hardware", "Free Hardware", "Open Manufacturing" and "Open Production" and their abbreviations and different spellings were included due to the lack of a uniform term in the field, ensuring comprehensive coverage of all relevant studies. Fig. 1 shows the result of the systematic literature review in total 59 articles were reviewed and coded. The evaluation criteria used to build a theory and answer the research questions are outlined in the next section.

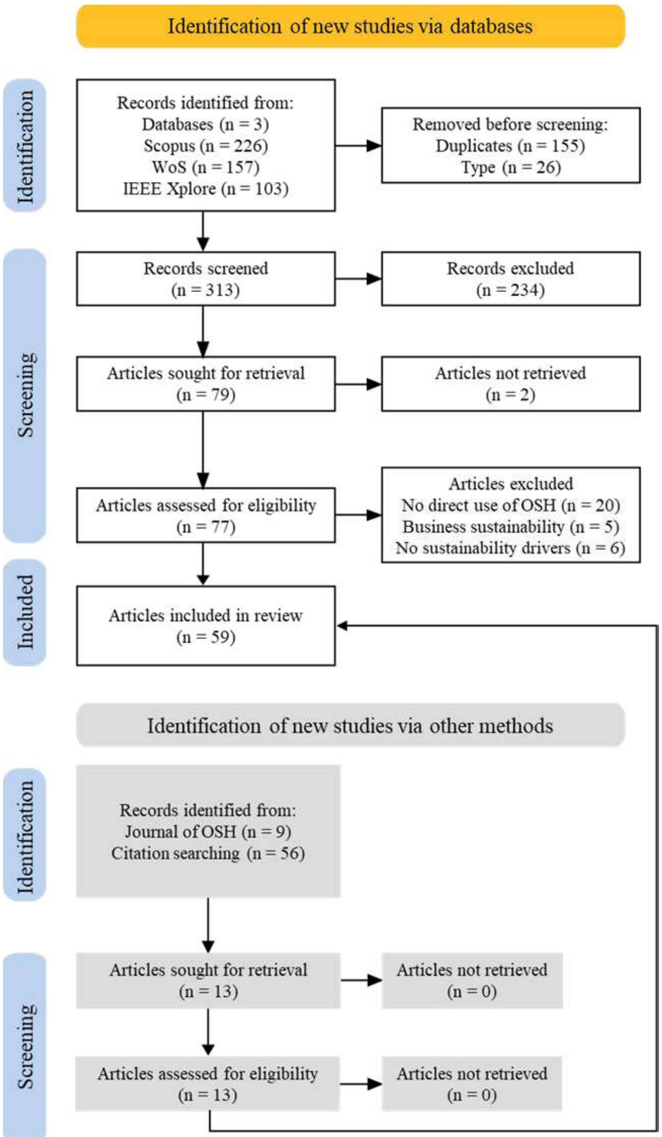

Fig. 1 PRISMA Method – Structured Literature Review

2.2. Evaluation Criteria

Four evaluation criteria were defined to assess the found literature (drivers of sustainability, study approach, investigated life cycle phases and used methods). In the following the evaluation criteria and the reasoning behind them are explained.

Drivers of sustainability: OSH is a multi-disciplinary concept spanning a product's entire life cycle, exemplifying open innovation through both process and outcome transparency [8]. Consequently, various factors influence its overall sustainability.

To identify the key drivers of sustainability for OSH four publications [9–12] were assessed, and the relevant sustainability factors were extracted. The selection of these four publications was made on the premise that they offer comprehensive analyses of the core aspects of open source hardware sustainability, addressing these aspects from a variety of perspectives. These factors were mostly focused on environmental sustainability, but it is evident that OSH as a concept also aims at economic and social sustainability. A total of 12 factors were identified in the above-mentioned papers, and two factors, "cost reduction" and "negative impacts", were added.

Study approach: Preliminary examination of the subject area between OSH and sustainability has left the subjective impression that most studies and articles on this topic are based on purely qualitative criteria. For this reason, the articles are also examined in terms of the type of approach used. A distinction is made between purely qualitative and quantitative approaches and mixed approaches. Qualitative approaches only refer to previous literature or presumed advantages and disadvantages in case studies, which are not examined using quantitative methods such as LCA. Mixed approaches were often found where costs were also evaluated, in some cases comparing the costs of the OSH with the costs of a proprietary solution.

Investigated life cycle: An initial classification of the relevant life cycle stages - design, production, transport, use and end of life - clarifies how the sustainability advantages or disadvantages of OSH manifest themselves. This categorization supports more robust theory development by contextualizing where and why these effects occur.

Used method: Until now, there has been no clear picture of the methods used to make claims about the sustainability impacts of OSH. Therefore, the methods used in the reviewed articles were assessed. The aim of this assessment was to understand the variety of approaches used in the current scientific discourse.

To map the content of the reviewed articles to specific evaluation criteria, the data must be systematically coded. In qualitative research, coding involves disaggregating data, comparing units of information, and grouping them based on emergent similarities and differences. This iterative, inductive process supports the organization of data and the generation of themes, descriptions, and theories [13]. The coding used in this paper loosely follows the grounded theory approach by Glaser and Strauss, summarized in the article by Walker and Myrick [13].

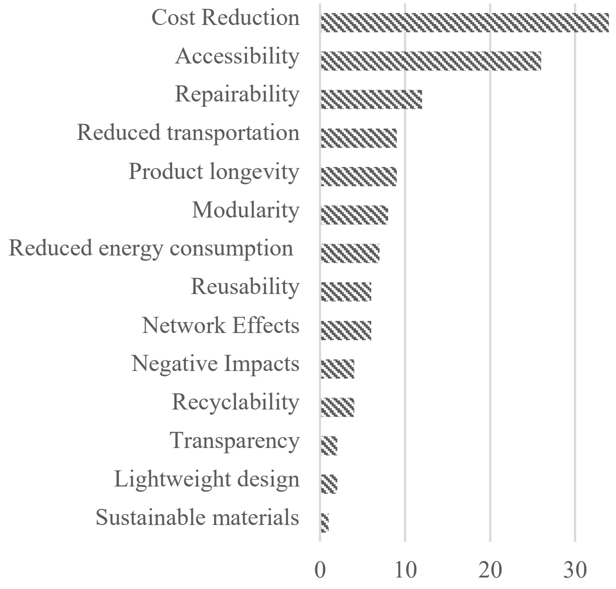

Fig. 2 Sustainability Drivers

3. Results

The evaluation of the sustainability drivers (Fig. 2) indicates an emphasis on factors relating to economic and social dimensions. Of the 59 articles reviewed, 34 publications cited cost reductions as a factor. OSH solutions can result in reduced costs by eliminating expenses associated with product development, marketing, and legal fees [14], which are often incurred by users of proprietary products. Costs can be further reduced by having a high in-house share in the production of the product [15] (either by manufacturing individual components using an in-house 3D printer or by assembling a kit yourself). In addition, the use of widely available standard components, as opposed to expensive special developments, can reduce costs even further [16].

This is followed by the accessibility factor with 26 mentions. It is particularly striking that in 16 articles, both cost reduction and accessibility were mentioned as advantages in terms of sustainability. The connection is obvious, as OSH is often placed in the context of sustainable development, especially in developing and emerging countries (often under the keyword "open-source appropriate technology" (OSAT)). One barrier to development in such countries is often a lack of capital for the acquisition of technical innovations, be it in the field of machine tools [17], technologies for the generation of renewable energy [18] , education in engineering [19] or in the health sector [20]. The accessibility factor is crucial not only for sustainable development but also for specific sectors in industrialized nations, such as research and education, which often face resource constraints [21, 22]. Another dimension of the accessibility factor is the free availability of designs on the Internet, which represents a relatively barrier-free access to knowledge [23, 24]. OSH is therefore often used in citizen science projects [25] or in the education sector [24].

In terms of environmental sustainability, the impacts of OSH can be categorized into three main areas: mode of production, design inherent principles, and open design documentation. Reduced transportation and reduced energy requirements are drivers of sustainability in terms of mode of production. Production close to the end consumer or by the end consumer himself is assumed to reduce transportation distances. This was mentioned in a total of nine articles. However, four of them alone refer to a very similar use case, namely the recycling of plastic [26–29]. Reduced energy requirements can for example be achieved through the better integration of renewable energy in small and decentralized production systems [30]. Reduced energy consumption can also be considered as design-inherent principle when energy efficient components are used in the design of the product [31].

Other design-inherent principles, like repairability, modularity and reusability impact the product longevity and recyclability while the use of lightweight (two mentions) and sustainable materials (e.g., recycled materials; one mention) is of minor interest in the reviewed articles. Especially repairability (12 mentions) and product longevity (nine mentions) are relevant topics in the discussion of ecological sustainability of OSH. The reparability of products is of course a decisive factor for longevity. The most in-depth analysis of the relationship between reparability and product longevity can be found in [32]. Repairability can be achieved through direct interventions in the design process and by making relevant data accessible. The open and accessible documentation of the design not only improves the repairability but also enables network effects and transparency. Network effects refer to the phenomenon that the value of OSH increases as more people and organizations participate in its development, use, and support. This, can enable sustainable practices like circularity [12] and lead to the strengthening of the local knowledge base [33], which in turn supports social sustainability [34].

The results in terms of approach, life cycle phase and method are presented in Fig. 3. Only seven articles use purely quantitative methods to show the impact on sustainability. Mixed methods were only identified for the "cost reductions" factor. Most of the articles use qualitative methods, including case studies and reviews, for example. Accordingly, there is often no mention of specific life cycle phases. The LCA method is only used in four articles, all of which were written by authors from Michigan Technological University [26, 27, 29, 30].

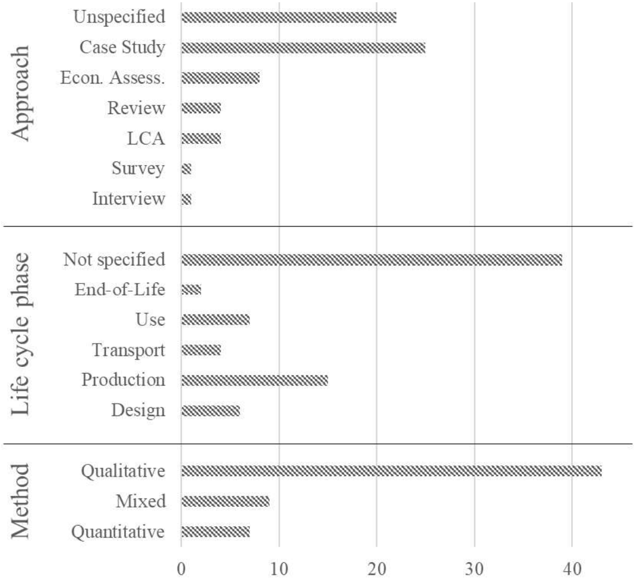

Fig. 3 Study approach, evaluated life cycle phases and used methods

4. Framework for sustainable OSH

OSH promotes collaborative design and open sharing. It can enhance ecological sustainability by increasing product longevity and repairability. The objective of environmental sustainability in OSH cannot be achieved by focusing on individual factors in isolation.

Instead, sustainability requires a holistic approach in which several drivers or "key enablers" come together and work synergistically. For example, a product may have open and transparent documentation and an unrestricted license and be manufactured in a state-of-the-art factory powered entirely by renewable energy. However, if the product design is flawed - for example, using adhesives that make it difficult to disassemble and recycle - then the overall sustainability goal is compromised.

To visualize this, we introduce the framework for sustainable OSH as a town square, where each road leading into the square represents a key enabler of sustainability (design principles, documentation, production practices and licensing). These roads must all connect to form a functional, accessible square that serves as a meeting place for sustainable OSH. But the square itself is not enough; it would be lifeless without a community of people and organizations actively using it, sharing ideas, and working together.

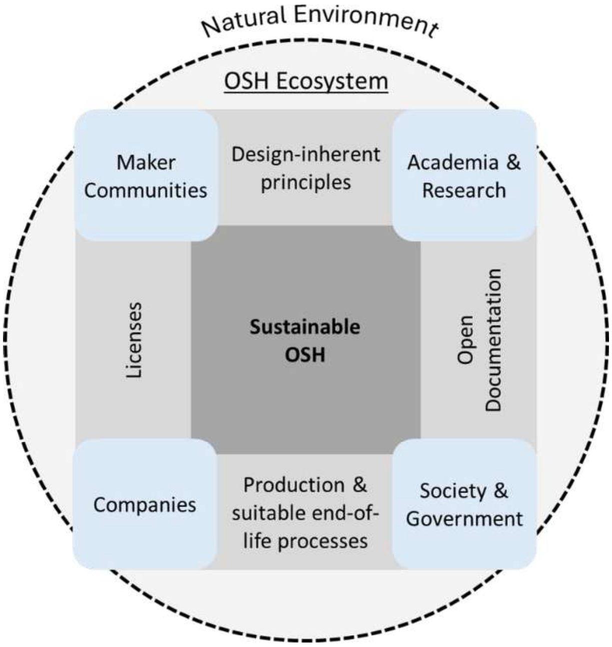

Fig. 4 Framework for sustainable OSH

This metaphor emphasizes the need for an interconnected knowledge ecosystem, where various stakeholders play distinct but interdependent roles in promoting sustainability. Shi and Chen (2022) highlight the importance of multi-agent and multi-level knowledge ecosystems, where makerspaces serve as key orchestrators of resources and platforms for innovation [35]. Applying this perspective to OSH, open-source hardware projects can thrive in environments that facilitate knowledge exchange, collaboration, and iterative design improvements. Successful OSH projects such as Arduino and RepRap exemplify this concept, as they have benefited from active, engaged communities that drive co-creation and refinement. By fostering collaboration among these stakeholders, this ecosystem amplifies the network effects previously discussed, further enhancing the value of OSH.

In contrast, open source projects in areas such as manufacturing often struggle due to the lack of a robust community or infrastructure that encourages engagement and collaboration [36]. Although case studies show that even without a large ecosystem, meaningful projects in the field of mechanical engineering can already be implemented [37]. This highlights the need for structured collaboration mechanisms.

In a sustainable OSH ecosystem, different entities bring unique strengths and contribute to the overall resilience of the system. The Quintuple Helix framework expands on traditional innovation models by incorporating civil society and the natural environment as crucial dimensions [38]. Applying this framework to OSH sustainability emphasizes that:

- **Academia and research organizations** often serve as the nucleus for new ideas and technologies. They provide basic research, initiate projects, and disseminate knowledge that can seed innovation.
- **Maker communities and independent innovators** act as early adopters and co-designers, experimenting with prototypes, sharing feedback, and adapting designs to real-world needs. They help bridge the gap between theory and practice [35].
- **Industry and businesses** provide manufacturing capabilities and commercialization strategies, ensuring scalability while maintaining OSH principles.
- **Society** provides a source of inspiration and feedback, both as idea generators and as end users. The wider public can shape the direction of OSH by expressing their needs and values, which can influence the types of projects pursued.
- **Governments and policy bodies** establish regulations and incentives to foster OSH adoption and promote sustainable, circular economy models. In addition, they can facilitate co-opetition—a strategic balance between competition and cooperation—by supporting shared infrastructure, open standards, and best-practice exchanges. Co-opetition enhances regional innovation ecosystems, allowing companies to compete in product differentiation while collaborating on sustainability frameworks and knowledge sharing [38].

5. Conclusion & Outlook

The sustainable OSH square provides a structured framework for analyzing key enablers of sustainability, but also exposes methodological challenges in quantifying and validating their interactions. Addressing these challenges requires rigorous, data-driven methodologies, particularly for managing uncertainty in LCAs — an aspect often treated as secondary in existing research [39]. However, uncertainty plays an even greater role in OSH due to high variability in production methods, materials, and geographic contexts.

Despite the proliferation of OSH projects addressing sustainability challenges, such as decentralized renewable energy solutions, the existing literature remains predominantly qualitative, offering scant empirical evidence on their environmental impact. For instance, Reinauer & Hansen examined 60 small wind turbine projects [40], yet systematic comparative LCAs of OSH versus proprietary hardware remain sparse. This deficit hinders the substantiation of sustainability claims and the guidance of OSH innovations toward environmentally and economically sound practices.

To address this knowledge gap, future research should prioritize comprehensive LCAs that assess the full environmental implications of OSH. Incorporating OSH-specific data into LCA databases [41] could significantly improve transparency, comparability and overall data availability. Furthermore, real-world case studies are needed to validate the proposed framework and refine methodologies for evaluating OSH from an ecological sustainability perspective.

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