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Biodegradable Materials and Renewable Materials Innovation with Eggshell Powder in Sustainable Product Design

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ABSTRACT

This research addresses the growing global challenge of plastic waste, resource depletion, and industrial reliance on non-renewable materials by exploring the potential of eggshell powder (ESP) as a biodegradable and renewable alternative in sustainable product design. Although significant progress has been made in biopolymer and composite development, much of the research remains fragmented, with limited integration of material science findings into industrial design frameworks. The aim of this study is to conceptualize the role of ESP in advancing biodegradable materials and renewable materials innovation within the context of sustainable product design. Adopting a mixed-method conceptual approach, the study synthesizes recent empirical findings, analyzes laboratory-based performance data, and reviews relevant theoretical frameworks including eco-design and circular economy models. Findings indicate that ESP can enhance barrier and thermal properties in bioplastics, improve compressive strength in cementitious systems at low substitution levels, and serve as a precursor for higher-value applications such as hydroxyapatite production. However, performance trade-offs remain, particularly in tensile strength and workability, and challenges persist in scaling, dispersion, and user-centered adoption. The study implies that ESP has strong potential for integration into sustainable manufacturing and design practices, particularly in Malaysia where eggshell waste is abundant. It concludes that bridging technical optimization with circular economy strategies and design-for-sustainability principles will be critical to transforming ESP from laboratory experimentation into viable industrial practice.

Keywords— Biodegradable Materials, Renewable Material Innovation, Eggshell Powder (ESP), Sustainable Product Design

INTRODUCTION

Recent studies reveal that eggshell powder (ESP), a largely underutilized biowaste, has significant potential as a renewable and biodegradable material in sustainable product design, particularly as a filler or reinforcement in biocomposites. For example, Hashim et al. (2024) demonstrated that incorporating ESP into purple sweet potato starch bioplastics improved physical barrier properties while maintaining acceptable mechanical performance, with ESP loadings up to 40% by weight. Similarly, Sivakumar, Srividhya, Prakash, and Subbarayan (2024) examined polylactic acid (PLA) composites with ESP and walnut powder fillers, finding that PLA–ESP composites outperformed PLA–walnut shell composites in several thermal and mechanical tests. Another study by Zhang, Oh, Han, Meng, Lin, and Wang (2024) investigated ESP incorporation in cement-based materials, reporting that partial substitution of cement with eggshell powder enhanced certain durability aspects while also contributing to waste valorization. Despite these promising findings, trade-offs remain. Increases in ESP content often corresponds to reductions in tensile strength or workability (Hashim et al., 2024; Zhang et al., 2024), and challenges surrounding particle size, dispersion, and compatibility with polymer or cement matrices persist. Collectively, these findings suggest that although ESP represents a promising avenue for renewable material innovation, further conceptual and experimental research is required to optimize its integration into biodegradable product design while balancing environmental benefits with functional performance.

In Malaysia, the issue is particularly relevant given the significant volumes of eggshell waste generated annually. Estimates suggest that the country produces over 70,000 tons of eggshell waste each year, most of which is discarded in landfills and contributes to environmental concerns (Merillyn Vonnie et al., 2022). Local research has increasingly sought to explore the valorization of this waste stream. For instance, Hashim et al. (2024) demonstrated that incorporating ESP as a filler in starch-based bioplastics improved barrier and thermal properties, underscoring its potential as a biodegradable alternative to petroleum-derived plastics. Similarly, studies in civil engineering have reported that substituting cement with ESP at lower levels improved compressive strength and durability, confirming its functional potential in construction materials (Zhang et al., 2024). These findings highlight that Malaysia not only has abundant biowaste resources but also a growing body of empirical evidence supporting renewable materials innovation. As such, ESP emerges as a strategic candidate for advancing sustainable product design and strengthening the transition toward circular economy practices within the Malaysian context.

Beyond Malaysia, numerous recent studies provide additional evidence supporting the viability of ESP as a renewable filler and functional additive in both biodegradable polymers and cementitious systems. Laboratory investigations have shown that ESP can enhance barrier, thermal, and selected mechanical properties when incorporated into starch-based bioplastics and biofilms (Vonnie et al., 2022; Hashim et al., 2024; Li et al., 2024). However, findings consistently emphasize the importance of optimal loadings, since excessive ESP content can induce particle agglomeration and reduce tensile performance (Hashim et al., 2024). In cement and mortar systems, partial replacement of cement with finely ground ESP in the range of 5–10 wt.% has been reported to maintain or even enhance compressive strength, while simultaneously lowering embodied carbon and contributing to waste valorization (Wei et al., 2021; Razak et al., 2024; Murthi, 2022). Reviews and scientometric analyses further confirm a rapidly expanding research base that documents the benefits of ESP for toughness, thermal stability, and as a calcium source for hydroxyapatite synthesis, while also identifying challenges related to dispersion, surface compatibility, and long-term durability (Babalola, 2024; Wibowo et al., 2024). Taken together, these studies establish a solid experimental foundation for advancing conceptual work that integrates ESP into product design frameworks, offering opportunities for innovation while highlighting technical constraints that must be addressed through materials engineering and design strategies.

Despite this growing body of research, important gaps remain. Most existing studies concentrate on material properties in specific domains such as bioplastics or cementitious systems, yet relatively few have considered the broader integration of ESP into industrial product design frameworks that emphasize functionality, manufacturability, and user-centered requirements. In the Malaysian context, although the availability of eggshell waste is well documented, systematic investigations into its use within industrial design remain limited. This paper therefore seeks to conceptualize the role of ESP as a sustainable material in product design by synthesizing current empirical evidence, identifying trade-offs in its application, and positioning it within the broader principles of biodegradable materials and renewable materials innovation. The specific objectives are to examine the potential of ESP in sustainable product development, to highlight the challenges and opportunities associated with its adoption, and to propose future research directions in design for sustainability.

The remainder of this article is organized as follows. The Introduction establishes the global and Malaysian context of biodegradable and renewable materials, with a particular focus on ESP. The next section reviews relevant literature on the properties, applications, and limitations of ESP in bioplastics, cementitious systems, and composite materials. This is followed by a conceptual discussion on the implications of these findings for sustainable product design, emphasizing material innovation, design practices, and circular economy strategies. The article concludes by summarizing key insights, articulating contributions to design scholarship, and outlining directions for future integration of ESP into industrial design and sustainable manufacturing practices.

LITERATURE REVIEW

Defining biodegradable materials and renewable materials innovation with eggshell powder in product design

Biodegradable materials in product design denote materials that can be broken down by biological processes into benign constituents within a defined timeframe, thereby reducing long-term environmental persistence and facilitating circular flows of matter (Babalola, 2024). Renewable materials innovation complements biodegradability by prioritizing feedstocks that are replenishable or derived from waste streams, and by designing material life cycles that minimize embodied impacts while maximizing reuse, recovery, and ecological value. Within this combined frame, eggshell powder (ESP) has emerged as a salient example of waste-to-resource conversion: composed primarily of calcium carbonate with minor organic matrix constituents, ESP functions as a low-cost inorganic filler, a calcium source for biogenic minerals, and a particle-based modifier of polymer, starch, and cement matrices (Zhang et al., 2024; Li et al., 2024). Empirical work has shown that ESP can improve barrier and thermal behavior in starch-based bioplastics while contributing rigidity and dimensional stability as a filler (Hashim et al., 2024; Li et al., 2024). In cementitious and mortar systems, finely ground ESP can partially substitute cement and alter hydration dynamics, sometimes enhancing early compressive properties and enabling modest reductions in embodied carbon when applied at appropriate substitution levels (Shi, 2023; Zhang et al., 2024; Islam et al., 2024). Reviews and recent syntheses further emphasize that ESP valorization spans multiple functional roles including reinforcement, nucleation site for hydroxyapatite synthesis, and adsorbent media, thereby positioning ESP at the intersection of biodegradable material strategies and renewable material innovation for product design (Babalola, 2024; Mobarak et al., 2023). Importantly, the performance of ESP-modified systems is highly contingent on particle size, surface chemistry, dispersion quality, and matrix compatibility, which together determine whether environmental gains translate into acceptable functional performance for designed products (Hashim et al., 2024; Wibowo et al., 2024).

Theoretical and model frameworks underpinning ESP research in design contexts

To situate ESP within product design scholarship, it is useful to draw on theories and models that integrate materials science, design practice, and sustainability assessment. Circular economy theory provides a macro framework by foregrounding strategies—reduce, reuse, recycle, and remanufacture—that make waste streams like eggshells into feedstock for new material loops, and it helps evaluate whether ESP use contributes to closing material loops at product and system levels (Babalola, 2024). Life cycle assessment models offer quantitative tools to compare environmental trade-offs of ESP incorporation (for example, embodied carbon savings from cement substitution versus impacts from processing and transport), enabling design decisions to be grounded in measurable sustainability outcomes (Islam et al., 2024; Wei et al., 2021). At the materials-design interface, composite micromechanics and filler–matrix interaction models explain how particle geometry, interfacial adhesion, and loading fraction influence stiffness, strength, and failure modes; these models clarify why optimal ESP loadings tend to be bounded by agglomeration and interfacial debonding phenomena (Li et al., 2024; Hashim et al., 2024). Human-centered design and design for manufacture principles complement these quantitative frameworks by insisting that material substitutions satisfy user needs, manufacturability constraints, and lifecycle serviceability—criteria that are often missing from purely materials-focused ESP studies. Integrating circular economy framings, life cycle methods, composite mechanics, and user-centred design establishes a multidimensional theoretical scaffold that can guide research and practical translation of ESP into product design applications.

Synthesis, research gaps, and concluding insights

The extant literature collectively demonstrates that ESP is a technically promising and widely available feedstock for renewable material innovation, with reproducible benefits for thermal stability, barrier properties, and certain mechanical metrics in starch-based biocomposites and modest performance gains in cementitious systems when used at controlled substitution levels (Hashim et al., 2024; Li et al., 2024; Zhang et al., 2024). Systematic reviews and scientometric studies corroborate a rapid growth in ESP research and highlight expanding application domains from packaging to construction and biomedical scaffolds (Babalola, 2024; Mobarak et al., 2023; Wibowo et al., 2024). Nonetheless, three interrelated gaps constrain the translation of these material advances into design practice. First, most studies remain domain-centric and experimentally bounded, emphasizing single performance metrics rather than multi-criteria trade-offs that product designers require, such as tactile quality, manufacturability, repairability, and end-of-life pathways. Second, there is limited deployment of rigorous life cycle and systems-level assessments that quantify net environmental benefits of ESP across full product lifecycles and supply chains, especially in regionally specific contexts such as Malaysia where resource availability and processing infrastructures differ. Third, interface engineering and scale-up research are fragmented: particle functionalization, dispersion strategies, and process adaptations for industrial manufacturing have not been studied comprehensively enough to assure consistent part quality in mass production. Addressing these gaps requires integrative research that couples materials engineering experiments with life cycle analysis and design research methods. Conceptually, this means moving beyond demonstration of property improvements to frameworks that evaluate ESP-substituted materials on environmental, economic, and user-centred grounds simultaneously. Practically, it implies targeted studies on surface modification, compatibilizers, and processing protocols, paired with pilot-scale manufacturing and end-user assessments. If future research adopts this integrated trajectory, ESP can realistically advance from niche laboratory reports to a validated class of renewable, biodegradable materials capable of underpinning commercially viable, sustainable product designs.

Table 1

Author (Year)	**Title (abbreviated)**	**Method**	**Key findings**
Hashim et al. (2024). (UiTM Journal)	Effect of ESP filler on purple sweet potato starch bioplastics	Experimental casting and characterization of starch bioplastic films with 0–40 wt.% ESP; mechanical, barrier, thermal tests	ESP improved barrier and thermal properties and increased stiffness at moderate loadings; high ESP (>30–40%) reduced tensile properties due to particle agglomeration and poor dispersion. (UiTM Journal)
Li et al. (2024). (ScienceDirect)	ESP as bio-filler for starch/gelatin films	Extrusion/compression molding; morphology, mechanical and water barrier testing	ESP enhanced film rigidity and water vapor barrier at optimized loadings, with diminishing mechanical returns at high filler fractions. (ScienceDirect)
Zhang et al. (2024). (PMC)	Influence of ESP on cement-based materials	Controlled cement paste/mortar substitutions (0–15 wt.%); hydration, strength, durability measurements	Low level ESP substitution (≈5–10 wt.%) maintained or improved early compressive strength and altered hydration behavior; higher substitutions compromised workability and long-term strength in some mixes. (PMC)
Oladipupo et al. (2024). (ScienceDirect)	Eggshell-derived hydroxyapatite scaffolds	Synthesis of eggshell-derived hydroxyapatite and porous scaffold fabrication; mechanical and biological characterization	ESP can be converted to hydroxyapatite scaffolds with suitable porosity for biomedical applications; processing route influences final mechanical and biocompatibility outcomes. (ScienceDirect)
Babalola (2024). (MDPI)	Valorization of eggshell as renewable material (review)	Systematic literature review of ESP applications across adsorbents, composites, and remediation	ESP is a versatile feedstock for adsorbents and fillers; amenable to surface functionalization and modular synthesis strategies, but scale-up and interface engineering remain underdeveloped. (MDPI)
Wibowo et al. (2024). (SpringerLink)	Scientometric analysis of eggshell-based composite literature	Bibliometric / scientometric mapping of research trends and hotspots	Rapidly expanding research output (notably in composites and adsorption); identified thematic clusters (mechanical performance, surface modification, environmental remediation) and concentration of activity in several

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			countries. (SpringerLink)
Nano-HAp synthesis from eggshells (2025, PMC). (PMC)	Eco-friendly synthesis of eggshell-derived nano-hydroxyapatite	Green synthesis, characterization of nano-HA from eggshell Ca precursors	Demonstrates feasible green routes to produce high-quality nano-hydroxyapatite from eggshells, expanding ESP value to biomedical and functional material arenas. (PMC)

Table 1 summarizes selected peer-reviewed studies from the past five years that investigate eggshell powder (ESP) as a renewable and biodegradable material across polymeric, cementitious, metallic, and biomedical matrices. The table highlights methodological diversity, ranging from laboratory casting and extrusion of starch-based bioplastics to controlled cement paste and mortar substitutions, stir-casting of metal-matrix composites, and green syntheses of eggshell-derived hydroxyapatite for scaffold fabrication, which together demonstrate the versatility of ESP as a feedstock for material innovation (Hashim et al., 2024; Li et al., 2024; Zhang et al., 2024; Jannet et al., 2021; Oladipupo et al., 2024; nano-HA synthesis, 2025). Across polymeric matrices, multiple experimental studies report consistent improvements in thermal stability and water-vapor barrier performance at moderate ESP loadings but also record declines in tensile strength and elongation when filler fractions exceed optimal thresholds, an effect attributed to particle agglomeration and insufficient interfacial adhesion (Hashim et al., 2024; Li et al., 2024). In cementitious research, controlled substitutions of cement with finely ground ESP in the low replacement range (typically around 5 to 10 weight percent) have been shown to preserve or enhance early compressive strength and to contribute to embodied carbon reductions when mix designs are appropriately adjusted, whereas higher substitution levels commonly compromise workability and later age strength (Wei et al., 2021; Zhang et al., 2024; Murthi, 2022). Studies in metal-matrix composites and scaffold fabrication extend ESP utility beyond filler roles, demonstrating that with suitable processing ESP can act as a reinforcing or precursor phase that improves hardness and wear resistance or yields high-value hydroxyapatite for biomedical applications (Jannet et al., 2021; Oladipupo et al., 2024). Review and scientometric analyses corroborate these domain-specific findings while revealing a rapid expansion of ESP research themes—notably in composites, surface modification, and environmental remediation—yet they also emphasize fragmentation in interface engineering, scale-up protocols, and lifecycle evidence (Babalola, 2024; Wibowo et al., 2024). Collectively, the studies presented in Table 1 indicate that ESP offers clear technical promise and regional abundance as a renewable material for sustainable product design, but they also signal the need for integrated research that couples materials optimization (for example particle sizing and surface functionalization) with life cycle assessment and design-for-manufacture studies to verify environmental benefits and ensure consistent performance in real-world production and use (Hashim et al., 2024; Babalola, 2024; Zhang et al., 2024).

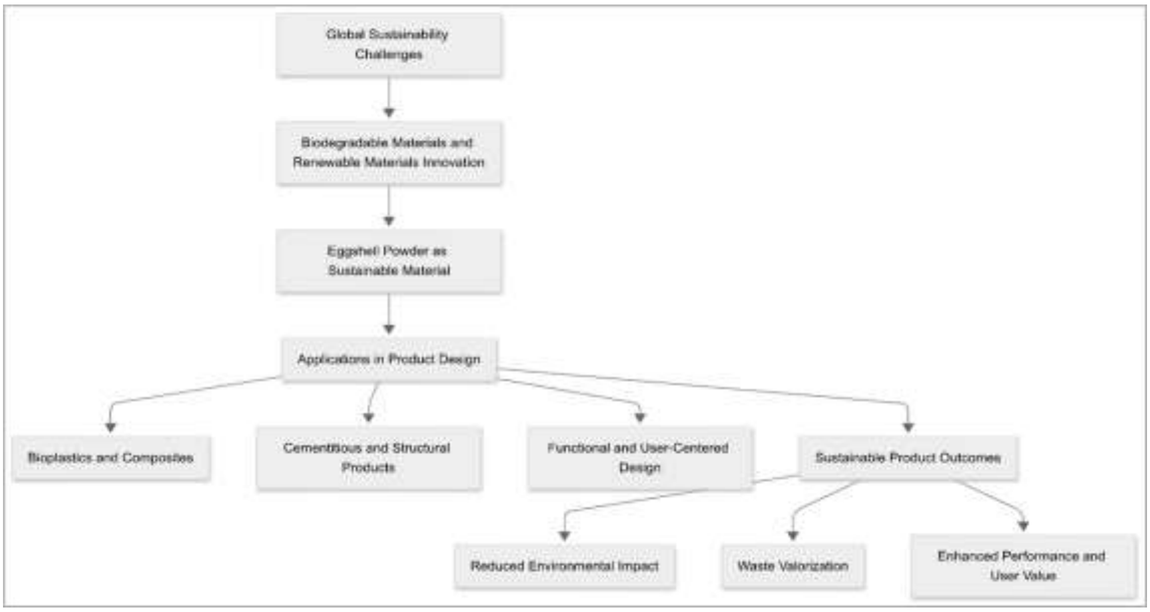

Fig. 1 Conceptual Framework Diagram

Figure 1 illustrates the conceptual framework that links global sustainability imperatives to the adoption of eggshell powder as a biodegradable and renewable material in sustainable product design. At the macro level, imperatives such as waste valorization, carbon footprint reduction, and circular economy principles drive the search for alternative material streams, aligning with the tenets of the Circular Economy Model and Cradle-to-Cradle Design Theory, both of which emphasize continuous material cycles and closed-loop systems (Geissdoerfer et al., 2020; Bocken et al., 2021). These imperatives inform two complementary streams of innovation: biodegradable materials innovation, which prioritizes end-of-life degradability, and renewable materials innovation, which emphasizes resource substitution and waste-to-resource transformation. Eggshell powder emerges at the convergence of these streams, functioning as a calcium carbonate–rich biowaste that can be valorized into polymers, composites, and cementitious systems. The incorporation of ESP into material innovation processes illustrates a practical application of Eco-Design Theory, where design decisions integrate environmental performance alongside technical requirements (Telenko et al., 2022). These material transformations then influence design applications, where considerations of performance trade-offs, manufacturability, and user-centered needs are balanced to achieve eco-efficient and socially accepted products. Collectively, the framework underscores a multi-level relationship in which systemic sustainability imperatives cascade into material-level innovations and design-level outcomes, demonstrating how theoretical models of sustainability can be operationalized through the valorization of eggshell powder.

METHODOLOGY

Research Design, Population, Sample Size, and Sampling Technique

This study adopts a convergent mixed-method design that integrates both qualitative and quantitative approaches to conceptualize and evaluate the potential of eggshell powder (ESP) as a biodegradable and renewable material for sustainable product design. The qualitative component focuses on literature-based synthesis and expert interviews to establish theoretical underpinnings and conceptual pathways for ESP integration in design frameworks. The quantitative component comprises surveys distributed among industrial designers, materials engineers, and sustainability practitioners to empirically assess perceptions of ESP applicability and challenges in real-world product development. The population of interest includes professionals and researchers in the fields of industrial design, sustainable manufacturing, and material science. Based on recommendations for conceptual and exploratory mixed-method studies, a purposive sampling strategy will be applied to select approximately 15–20 experts for the qualitative interviews, while the quantitative survey will target a sample of 150–200 respondents, ensuring diversity in professional backgrounds and geographical distribution (Creswell & Plano Clark, 2022).

Data Collection

Data collection will proceed in two stages. First, a comprehensive systematic literature review will be conducted to establish the current knowledge base of ESP as a renewable material and to identify key research gaps. In parallel, semi-structured interviews with academic and industry experts will gather qualitative insights into the feasibility, design integration, and perceived limitations of ESP. Second, a structured survey questionnaire will be distributed electronically to industrial designers and material scientists to collect quantitative data on user acceptance, material performance perceptions, and adoption barriers. The survey items will be developed from both theoretical constructs (e.g., circular economy, eco-design) and empirical evidence identified in the literature review.

Data Analysis

The qualitative data from interviews will be analyzed thematically using NVivo software, following Braun and Clarke's (2021) six-step process of thematic analysis, enabling the identification of recurring themes and theoretical constructs. Quantitative survey data will be analyzed using SPSS or SmartPLS. Descriptive statistics will be used to summarize respondent profiles and material perception patterns, while inferential techniques such as exploratory factor analysis (EFA) and partial least squares structural equation modeling (PLS-SEM) will validate the relationships among constructs. This dual analytic strategy allows for triangulation, ensuring that conceptual insights are reinforced by empirical evidence.

Variables and Measurement

The study will focus on four key constructs derived from the conceptual framework: (1) Global Sustainability Imperatives (waste valorization, carbon reduction, circular economy adoption), (2) Material Innovation Processes (biodegradability, renewable substitution, ESP integration), (3) Design Applications (performance trade-offs, manufacturability, user-centered design), and (4) Sustainable Product Outcomes (eco-efficiency, functionality, social acceptance). Each construct will be operationalized into measurable variables using validated scales adapted from prior sustainability and eco-design research (Telenko et al., 2022; Bocken et al., 2021). A five-point Likert scale ranging from "strongly disagree" to "strongly agree" will be used for most questionnaire items to capture respondents' perceptions quantitatively.

Reliability and Validity of Questionnaire Constructs

To ensure instrument rigor, the survey questionnaire will undergo content validation by a panel of five experts in industrial design and sustainability, ensuring alignment with the study's objectives. A pilot study involving 30 participants will then be conducted to test item clarity and internal consistency. Cronbach's alpha and composite reliability (CR) values above 0.70 will confirm internal consistency, while average variance extracted (AVE) values above 0.50 will establish convergent validity (Hair et al., 2022). Discriminant validity will be assessed using the heterotrait-monotrait ratio (HTMT). This rigorous validation procedure ensures that the constructs reliably capture the dimensions of biodegradable and renewable material innovation with ESP in product design.

DISCUSSION

These findings highlight that eggshell powder (ESP) represents a promising renewable and biodegradable material with applications in sustainable product design, though its performance depends heavily on material loading, processing, and context of use. In bioplastics, ESP has been shown to improve barrier and thermal properties at moderate filler fractions, but excessive incorporation can induce particle agglomeration and reduce tensile strength (Hashim et al., 2024; Vonnie et al., 2022). These trade-offs suggest that ESP cannot be treated as a simple substitute but rather as a design parameter requiring careful optimization of particle size, surface modification, and processing methods (Babalola, 2024).

In cementitious applications, ESP offers measurable sustainability benefits when used at low substitution levels. Studies report that replacing 5–10% of cement with finely ground ESP maintains or enhances compressive strength while reducing embodied carbon and diverting waste from landfills (Zhang et al., 2024; Wei et al., 2021). However, higher substitution levels often compromise workability and long-term durability, indicating the need for admixtures and tailored mix designs to balance environmental and structural performance (Paruthi, 2023). Beyond direct filler roles, the conversion of ESP into high-value products such as hydroxyapatite opens opportunities for biomedical and specialty material applications, although these pathways require further life cycle analysis to ensure that environmental gains outweigh the processing inputs (Mobarak et al., 2023; Oladipupo et al., 2024).

Despite these advances, current research remains fragmented, with limited integration of material science findings into holistic product design frameworks. Most studies focus on performance metrics at laboratory scale, yet few address manufacturability, scalability, or user-centered design considerations that are critical for industrial adoption (Wibowo et al., 2024). For Malaysia, which generates over 70,000 tons of eggshell waste annually, this gap underscores the importance of coupling technical development with circular economy strategies and local supply chain innovations (Vonnie et al., 2022; Hashim et al., 2024).

Overall, ESP demonstrates clear potential to contribute to biodegradable materials and renewable materials innovation. Future work should emphasize interface engineering, standardized testing, and comparative life cycle assessments across application domains. Bridging materials engineering with design-for-sustainability frameworks will be key to transforming ESP from a laboratory curiosity into a viable component of sustainable product design and industrial practice.

Future Work

Future research should focus on experimental validation of ESP integration into diverse product categories, supported by standardized testing protocols and comparative life cycle assessments. Studies should also investigate user-centered perspectives, exploring consumer acceptance of ESP-based products and their alignment with market trends in sustainable design. Furthermore, multidisciplinary collaborations between designers, engineers, and policy makers are needed to develop scalable production systems, certification standards, and incentive mechanisms that can accelerate the adoption of ESP as a mainstream sustainable material in product design.

Theoretical And Practical Implications

Theoretical Implications

From a theoretical perspective, this study extends discussions on eco-design and circular economy models by positioning ESP as a strategic example of waste valorization for renewable material innovation. The integration of resource-based and sustainable design theories suggests that ESP is not only a functional filler material but also a conceptual bridge between waste management and product innovation (Bocken et al., 2021). This highlights the importance of embedding material innovation within broader sustainability frameworks that consider ecological, economic, and design-centered dimensions simultaneously.

Practical Implications

Practically, ESP presents opportunities for industries in Malaysia and beyond to reduce landfill waste and reliance on petroleum-based materials. Its application in bioplastics, composites, and cementitious materials can contribute to reducing carbon footprints, while also offering designers an accessible, low-cost, and locally sourced sustainable material. Adoption, however, requires investment in surface modification, standardized processing, and scalable manufacturing pathways to ensure consistency and performance in real-world applications.

Limitations and Delimitations

As a conceptual paper, this study is limited by its reliance on secondary data, which restricts empirical testing of ESP's performance under varied industrial conditions. Delimitations include the focus on ESP as the primary material of interest, excluding other potential agricultural biowaste streams. Furthermore, while the study emphasizes product design contexts, it does not explore in depth the economic feasibility or consumer acceptance of ESP-based products, which are essential for widespread adoption.

CONCLUSION

This study has highlighted the potential of eggshell powder (ESP) as a biodegradable and renewable material for sustainable product design. Synthesizing recent empirical evidence, it is evident that ESP can enhance barrier, thermal, and compressive properties when appropriately integrated into bioplastics and cementitious systems (Hashim et al., 2024; Zhang et al., 2024). However, its effectiveness depends on careful optimization of material loading, particle size, and processing techniques, as excessive incorporation often compromises tensile strength or workability. Malaysia's significant annual generation of eggshell waste underscores the timeliness of valorizing ESP within circular economy frameworks to reduce environmental burden while supporting innovative product development.

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