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Bridging Circular Design Strategies and Natural Fiber Reinforced Polymer Composites: A Preliminary Conceptual Framework

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Abstract

Natural Fiber Reinforced Polymer Composites (NFRPCs) are gaining attention as sustainable alternatives to conventional composite materials, due to their renewable origin, potential biodegradability, and possibly lower environmental impact. However, while technical advances in NFRPCs have progressed, the application of Circular Design (CD) strategies to their development remains underexplored. This paper presents a preliminary conceptual framework developed at the University of Las Palmas de Gran Canaria, aligning CD principles with the specific challenges and opportunities of NFRPCs. Building upon an extensive literature review, the study identifies and critically evaluates key design principles, tools, and strategies, assessing their relevance for guiding decision-making in this material context. The proposed framework offers guidance for integrating CD strategies from the earliest stages of product development, encompassing material selection, lifecycle mapping, and end-of-life planning. To assess its usability and practical value, the framework was tested through two academic case studies. The feedback gathered highlights both the framework's potential as a learning and design support tool and the need for improved accessibility and clarity in Circular Design resources. Overall, this work contributes to bridging the gap between sustainable materials research and practical design application, offering a material-specific, adaptable, and bilingual resource for students, early-career engineers, and designers seeking to adopt circular practices. By combining systemic thinking with material-specific considerations, the framework fosters the development of more inclusive, regenerative, and ethically responsible design solutions.

Keywords: circular design; natural fiber-reinforced polymer composites; material selection; product design

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Academic Editor: Jasiulewicz-Kaczmarek Małgorzata

Received: 31 July 2025
Revised: 5 September 2025
Accepted: 11 September 2025
Published: 14 September 2025

Citation: Narganes-Pineda, A.; Hernández-Castellano, P.M.; González-Suárez, P. Bridging Circular Design Strategies and Natural Fiber Reinforced Polymer Composites: A Preliminary Conceptual Framework. *Sustainability* **2025**, *17*, 8260. https://doi.org/10.3390/su17188260

1. Introduction

Climate change, biodiversity loss, and the growing pressure on natural resources are key drivers of the ongoing global transformation in production and consumption systems [1,2]. The extensive exploitation of our planet's resources and the globalized use of materials with a significant environmental footprint, is a challenge that the scientific community has faced in recent decades. The global reliance on plastic materials poses an increasing sustainability challenge. The extensive use of plastic and the challenges associated with its waste management have driven researchers to explore viable and environmentally friendly alternatives [3,4]. In this context, the use of more sustainable materials plays a central role in mitigating the negative environmental impacts associated with product manufacturing and usage. Specifically, the polymer composites industry, traditionally dominated by non-renewable synthetic materials, has faced growing criticism due to its significant ecological footprint and limited recyclability [5,6]. In response, Natural Fiber Reinforced Polymer Composites (NFRPCs) have emerged as a promising alternative.

NFRPCs are composite materials in which natural fibers derived from natural sources are used to reinforce a polymer matrix. Their primary appeal lies in their use of renewable resources, lower density compared to conventional synthetic materials and, in certain cases, potential biodegradability [7]. These materials have already found applications in sectors such as automotive, construction, furniture and packaging [2,8]. However, their adoption still faces several technical, economic and design-related challenges. These include fiber variability, sensitivity to moisture, compatibility with polymer matrices and a notable lack of design strategies that account for their behavior over extended or circular life cycles [9,10].

This research builds upon previous work conducted by the Integrated and Advanced Manufacturing Research Group at the University of Las Palmas de Gran Canaria, supported by the European Regional Development Fund (ERDF) under the INTERREG MAC 2014–2020 program. The previous work consists of two projects: ecoFIBRAS (Grant number MAC/4.6d/040) and Inv2Mac (Grant number MAC2/4.6d/229). The main objective of ecoFIBRAS was to explore the feasibility of converting biomass waste generated during eradication and control campaigns of four invasive plant species in the Canary Islands into valuable resources. Building on this foundation, Inv2Mac expanded the scope to investigate the utilization of residual biomass derived from the management of invasive plant species across the wider Macaronesian region [11]. In addition, these projects have also fostered the creation of technology-based companies, including some located within the Gran Canaria Technology Park's Experimental Area for Circular Economy [12]. The present proposal aims to continue and further explore this research line, strengthening knowledge transfer and promoting innovative approaches to valorize these bio-based resources within a Circular Economy context.

Building on these efforts to valorize bio-based resources, the concept of Circular Design (CD) emerges as a complementary and increasingly relevant paradigm. Deeply aligned with Circular Economy principles, this design approach focuses on extending product lifespans, facilitating reuse and recycling and minimizing waste from the earliest stages of product development [13]. Circularity refers to an economic system aimed at eliminating waste and keeping products, components and materials in use at their highest value for as long as possible [14]. Unlike the traditional linear model ("take–make–dispose"), CD seeks to retain material value within the economic system for extended periods of time [15]. Tools such as design for disassembly, design for recyclability and life cycle assessment have become central principles in sustainable product development [16–18]. Nevertheless, the integration of CD principles into the development of NFRPCs remains underexplored. This gap presents a critical opportunity to enhance both the environmental performance and long-term commercial viability of these materials.

Although the technical literature on NFRPCs has made substantial progress in areas such as processing techniques, mechanical properties and industrial applications, there is a clear lack of approaches that address the design of NFRPC-based products from a circular and sustainable perspective [19,20]. Most existing studies focus on material characterization or performance enhancement, often overlooking aspects related to product design, strategic development and end-of-life management. Furthermore, many current CD tools were developed with traditional wood, metallic or plastic products in mind and do not adequately account for the unique behavior of bio-based composite materials [5], understanding bio-based materials as those derived wholly or partially from renewable biological resources rather than fossil-based sources [17,21].

This study introduces a preliminary conceptual framework that helps to systematically integrate CD strategies and tools during the early design stages with the specific opportunities and limitations of NFRPCs. Through a comprehensive review of academic and technical literature, it identifies the key CD principles applicable to these materials and translates them into a set of practical guidelines to support decision-making in early stages of product design and development.

2. Theorical Background

2.1. Definition and Characteristics of Natural Fiber Polymer Composites

NFRPCs consist of hybrid materials composed of a polymeric matrix reinforced with fibers derived from natural sources (see Figure 1) such as plants, animals, or minerals [19,22]. These fibers are valued for their potential renewable nature and environmental benefits, compared to synthetic counterparts like glass or carbon fibers [10]. The fibers act as reinforcement, providing mechanical strength, while the polymer matrix binds and protects the fibers, maintaining the structural integrity of the composite. The polymer matrix, either thermoplastic (e.g., polypropylene, polyethylene, polylactic acid) or thermoset (e.g., epoxy, polyester), functions as the binding medium [23]. Plant fibers are the most common [24].

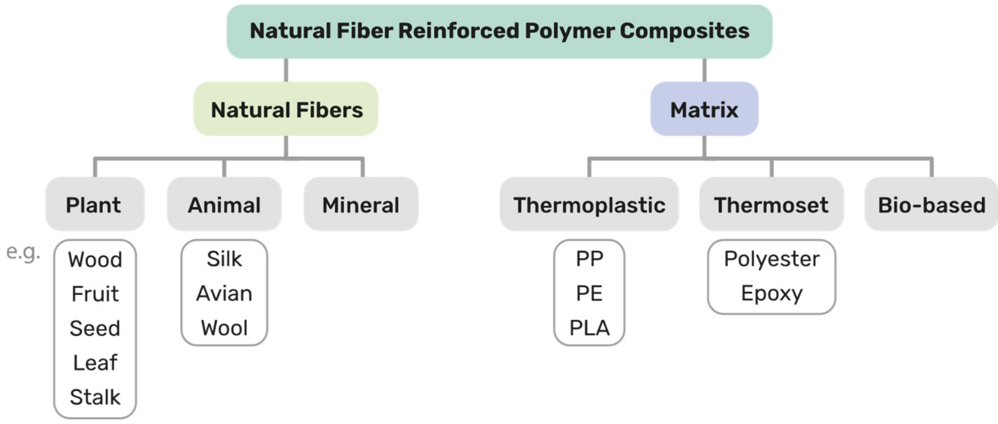

Figure 1. NFRPCs natural fibers and matrix types [1,25].

The manufacturing processes of NFRPCs vary depending on the fiber and matrix type, as well as the intended application. Common techniques include hand lay-up [26], compression molding [27], resin transfer molding [2], injection molding [28], rotational molding [29], and extrusion [30]. These processes require controlled parameters such as temperature, pressure, and curing time to ensure proper fiber dispersion and matrix impregnation. Fiber treatments, such as mechanical, chemical, or enzymatic, may also be applied to improve interfacial bonding. Particular attention must be paid throughout the entire manufacturing process to avoid the degradation of natural fibers, as this can compromise the mechanical properties and overall performance of the composite. Manufacturing efficiency, scalability, and energy consumption are critical factors influencing the circularity and environmental performance of the final composite [28].

As global attention shifts toward bio-based innovation, NFRPCs are being explored not only for their performance potential but also for their role in reducing dependence on fossil-based and non-recyclable composites. NFRPCs could potentially offer environmental and technical advantages over conventional fiber-reinforced composites [2,30]. The abundance of natural fibers, as well as their often renewable and biodegradable nature, could significantly reduce the ecological footprint of final products [19,22]. Moreover, their low density allows for lightweight design, crucial in transportation sectors for improving fuel efficiency [20]. Additionally, the energy required to produce and process natural fibers could potentially be lower than that needed for synthetic fibers [19].

Despite their advantages, NFRPCs exhibit several limitations. Natural fibers are inherently hydrophilic, which results in poor interfacial bonding with hydrophobic polymer matrices, leading to reduced mechanical performance [31]. Additionally, their properties are highly variable, influenced not only by factors such as fiber species, cultivation conditions, and processing methods [2], but also by the inherent variability of natural-origin materials themselves. Their limited thermal stability and susceptibility to moisture further constrain their application in high-demand environments. Moreover, the often-irreversible blending of natural fibers with synthetic polymers complicates recycling processes and poses significant challenges to Circular Economy implementation [20].

These materials are being applied across diverse sectors including automotive panels, interior components, building materials, and packaging, where lightweight and eco-conscious materials are demanded [2]. While the use of natural fibers is often assumed to enhance sustainability, a critical evaluation of the full material system, including polymer origin, processing impacts, and end-of-life scenarios, is necessary. Their potential alignment with CD principles such as resource conservation and life cycle extension remains conditional and should not be presumed based solely on the bio-based nature of the reinforcement phase.

2.2. Circular Design Principles

Circular Design represents an evolution from Eco-design within the broader framework of the Circular Economy. While Eco-design primarily focuses on minimizing environmental impacts throughout a product's life cycle, CD reimagines how products are conceived, produced and used, with the aim of preserving their value within the system for as long as possible [32]. As such, CD becomes a tangible pathway to implement Circular Economy principles through practical, scalable and innovative design strategies [33,34].

Rather than viewing waste as an inevitable end point, CD reframes it as a potential resource, challenging the prevailing culture of disposability that has historically shaped industrial production and consumption. It embeds Circular Economy principles not only to reduce negative impacts but to generate regenerative, long-term value [13]. This perspective is deeply informed by the Cradle-to-Cradle philosophy developed by McDonough and Braungart [35], which emphasizes the deliberate selection of materials from the earliest design stages to prevent downcycling and ensure compatibility with closed biological and technical loops.

Fundamentally, CD challenges the role of traditional design in perpetuating linear consumption and the continuous production of goods. Instead, it promotes an ethical, systems-thinking approach, one that considers social, environmental and economic impacts across the full lifecycle of products. In doing so, it aligns not only with ecological regeneration but also with social economy models, which emphasize community engagement, equity and inclusive value creation within local contexts [36,37].

From a previous review [38], four core principles have been identified as foundational to CD:

- **Resource Conservation:** focuses on designing for closed-loop material flows, reducing raw material extraction, and minimizing waste. It encourages the regeneration of natural systems and supports strategies such as recycling, upcycling, and cascading material use through multiple life cycles [16,39].

- **Lifecycle Extension:** prioritizes durability, modularity, and emotional attachment to prolong product use and discourage planned obsolescence. Practices such as reuse and repair reduce environmental impact over time [13,40,41].
- **Assembly and Disassembly:** advocates for modular designs and reversible connections to enable easy repair, component replacement, and efficient material recovery at end-of-life, facilitating practical circularity [13,16,32,39].
- **Repair and Maintenance:** promotes design for repairability and maintenance as standard features, allowing users to extend product lifespan while minimizing the need for new resources [13,16,32].

Together, these principles support a design paradigm that is environmentally responsible, socially inclusive, and technically feasible. By bridging material innovation with systems thinking, CD acts as a key enabler of sustainable transformation across multiple sectors, particularly when applied to materials like NFRPCs, which present distinctive challenges and opportunities for circular innovation.

2.3. Gaps in Aligning NFRPCs with Circular Design Strategies

This study builds upon two research phases. Phase 1 involved a systematic literature review on CD from previous work, aimed at identifying key principles, strategies and tools, which served as the conceptual basis [38]. Phase 2, developed within the scope of this work, involved a comparative literature review to characterize the current state of NFRPCs, addressing aspects such as material composition, processing methods, mechanical performance, sustainability considerations, and technical challenges.

The selected sources were reviewed not only for technical data, but also for their treatment of sustainability and life cycle considerations in the design and development of NFRPCs. The analysis revealed that, although sustainability is frequently highlighted as a key advantage, there is a notable lack of standardized metrics and comprehensive assessments addressing critical aspects such as raw material sourcing, processing efficiency, end-of-life recyclability, and biodegradability [7].

Several critical gaps were identified in the current literature regarding the sustainable development of natural fiber-reinforced polymer composites (NFRPCs). Firstly, there is an absence of clear and structured design strategies explicitly oriented towards sustainability goals. While references to sustainability are common, they often remain vague and unsupported by measurable indicators or lifecycle-based assessments. Furthermore, practical guidelines for implementing Circular Economy and Circular Design principles within the context of bio-based composites are notably lacking. Existing CD tools exhibit limited adaptability to the specific behaviors of NFRPCs, particularly concerning their degradation profiles, structural variability, and end-of-life scenarios. These gaps highlight the urgent need for a tailored methodological framework that effectively integrates CD strategies with the unique material, functional, and environmental characteristics of NFRPCs.

3. Method

This study adopts a qualitative, exploratory design grounded in secondary data analysis, with the primary objective of constructing a conceptual framework that supports the integration of CD principles into the development and utilization of NFRPCs. Given the interdisciplinary scope of the topic, including material science, sustainable manufacturing and Circular Design theory, a conceptual synthesis approach based on secondary data was deemed the most suitable. The methodology consists of four stages (see Figure 2): (1) two distinct but complementary phases of literature review, (2) aimed at identifying and clarifying conceptual gaps within existing research, (3) followed by the formulation of a preliminary framework and (4) two design-oriented case studies. These gaps refer specifically to unexplored or insufficiently addressed intersections between CD principles and NFRPC applications. This multi-stage approach enhances understanding of both theoretical foundations and practical implementation strategies for CD in the context of NFRPCs. The inclusion of the research method serves to justify the systematic basis for the framework's development.

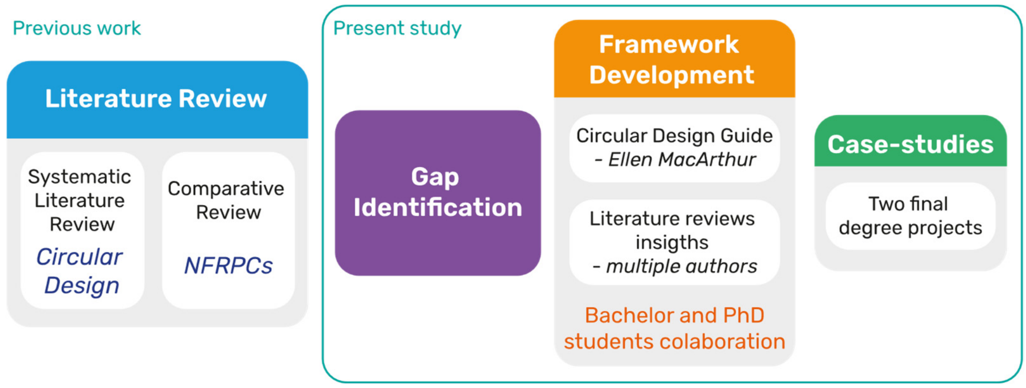

Figure 2. Research method overview.

3.1. Research Questions

The study was guided by the following research questions:

- RQ1: What are the current challenges and opportunities associated with NFRPCs?
- RQ2: What Circular Design strategies, tools, or principles have been applied to materials or products with similar characteristics?
- RQ3: How can Circular Design principles be effectively adapted to the specificities of NFRPCs to support sustainable product development?

These questions aim to bridge the technical dimension of NFRPC with systemic design approaches.

3.2. Development Process of the Framework

The aim of the development of this framework is to map current knowledge, identify gaps, and extract design-relevant principles applicable to the development of NFRPC products within a Circular Economy paradigm. Therefore, the Circular Design Guide by the Ellen MacArthur Foundation [14] was adopted as the foundational reference for developing the proposed framework. All design activities and tools suggested in this guide were analyzed for their relevance and applicability to NFRPCs. This involved a critical examination of their alignment with the material-specific challenges and opportunities observed in the previous phase.

From this analysis, a selection of core tools was made and subsequently adapted to address the design, manufacturing, and lifecycle characteristics of NFRPCs. These adaptations involved adjusting language, scope, and focus to better suit bio-based composite materials, while preserving the intent and structure of the original tools.

To test the applicability and usability of the adapted tools, two case studies were conducted through two industrial design engineering bachelor theses. In both cases, the students applied modified tools to product development challenges involving NFRPCs. These students received guidance on how to use the tools within their design processes and were encouraged to provide feedback on their clarity, usefulness, and relevance. Based on their feedback and results, adjustments were made to the framework to enhance its clarity and contextual relevance.

4. Results and Discussion

The results of this study encompass the preliminary development of the proposed framework as well as its application in two case studies. Building on the Circular Design Guide developed by the Ellen MacArthur Foundation, the framework adapts and extends existing design tools to address the specific challenges and opportunities of NFRPCs. While the original guide is structured around four stages (Understand, Define, Make and Release), the present framework introduces two additional stages and redefines the scope of one of the existing phases to better align with material-specific considerations.

This section outlines the critical aspects identified for NFRPCs and the CD principles associated with them. It presents the outcomes of the tool selection and adaptation process within the preliminary framework and it discusses feedback from the case studies, highlighting the key insights derived from their implementation.

4.1. Mapped Circular Design Principles to NFRPC

In order to enhance the circularity of products manufactured with NFRPCs, this study maps core CD principles to the specific opportunities and constraints of these materials. The mapping exercise aims to provide a structured link between design intentions and material selection strategies, supporting engineers, designers and manufacturers in the transition from linear to circular product development [18]. The four selected CD principles (see Figure 3), Resource Conservation, Lifecycle Extension, Assembly and Disassembly, and Repair and Maintenance [38], were examined in relation to their corresponding design objectives, applications to NFRPCs, key considerations, strategies and tools, as well as associated sustainability metrics.

- **Resource Conservation:** this principle focuses on minimizing the extraction and use of finite resources while promoting renewable and low-impact materials [16,39]. NFRPCs could offer an advantage in this area, as they often utilize agricultural by-products or renewable fibers such as jute, sisal or abaca [42,43]. Moreover, pairing these fibers with bio-based or recyclable polymer matrices can further reduce the environmental footprint of composite production. However, variability in fiber quality, geographical limitations of sourcing and the carbon intensity of some biopolymers require careful evaluation. In addition, the instability of agricultural by-product supply and the potential risk of contamination remain critical barriers to wider adoption. Resource efficiency can also be pursued by optimizing the material-to-performance ratio, for example, by reducing part thickness or weight without compromising function.
  To address these challenges, strategies such as green material selection matrices, eco-materials compasses and the Material Circularity Indicator (MCI) can support early-stage design and decision-making [44]. Likewise, digital tools such as CAD can aid in optimizing material efficiency. For performance assessment, a range of sustainability metrics can be applied, including renewable content (%), waste-derived input (%), reduction in material use, embodied energy (MJ/kg), land use, water use and other Life Cycle Assessment (LCA) indicators [45–47].
- **Lifecycle Extension:** prolonging the useful life of NFRPC products through enhanced durability or secondary use potential is a critical component of circularity [13,40,41]. While NFRPCs can offer competitive strength-to-weight ratios, their long-term performance is often challenged by environmental factors such as moisture or UV exposure [9,31,48,49]. Addressing these vulnerabilities requires strategies that increase both technical durability, through protective coatings, modular part replacement, or design for multi-use cycles [50] and emotional durability, by strengthening user perception and attachment to products [15]. Moreover, enabling circular business models such as take-back schemes, product-as-a-service and material traceability can

support secondary use scenarios and extend product lifespans beyond their initial function [51,52].

To operate these approaches, design tools such as Product Journey Mapping, LCA scenario analysis, the Circular Business Model and material or product passports provide actionable support for decision-making [14,32,53]. Corresponding sustainability metrics include estimated product lifespan, percentage of reused or refurbished components, durability testing results, business model return on investment, user retention and service life cycles.

- **Assembly and Disassembly:** ease of disassembly is essential for facilitating reuse, remanufacturing or high-quality material recovery [13]. In the case of NFRPCs, this principle presents both challenges and innovation potential. Minimal assembly, non-destructive disassembly and modularity are particularly valuable, as they ensure the proper, agile and efficient separation of parts [16,32,39]. This not only facilitates product recycling and reuse but also enables component replacement and functional upgrades. While adhesive and mechanical joining methods are generally compatible with NFRPC parts [54], the irreversible bonding often used in conventional composites (e.g., epoxy resins) can hinder separation [55].

  To overcome these limitations, strategies such as Design for Disassembly (DfD) guidelines, modular configurations and circular joining techniques can be employed. Tools such as Disassembly Maps [56] and Design of Circular Disassembly [16] can support the implementation of this principle. Suitable indicators include disassembly time, recovery rates and compatibility of joining techniques with material properties [16,56].
- **Repair and Maintenance:** the implementation of repairability features, standardization and design for maintenance and upgradability plays a pivotal role in enabling longer product lifecycles and fostering opportunities for reuse [50,57]. Within the context of NFRPCs, however, repairability remains a challenge, as these composites are often perceived as difficult to modify or unsuitable for remanufacturing [58–60]. Overcoming these limitations requires development strategies that emphasize modular configurations, part standardization, and the replaceability of worn components, together with the possibility of refinishing surfaces to extend functionality [50].

  The integration of maintenance manuals, design-for-repair checklists and context-specific toolkits tailored to the material characteristics of NFRPCs can facilitate accessibility and user engagement [56]. These measures not only enhance repairability but also support functional upgrades and encourage more sustainable usage patterns. Indicators such as repair rate, repair time, cost-to-repair ratios, maintenance frequency and part availability provide actionable insights into the feasibility and effectiveness of repair-oriented design strategies [50].

The mapping exercise reveals that while NFRPCs align well with many CD goals in theory, their practical implementation is often limited by technical or knowledge-based constraints. The adaptation of CD tools, originally developed for metals, plastics or other traditional materials, to the context of NFRPCs requires critical adjustments, particularly regarding material behavior, joining methods and end-of-life options. By establishing clear connections between design intentions, material behavior and measurable sustainability outcomes, this mapping contributes to bridging the gap between abstract design frameworks and the material-specific realities of bio-based composites.

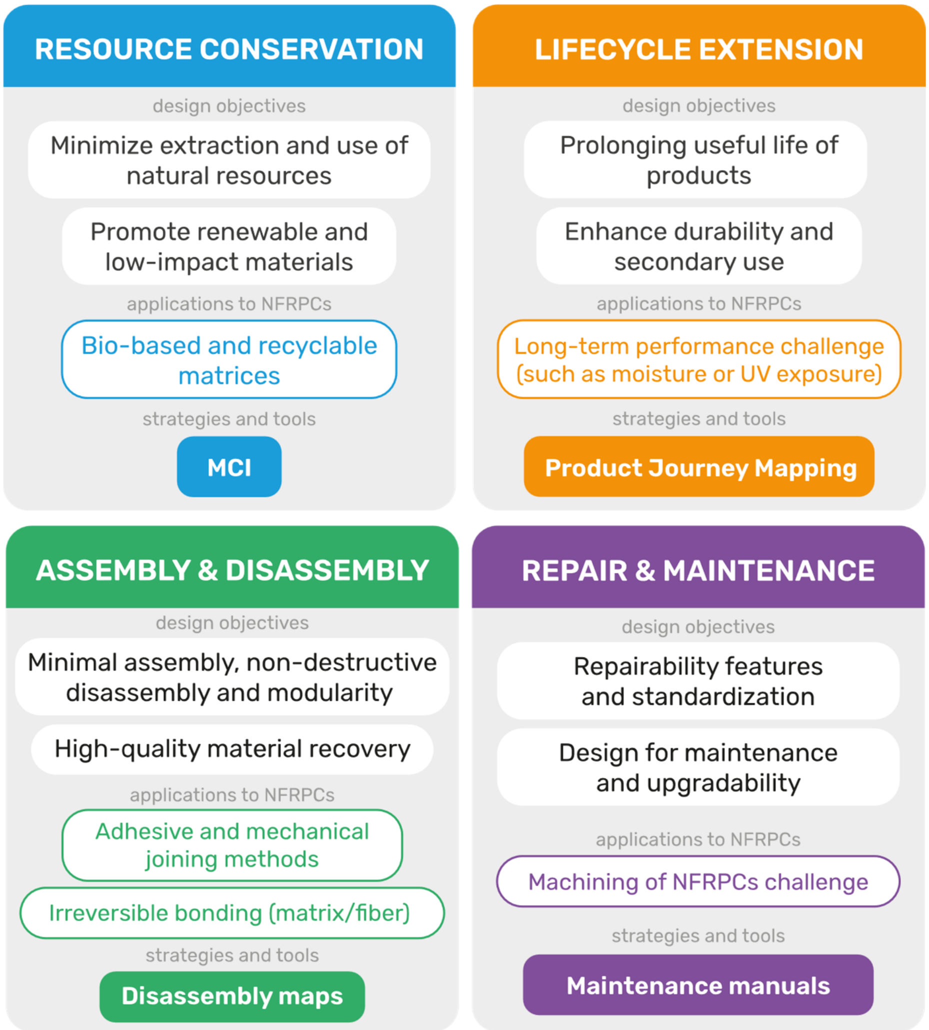

Figure 3. Circular Design principles for NFRPCs and strategic tools.

4.2. Proposed Preliminary Conceptual Framework

This study proposes a preliminary conceptual framework designed to facilitate the systematic integration of CD principles into the development of products using NFRPCs. Drawing inspiration from the widely recognized Circular Design Guide developed by the Ellen MacArthur Foundation and IDEO [14], the framework adapts and extends its structure to address the specific opportunities and constraints presented by bio-based composite materials. The result is a process-oriented tool that supports iterative and reflective design practices grounded in sustainability.

Structure of the Framework

The framework follows a six-step process, each expressed in the gerund form to emphasize its dynamic and iterative nature. These phases structure the design journey from understanding circularity to managing post-use material flows. Each phase incorporates and adapts specific tools from the Circular Design Guide, complemented by custom activities developed to address the specific characteristics of working with NFRPCs.

1. **Understanding Circularity**: This initial phase introduces key concepts of circularity while grounding them in local ecosystems and the availability of material resources. It encourages a systems-thinking approach and awareness of environmental impact across the product lifecycle. Four adapted tools guide this stage: *Understand Circular Flows* helps map material lifecycles to identify opportunities for regeneration

and closed loops, particularly for natural fibers and polymer matrices; *Service Flip* invites designers to rethink products as services, supporting business models based on sharing, reuse, or leasing; *Insides Out* focuses on analyzing components and material choices; finally, *Learn from Nature* applies biomimicry to inspire efficient and regenerative design strategies. Together, these tools establish a critical foundation for making informed, sustainable decisions in subsequent design phases.

2. **Defining the Problem through Circularity**: This phase focuses on framing a clear and strategic design brief explicitly grounded in circular principles. Rather than treating the brief as a purely functional or aesthetic exercise, it encourages designers to integrate environmental, systemic and material-specific considerations from the outset. Within the context of NFRPCs, this requires particular attention to issues such as variability in fiber quality, durability under environmental exposure and the challenges of repairability or end-of-life recovery. Addressing these aspects early ensures that the design intent is aligned not only with user needs but also with the long-term sustainability of the material. Two tools support this stage: *Define Your Challenge* helps identify the core problem and CD priorities, while *Circular Opportunities* guides exploration of impactful interventions, such as reducing waste or enhancing material reuse. Together, they orient the project toward meaningful outcomes by aligning the design intent with circular strategies from the earliest stages.
3. **Applying Circularity**: This phase enables the practical implementation of CD through hands-on engagement with materials, ideation and testing. Within the context of NFRPCs, it requires balancing sustainability ambitions with the material's challenges, such as variability in quality, susceptibility to environmental and machining degradation or limited repairability, while leveraging their advantages as renewable sources or lightweight composites. Several tools could guide this process. *Circular Brainstorming* facilitates idea generation guided by circular principles, such as reuse, modularity, or minimal material use, ensuring that creative exploration aligns with sustainability goals. *Smart Material Choices* helps designers evaluate NFRPCs based on sourcing, durability, recyclability, and environmental impact, promoting informed decisions that go beyond aesthetics or performance. *Material Journey Mapping* visualizes the entire lifecycle of a material within the product system, helping anticipate bottlenecks, waste points and opportunities for recovery. *Rapid Prototyping* supports early testing of concepts using NFRPCs, encouraging iterative development and material sensitivity. Collectively, these tools help bridge theory and practice, empowering designers to create circular solutions that are feasible, resource-conscious and aligned with user needs. These tools bridge theory and practice by encouraging experimentation while maintaining a systemic perspective. They empower practitioners to create solutions that are feasible, resource-efficient and grounded in the realities of working with NFRPCs, ultimately contributing to longer product lifecycles and more sustainable innovation.
4. **Exploring User Perception**: This phase emphasizes the importance of user acceptance and emotional connection in the success of circular products made with NFRPCs. Beyond technical performance, the sensory qualities of these composites, their texture, natural aesthetics and tactile warmth, shape how users perceive and value them. User-centered tools, such as perception testing and feedback collection, are employed to evaluate responses not only to sustainability claims but also to the experiential aspects of interacting with the material [61–64]. Factors such as trust, usability and perceived authenticity influence both immediate acceptance and the long-term attachment to the product. By acknowledging and designing for these subjective and emotional dimensions, engineers and designers can address skepticism, strengthen emotional

durability and cultivate a deeper sense of care and responsibility toward products, an essential driver of circularity in consumer culture [50].

5. **Following the Product Lifecycle**: This phase focuses on tracking the product's lifecycle beyond its initial release to ensure that circular strategies remain effective in real-world contexts. By integrating lifecycle extension principles with the specific characteristics of NFRPCs, it underscores the need to anticipate material degradation challenges, such as sensitivity to moisture or UV exposure, while actively enabling strategies for reuse, repair, and repurposing. *Product Journey Mapping* helps visualize each stage of the product's life, from production to use, maintenance, and end-of-life, enabling the identification of circular interventions across the timeline such as modular upgrades, secondary use or recovery of fibers and matrices. *Launch to Learn* encourages early market introduction of prototypes to gather real user insights, revealing unforeseen challenges and validating assumptions about NFRPCs' performance and perception. *Continuous Learning Loops* formalize feedback cycles, allowing iterative improvements based on actual user behavior and system-level outcomes. Together, these tools could support adaptive, evidence-based design processes, promoting the long-term viability and circular performance of NFRPC-based products.
6. **Managing Residues and Resources**: This final phase addresses the end-of-life stage of products, focusing on recovering value and minimizing environmental impacts through strategies tailored to NFRPCs. While conventional composites often face significant barriers to recyclability [5,6], NFRPCs introduce both opportunities and challenges: their renewable fibers may enable biodegradation or energy recovery, yet their polymer matrices, whether thermoset or thermoplastic, bio-based or fossil-derived, determine the feasibility of material recovery [65]. Consequently, assessing compatibility with existing recycling systems and identifying alternative circular pathways such as reuse, modular remanufacturing, mechanical recycling, or controlled composting becomes essential. Equally critical is ensuring material traceability and transparency, providing clear information on fiber origin, polymer type and additives, which facilitates efficient sorting and specialized recycling streams. This becomes critical given fiber variability and the lack of harmonized compostability standards. Tools like end-of-life flow mapping or material passports support structured resource recovery from the design stage onward [66,67]. Key indicators, recovery efficiency, recyclability percentages, biodegradability potential and traceability scores, offer actionable insights to ensure that NFRPCs products transition from waste to resource, reinforcing systemic circularity.

This structure is illustrated in Figure 4, which represents the six stages of the proposed preliminary conceptual framework for CD, with a specific focus on NFRPCs. The figure adopts a circular "wheel" layout to emphasize the iterative nature of the process, with each stage assigned a distinct color and the corresponding tools displayed within its section. This format is both structured and flexible, supporting use by novice and experienced practitioners alike and is particularly suited to the early phases of product design and development, while remaining compatible with complementary methodologies such as Life Cycle Assessment (LCA). The proposed tools are provided in a worksheet format, facilitating systematic documentation of insights, decisions and challenges encountered throughout the design process. A reduced version of these worksheets is included in the Supplementary Material Files to provide an overview of some of the tools used.

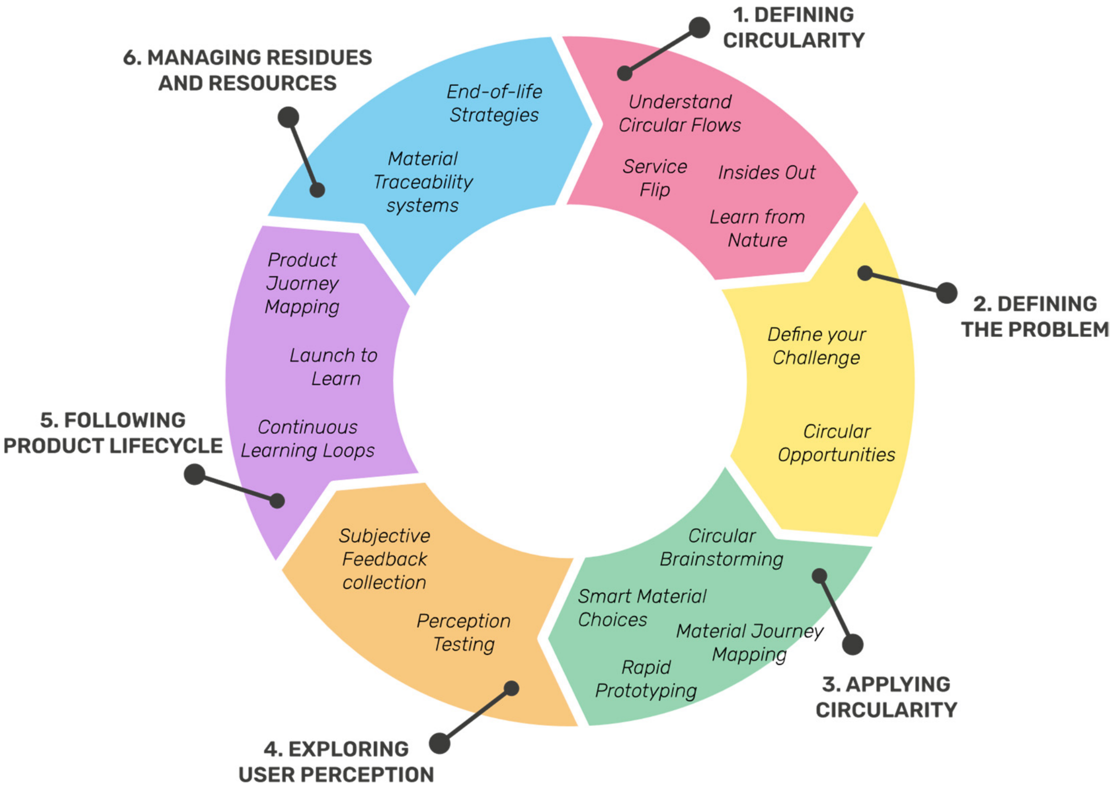

Figure 4. Preliminary conceptual Circular Design framework diagram.

4.3. Two Case Studies Feedback

To assess the usability and relevance of the proposed preliminary conceptual framework, two case studies were conducted in an academic setting by two undergraduate students from the bachelor's degree in Industrial Design Engineering and Product Development. As part of their final degree project, the students engaged directly with the framework, both contributing to its development and applying it in their design processes. Specifically, they worked with phases 1 (Understanding Circularity), 2 (Defining the Design Challenge), 3 (Applying Circularity) and 5 (Following the Product Lifecycle).

One of the projects focused on the development of university-branded courtesy gifts, which was resolved through the design of a modular chess set made from NFRPCs. The other project involved the creation of an educational game aimed at fostering STEAM (Science, Technology, Engineering, Art and Mathematic) vocations in children, with a particular focus on improving spatial skills through inclusive and gender-sensitive play experiences. Both projects served as context-specific case studies to explore how the framework supports circular thinking and material-specific design strategies.

This hands-on engagement enabled the students to evaluate the accessibility and clarity of the tools and methods provided. Through this process, they gained valuable insights into the strengths and limitations of the existing Circular Design tools. Key issues identified included the absence of concise guidance, the language barrier (many tools were only available in English) and the overwhelming amount of information not always contextualized for material-specific or local design challenges.

The students' feedback also emphasized the importance of adaptable, visually clear and modular resources, particularly when applied to the complexity of working with bio-based composites such as NFRPCs. By iteratively applying and modifying selected tools, they were able to tailor the framework to suit their project needs, reinforcing the potential for flexible applications in diverse educational and professional contexts. Figure 5 presents representative images documenting the development process and the practical implementation of the framework as applied in the two student-led design projects.

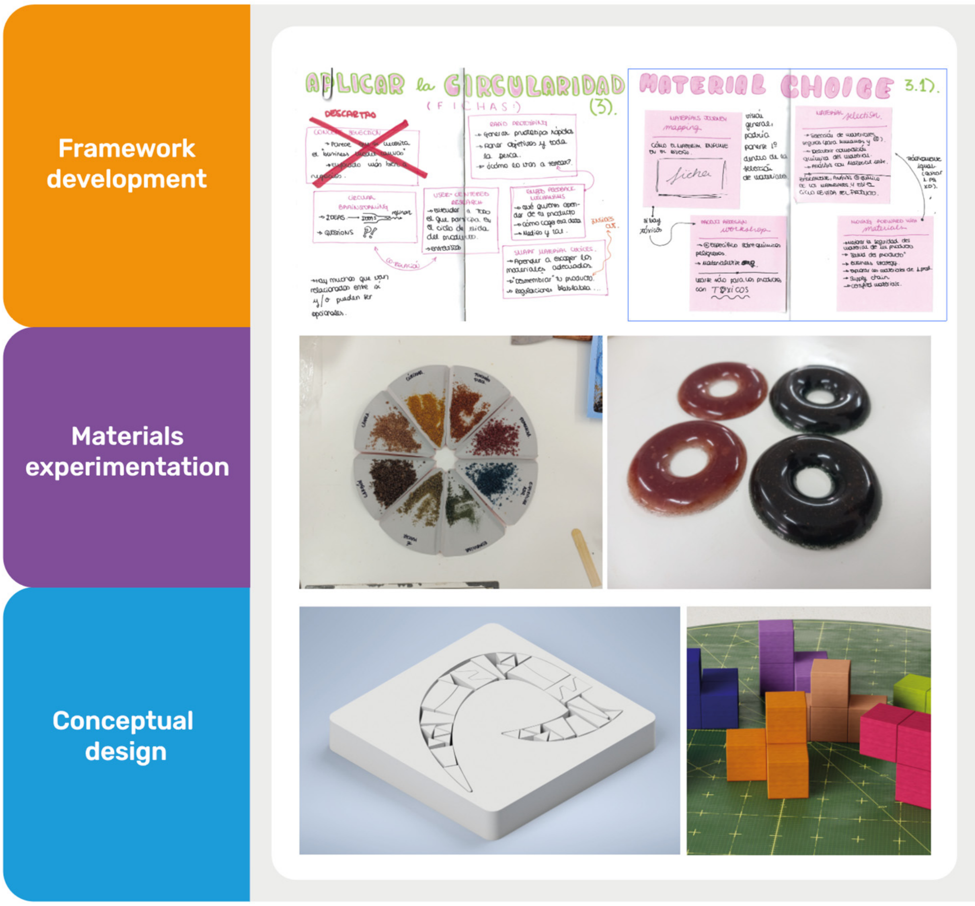

Figure 5. Implementation of the conceptual Circular Design framework in two undergraduate projects: a sustainable chess gift set and an educational STEAM game.

These case studies highlight the framework's educational value and point to its potential as a scalable design aid. It also reinforces the need for clearer integration strategies and localized adaptations to make CD more actionable in real-world scenarios [41,57].

The proposed preliminary conceptual framework serves as a decision-making tool that spans the entire design process, from early material selection to end-of-life planning supporting the integration of circularity in both conceptual and practical stages [68]. It empowers designers to choose materials aligned with functional and environmental goals, incorporate circular CD principles during ideation and evaluation, and anticipate the implications of their decisions in terms of user experience, modularity, disassembly, recyclability, and environmental impact. Additionally, it provides mechanisms to assess the level of circularity achieved, helping identify areas for improvement and guiding iteration.

Designed for a wide range of users, including product and industrial designers, materials engineers, design educators and students, and sustainability researchers, the framework is intentionally adaptable. Its bilingual (Spanish–English) format broadens accessibility, while its modular structure allows users to adjust its use to different levels of expertise and contexts, from academic to professional environments. Whether for research, education, or applied design, the framework offers a structured yet flexible guide to embed circular thinking into real-world processes.

5. Conclusions

This study introduces a preliminary conceptual framework that integrates CD principles with the specific technical, perceptual and lifecycle consideration of NFRPCs, a material often underrepresented in conventional CD methodologies. Unlike generic design guides, this framework is material-specific, addressing a complex yet promising class of composites. Its novelty lies in offering a structured, early-stage design and development framework specifically tailored to the unique characteristics of NFRPCs, thereby bridging the gap between sustainable materials research and practical design application.

The framework's novelty lies not only in its focus on NFRPCs but also in its dual function. It supports both strategic decision-making and creative ideation through dedicated toolkits, while incorporating user perception and aesthetic dimension into the design process. It aims to be accessible and adaptable, with bilingual (Spanish and English) resources specifically intended for junior engineers and designers working to implement circular strategies in real-world contexts.

Initial implementation of early stages of the framework within an academic setting revealed key challenges. Existing tools and methodologies are often fragmented, overly technical, or linguistically inaccessible, making it difficult for junior users to apply circular strategies without prior expertise. These findings underscore the need for design frameworks that are both educational and actionable, clear enough to guide application, yet flexible enough to adapt to varied levels of expertise and project requirements.

The modular structure of the framework enables its adaptation to other materials, industries or user needs, opening avenues for future refinement that balance simplicity with comprehensiveness. By combining material-specific insights with systems thinking and usability, this framework contributes to the development of more inclusive and regenerative design cultures. Ultimately, it supports a more ethical and transformative design practice, one that responds not only to environmental and technical demands but also empowers emerging practitioners to generate lasting value through circular and context-sensitive innovation.

Future work will focus on expanding and refining the framework through additional iterations. The first implementation was conducted in an academic setting, engaging a limited number of students, but subsequent cycles will involve a broader cohort to strengthen the robustness and applicability of the approach. Beyond the academic context, the framework is expected to be transferred to local initiatives, particularly within social economy projects supported by the Cabildo of Gran Canaria. This transition will provide a valuable opportunity to test its relevance in real-world scenarios, evaluate its scalability, and foster collaboration between academia, industry, and public institutions. Ultimately, these efforts aim to consolidate the framework as a practical and adaptable tool, supporting the adoption of circular strategies for NFRPC-based products in both educational and professional environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17188260/s1.

Author Contributions: Conceptualization, A.N.-P. and P.M.H.-C.; methodology, A.N.-P. and P.G.-S.; software, A.N.-P. and P.G.-S.; validation, A.N.-P., P.M.H.-C. and P.G.-S.; formal analysis, A.N.-P.; investigation, A.N.-P. and P.M.H.-C.; resources, P.M.H.-C.; data curation, A.N.-P.; writing—original draft preparation, A.N.-P.; writing—review and editing, P.M.H.-C. and P.G.-S.; visualization, A.N.-P. and P.G.-S.; supervision, P.M.H.-C.; project administration, A.N.-P. and P.M.H.-C.; funding acquisition, A.N.-P. and P.M.H.-C. All authors have read and agreed to the published version of the manuscript.

Funding: Work co-financed by the Agencia Canaria de Investigación, Innovación y Sociedad de la Información de la Consejería de Economía, Conocimiento y Empleo y por el Fondo Social Europeo (FSE) Programa Operativo Integrado de Canarias 2014–2020, Eje 3 Tema Prioritario 74 (85%).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors wish to acknowledge the contributions of Catherine Borges Martín and Isamar Sartal Blanco, whose final degree projects contributed to the development and validation of this model within the framework of the present research. During the preparation of this manuscript/study, the authors used ChatGPT (https://chatgpt.com), free version, for the purposes of improving language. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

NFRPC	Natural Fiber-Reinforced Polymer Composites
CD	Circular Design
MCI	Material Circularity Indicators
LCA	Life Cycle Assessment
STEAM	Science, Technology, Engineering, Art and Mathematics

References

1. Elfaleh, I.; Abbassi, F.; Habibi, M.; Ahmad, F.; Guedri, M.; Nasri, M.; Garnier, C. A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. *Results Eng.* **2023**, *19*, 101271. [CrossRef]
2. Santhosh, N.; Praveena, B.A.; Gowda, A.C.; Duhduh, A.A.; Rajhi, A.A.; Alamri, S.; Berwal, P.; Khan, M.A.; Wodajo, A.W. Innovative eco-friendly bio-composites: A comprehensive review of the fabrication, characterization, and applications. *Rev. Adv. Mater. Sci.* **2024**, *63*, 20240057. [CrossRef]
3. Li, L.; Zuo, J.; Duan, X.; Wang, S.; Hu, K.; Chang, R. Impacts and mitigation measures of plastic waste: A critical review. *Environ. Impact Assess. Rev.* **2021**, *90*, 106642. [CrossRef]
4. Koelmans, A.A.; Besseling, E.; Foekema, E.; Kooi, M.; Mintenig, S.; Ossendorp, B.C.; Redondo-Hasselerharm, P.E.; Verschoor, A.; van Wezel, A.P.; Scheffer, M. Risks of Plastic Debris: Unravelling Fact, Opinion, Perception, and Belief. *Environ. Sci. Technol.* **2017**, *51*, 11513–11519. [CrossRef]
5. Joustra, J.; Flipsen, B.; Balkenende, R. Circular design of composite products: A framework based on insights from literature and industry. *Sustainability* **2021**, *13*, 7223. [CrossRef]
6. Marconi, M.; Bakshi, B.; Joustra, J.; Bakker, C.; Bessai, R.; Balkenende, R. Circular Composites by Design: Testing a Design Method in Industry. *Sustainability* **2022**, *14*, 7993. [CrossRef]
7. Suárez, L.; Castellano, J.; Díaz, S.; Tcharkhtchi, A.; Ortega, Z. Article are natural-based composites sustainable? *Polymers* **2021**, *13*, 2326. [CrossRef]
8. Kurien, R.A.; Anil, M.M.; Mohan, S.S.; Thomas, J.A. Natural fiber composites as sustainable resources for emerging applications—A review. *Mater Today Proc.* **2023**, *in press*. [CrossRef]
9. Mundhe, A.; Kandasubramanian, B. Advancements in natural fiber composites: Innovative chemical surface treatments, characterizaton techniques, environmental sustainability, and wide-ranging applications. *Hybrid Adv.* **2024**, *7*, 100282. [CrossRef]
10. Sathish, S.; Karthi, N.; Prabhu, L.; Gokulkumar, S.; Balaji, D.; Vigneshkumar, N.; Ajeem Farhan, T.S.; Akilkumar, A.; Dinesh, V.P. A review of natural fiber composites: Extraction methods, chemical treatments and applications. *Mater. Today Proc.* **2021**, *45*, 8017–8023. [CrossRef]
11. Grupo de Investigación de Fabricación Integrada y Avanzada (GIFIA). Inv2mac. Available online: https://www.inv2mac.com/index.php (accessed on 3 September 2025).

12. Parque Tecnológico de Gran Canaria Área Experimental de Economía Circular. E-CircularCanarias. Available online: https://e-circularcanarias.es/ (accessed on 3 September 2025).
13. Moreno, M.; De los Rios, C.; Rowe, Z.; Charnley, F. A conceptual framework for circular design. *Sustainability* **2016**, *8*, 937. [CrossRef]
14. Ellen McArthur Foundation. The Circular Design Guide. Available online: https://www.ellenmacarthurfoundation.org/circular-design-guide/overview (accessed on 31 July 2025).
15. Wastling, T.; Charnley, F.; Moreno, M. Design for circular behaviour: Considering users in a circular economy. *Sustainability* **2018**, *10*, 1743. [CrossRef]
16. Formentini, G.; Ramanujan, D. Design for circular disassembly: Evaluating the impacts of product end-of-life status on circularity through the parent-action-child model. *J. Clean. Prod.* **2023**, *405*, 137009. [CrossRef]
17. Ritzen, L.; Sprecher, B.; Bakker, C.; Balkenende, R. Bio-based plastics in a circular economy: A review of recovery pathways and implications for product design. *Resour. Conserv. Recycl.* **2023**, *199*, 107268. [CrossRef]
18. Dumée, L.F. Circular Materials and Circular Design—Review on Challenges Towards Sustainable Manufacturing and Recycling. *Circ. Econ. Sustain.* **2021**, *2*, 9–23. [CrossRef] [PubMed]
19. Palanisamy, S.; Murugesan, T.M.; Palaniappan, M.; Santulli, C.; Ayrilmiş, N. Fostering sustainability: The environmental advantages of natural fiber composite materials—A mini review. *Environ. Res. Technol.* **2024**, *7*, 256–269. [CrossRef]
20. Uppal, N.; Pappu, A.; Gowri, V.K.S.; Thakur, V.K. Cellulosic fibres-based epoxy composites: From bioresources to a circular economy. *Ind. Crop. Prod.* **2022**, *182*, 114895. [CrossRef]
21. *ISO 16620-1:2015*; Plastics—Biobased Content. International Organization for Standarization: Geneva, Switzerland, 2015.
22. Khalid, M.Y.; Al Rashid, A.; Arif, Z.U.; Ahmed, W.; Arshad, H.; Zaidi, A.A. Natural fiber reinforced composites: Sustainable materials for emerging applications. *Results Eng.* **2021**, *11*, 100263. [CrossRef]
23. Ramachandran, A.R.; Mavinkere Rangappa, S.; Kushvaha, V.; Khan, A.; Seingchin, S.; Dhakal, H.N. Modification of Fibers and Matrices in Natural Fiber Reinforced Polymer Composites: A Comprehensive Review. *Macromol. Rapid Commun.* **2022**, *43*, e2100862. [CrossRef]
24. Shebaz Ahmed, J.P.; Satyasree, K.; Rohith Kumar, R.; Meenakshisundaram, O.; Shanmugavel, S. A comprehensive review on recent developments of natural fiber composites synthesis, processing, properties, and characterization. *Eng. Res. Express* **2023**, *5*, 32001. [CrossRef]
25. Ghalme, S.; Hayat, M.; Harne, M. A Comprehensive Review of Natural Fibers: Bio-Based Constituents for Advancing Sustainable Materials Technology. *J. Renew. Mater.* **2025**, *13*, 273–295. [CrossRef]
26. Bhat, A.R.; Kumar, R.; Mural, P.K.S. Natural fiber reinforced polymer composites: A comprehensive review of Tribo-Mechanical properties. *Tribol. Int.* **2023**, *189*, 108978. [CrossRef]
27. Manral, A.; Kumar Bajpai, P.; Ahmad, F.; Joshi, R. Processing of sustainable thermoplastic based biocomposites: A comprehensive review on performance enhancement. *J. Clean. Prod.* **2021**, *316*, 128068. [CrossRef]
28. Govinda; Widiastuti, I. The Manufacturing Process of Recycled Polymer Composites reinforced with Natural Fibers—A Systematic Literature Review. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd.: Bristol, UK, 2021. [CrossRef]
29. Ortega, Z.; Romero, F.; Paz, R.; Suárez, L.; Benítez, A.N.; Marrero, M.D. Valorization of invasive plants from macaronesia as filler materials in the production of natural fiber composites by rotational molding. *Polymers* **2021**, *13*, 2220. [CrossRef]
30. Ajayi, N.E.; Rusnakova, S.; Ajayi, A.E.; Ogunleye, R.O.; Agu, S.O.; Amenaghawon, A.N. A comprehensive review of natural fiber reinforced Polymer composites as emerging materials for sustainable applications. *Appl. Mater. Today* **2025**, *43*, 102666. [CrossRef]
31. Munimathan, A.; Muthu, K.; Subramani, S.; Rajendran, S. Environmental behaviour of synthetic and natural fibre reinforced composites: A review. *Adv. Mech. Eng.* **2024**, *16*, 16878132241286020. [CrossRef]
32. Bocken, N.M.P.; de Pauw, I.; Bakker, C.; van der Grinten, B. Product design and business model strategies for a circular economy. *J. Ind. Prod. Eng.* **2016**, *33*, 308–320. [CrossRef]
33. Sumter, D.; de Koning, J.; Bakker, C.; Balkenende, R. Key competencies for design in a circular economy: Exploring gaps in design knowledge and skills for a circular economy. *Sustainability* **2021**, *13*, 776. [CrossRef]
34. Toth-Peter, A.; Torres de Oliveira, R.; Mathews, S.; Barner, L.; Figueira, S. Industry 4.0 as an enabler in transitioning to circular business models: A systematic literature review. *J. Clean. Prod.* **2023**, *393*, 136284. [CrossRef]
35. McDonough, W.; Braungart, M. *Cradle to Cradle: Remaking the Way We Make Things*; North Point Press: New York, NY, USA, 2002.
36. Shin, C. A conceptual approach to the relationships between the social economy, social welfare, and social innovation. *J. Sci. Technol. Policy Manag.* **2016**, *7*, 154–172. [CrossRef]
37. Husgafvel, R. Exploring social sustainability handprint—Part 1: Handprint and life cycle thinking and approaches. *Sustainability* **2021**, *13*, 11286. [CrossRef]
38. Narganes-Pineda, A.; González-Suárez, P.; Hernández-Castellano, P.M. A Definition Approach to Circular Design for Product Design and Development. In *Advances on Mechanics, Design Engineering and Manufacturing V*; Springer Nature: Cham, Switzerland, 2025; pp. 309–322. [CrossRef]

39. Chen, W.C.; Rau, H. A product evaluation and innovation process based on the circular design degree and patents evolution. *J. Clean. Prod.* **2023**, *405*, 136888. [CrossRef]
40. Guerreschi, A.; Wielopolski, M. Importance of Knowing What Your Customers Know to Effective Circular Design. *Environ. Eng. Manag. J.* **2023**, *21*, 1673–1682. [CrossRef]
41. Wang, J.X.; Burke, H.; Zhang, A. Overcoming barriers to circular product design. *Int. J. Prod. Econ.* **2022**, *243*, 108346. [CrossRef]
42. Singh, R.; Singh, B.; Gupta, M.; Tarannum, H. Composite building materials from natural fibers/agro-forest residues. *Indian J. Eng. Mater. Sci.* **2020**, *27*, 137–149.
43. Jeremiah Barba, B.D.; Madrid, J.F.; Penaloza, D.P., Jr. A Review of Abaca Fiber-Reinforced Polymer Composites: Different Modes of Preparation and Their Applications. *J. Chil. Chem. Soc.* **2020**, *65*, 3. [CrossRef]
44. Niero, M.; Kalbar, P.P. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. *Resour. Conserv. Recycl.* **2019**, *140*, 305–312. [CrossRef]
45. Desing, H.; Braun, G.; Hischier, R. Resource pressure—A circular design method. *Resour. Conserv. Recycl.* **2021**, *164*, 105179. [CrossRef]
46. Lieder, M.; Asif, F.M.A.; Rashid, A.; Mihelič, A.; Kotnik, S. Towards circular economy implementation in manufacturing systems using a multi-method simulation approach to link design and business strategy. *Int. J. Adv. Manuf. Technol.* **2017**, *93*, 1953–1970. [CrossRef]
47. Mansor, M.R.; Salit, M.S.; Zainudin, E.S.; Aziz, N.A.; Ariff, H. *Life Cycle Assessment of Natural Fiber Polymer Composites*; Springer International Publishing: Cham, Switzerland, 2015. [CrossRef]
48. Asyraf, M.R.M.; Syamsir, A.; Zahari, N.M.; Supian, A.B.M.; Ishak, M.R.; Sapuan, S.M.; Sharma, S.; Rashedi, A.; Razman, M.R.; Zakaria, S.Z.S.; et al. Product Development of Natural Fibre-Composites for Various Applications: Design for Sustainability. *Polymers* **2022**, *14*, 920. [CrossRef]
49. Kamarudin, S.H.; Mohd Basri, M.S.; Rayung, M.; Abu, F.; Ahmad, S.; Norizan, M.N.; Osman, S.; Sarifuddin, N.; Desa, M.S.Z.M.; Abdullah, U.H.; et al. A Review on Natural Fiber Reinforced Polymer Composites (NFRPC) for Sustainable Industrial Applications. *Polymers* **2022**, *14*, 3698. [CrossRef]
50. Go, T.F.; Wahab, D.A.; Hishamuddin, H. Multiple generation life-cycles for product sustainability: The way forward. *J. Clean. Prod.* **2015**, *95*, 16–29. [CrossRef]
51. Zeeuw Van Der Laan, A.; Aurisicchio, M. Designing product-service systems to close resource loops: Circular design guidelines. *Procedia CIRP* **2019**, *80*, 631–636. [CrossRef]
52. Reigado, C.R.; Fernandes, S.D.C.; Saavedra, Y.M.B.; Ometto, A.R.; Da Costa, J.M.H. A Circular Economy Toolkit as an Alternative to Improve the Application of PSS Methodologies. *Procedia CIRP* **2017**, *64*, 37–42. [CrossRef]
53. Nußholz, J.L.K. A circular business model mapping tool for creating value from prolonged product lifetime and closed material loops. *J. Clean. Prod.* **2018**, *197*, 185–194. [CrossRef]
54. Kumar, J.; Singh, Y.; Naik, T.; Rana, R.S.; Rakesh, P.K.; Singh, I. Adhesive joining behaviour of banana/bagasse/epoxy composites with different joint designs. *Biomass Convers. Biorefinery* **2023**, *14*, 31827–31836. [CrossRef]
55. Nagaraja, S.; Anand, P.B.; Mohan Kumar, K.; Ammarullah, M.I. Synergistic advances in natural fibre composites: A comprehensive review of the eco-friendly bio-composite development, its characterization and diverse applications. *RSC Adv.* **2024**, *14*, 17594–17611. [CrossRef]
56. De Fazio, F.; Bakker, C.; Flipsen, B.; Balkenende, R. The Disassembly Map: A new method to enhance design for product repairability. *J. Clean. Prod.* **2021**, *320*, 128552. [CrossRef]
57. van Dam, S.S.; Bakker, C.A.; de Pauw, I.; van der Grinten, B. The circular pathfinder: Development and evaluation of a practice-based tool for selecting circular design strategies. In *Plate Product Lifetimes and the Environment 2017: Conference Proceedings*; IOS Press: Amsterdam, The Netherlands, 2017. [CrossRef]
58. Mohammed, M.; Oleiwi, J.K.; Mohammed, A.M.; Jawad, A.J.M.; Osman, A.F.; Adam, T.; Betar, B.O.; Gopinath, S.C.B. A Review on the Advancement of Renewable Natural Fiber Hybrid Composites: Prospects, Challenges, and Industrial Applications. *J. Renew. Mater.* **2024**, *12*, 1237–1290. [CrossRef]
59. Slamani, M.; Chatelain, J.-F. A review on the machining of polymer composites reinforced with carbon (CFRP), glass (GFRP), and natural fibers (NFRP). *Discov. Mech. Eng.* **2023**, *2*, 4. [CrossRef]
60. Varma, M.; Chandran, S.; Vijay Kumar, V.; Suyambulingam, I.; Siengchin, S. A comprehensive review on the machining and joining characteristics of natural fiber-reinforced polymeric composites. *Polym. Compos.* **2024**, *45*, 4850–4875. [CrossRef]
61. Abella, A.; Llorach-Massana, P.; Pereda-Baños, A.; Marco-Almagro, L.; Barreda-Ángeles, M.; Clèries, L. Perception of Recycled Plastics for Improved Consumer Acceptance through Self-Reported and Physiological Measures. *Sensors* **2022**, *22*, 9226. [CrossRef]
62. Pardo-Vicente, M.Á.; Rodríguez-Parada, L.; Mayuet-Ares, P.F.; Aguayo-González, F. Haptic hybrid prototyping (HHP): An AR application for texture evaluation with semantic content in product design. *Appl. Sci.* **2019**, *9*, 5081. [CrossRef]
63. Nordvik, E.; Schütte, S.; Olof Broman, N. People's Perceptions of the Visual Appearance of Wood Flooring: A Kansei Engineering Approach. *For. Prod. J.* **2009**, *59*, 67–74. [CrossRef]

64. Eriksson, L.; Rosen, B.; Bergman, M. Affective Surface Engineering-Using Soft and Hard Metrologhy to Measure the Sensation and Perception in Surface Properties. In Proceedings of the NordDesign 2018, Linköping, Sweden, 14–17 August 2018.
65. Liedl, B.; Höftberger, T.; Burgstaller, C. Properties of Multiple-Processed Natural Short Fiber Polypropylene and Polylactic Acid Composites: A Comparison. *Macromol* **2024**, *4*, 723–738. [CrossRef]
66. Mathur, N.; Last, N.; Morris, K.C. A process model representation of the end-of-life phase of a product in a circular economy to identify standards needs. *Front. Manuf. Technol.* **2023**, *3*, 988073. [CrossRef]
67. Huang, Y.; Shafiee, M.; Charnley, F.; Encinas-Oropesa, A. Designing a Framework for Materials Flow by Integrating Circular Economy Principles with End-of-life Management Strategies. *Sustainability* **2022**, *14*, 4244. [CrossRef]
68. Pinheiro, M.A.P.; Seles, B.M.R.P.; De Camargo Fiorini, P.; Jugend, D.; Lopes de Sousa Jabbour, A.B.; da Silva, H.M.R.; Latan, H. The role of new product development in underpinning the circular economy: A systematic review and integrative framework. *Manag. Decis.* **2019**, *57*, 840–862. [CrossRef]