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Designing Circular Packaging Systems for Everyday Beverages Using Oil Palm Empty Fruit Bunch Waste

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ABSTRACT
The rapid growth of single-use beverage packaging has intensified environmental challenges due to high material complexity, limited recyclability, and continued dependence on fossil-based resources. Conventional recycling approaches have proven insufficient to address these structural issues, particularly for multilayer plastic packaging commonly used for liquid beverages. This study proposes a circular packaging system for everyday beverage applications utilizing oil palm empty fruit bunch (EFB) waste as a renewable fiber-based raw material. Indonesia, as the world's largest palm oil producer, generates tens of millions of tons of EFB annually, most of which remains underutilized or poorly managed. Through a system-oriented design approach, EFB is repositioned from low-value agricultural residue into a strategic material input for fiber-based beverage packaging. The research develops a conceptual circular packaging framework that integrates agricultural waste streams, fiber extraction and material engineering, packaging design, industrial compatibility, and end-of-life management within a closed-loop system. Rather than focusing on laboratory-scale material novelty, the study emphasizes system integration, value retention, and scalability using established fiber-processing technologies adapted to liquid packaging requirements. Comparative assessment indicates that EFB-based packaging offers significant advantages over conventional multilayer plastics in terms of material circularity, recyclability, carbon footprint reduction, and alignment with circular economy principles. The findings demonstrate that EFB-based circular packaging systems are technically feasible, industrially adaptable, and environmentally advantageous for everyday beverage applications. The primary contribution of this research lies in the development of a system-level circular packaging design model that simultaneously addresses agricultural waste management and packaging sustainability, offering a scalable pathway toward more resilient and circular production-consumption systems.

***Keywords*: Agricultural Waste Valorization; Beverage Packaging; Circular Economy; Circular Packaging; Oil Palm Empty Fruit Bunch**

INTRODUCTION

Packaging plays a crucial role in maintaining the quality, safety, and distribution of everyday consumer products. In modern food systems, packaging serves not only as a physical barrier but also as a guarantor of product stability, shelf life, and consumer safety. However, these essential functions are accompanied by significant environmental consequences. Packaging particularly single use packaging has become one of the major sources of environmental pollution due to the dominance of materials that are difficult to recycle and ultimately persist as waste [1]. In beverage products, especially milk and ready to drink liquid beverages, packaging commonly relies on multilayer plastics or composite materials that combine plastic, aluminum, and paper. While such material structures are functionally effective, they exhibit a high carbon footprint and significant limitations in end of life management [2]. In practice, most of these beverage packages do not return to effective recycling systems instead, they end up in landfills or pollute terrestrial and aquatic environments [3]. Dependence on fossil based plastics further extends the carbon emission chain from upstream to downstream processes, from raw material extraction to final disposal.

Various efforts have been made to improve material efficiency and recycling rates, these approaches have proven insufficient to address the problem at a structural level. Conventional recycling systems face technical, economic, and social constraints, making them inadequate to keep pace with the continuously increasing production and consumption of single-use packaging [4]. These conditions indicate that the packaging problem is not merely a matter of recycling technology, but fundamentally a system design issue. Therefore, a more transformative approach is required through the redesign of packaging systems based on circular economy principles [5]. This approach reframes waste not as an end residue, but as a resource that can be reintegrated as a value-added input in subsequent production cycles. Accordingly, the focus shifts not only toward reducing waste volume, but also toward transforming renewable resources and waste streams into functional materials capable of replacing conventional materials.

The agricultural sector plays a strategic role due to its generation of large and continuous quantities of biomass waste. One of the most significant examples in Indonesia is oil palm empty fruit bunch (EFB) waste from the palm oil industry. As the world’s largest palm oil producer, Indonesia processes more than 200 million tons of fresh fruit bunches (FFB) annually. Approximately 22–23% of this amount becomes empty fruit bunches, resulting in more than 45 million tons of biomass waste generated each year. Each ton of FFB produces about 220–230 kilograms of EFB, making it one of the largest solid waste streams within the national agro-industrial system [6].

Table 1. Quantitative Feedstock Baseline

Quantitative Parameter	Estimated Value	Description
Total annual FFB production	±200–205 million tons	National output of the oil palm industry
Proportion of EFB from FFB	22–23%	Average by-product ratio from palm oil processing
Annual EFB generation	±45–47 million tons	Major solid biomass residue
EFB generated per ton of FFB	220–230 kg	Standard conversion ratio in palm oil mills
High-value utilization of EFB	<30%	Majority still used in low-value applications
EFB stockpiled or poorly managed	>70%	Potential source of environmental burden
Continuity of EFB availability	Year-round	Follows the oil palm production cycle
Material characteristics	Fibrous biomass, rich in cellulose	Suitable for pulp- and fiber-based materials

Source: [6]

Although available in very large quantities, the utilization of EFB to date has remained largely limited to low value applications such as mulch, compost, or biomass fuel, and in many cases it instead becomes an environmental burden. The accumulation of EFB around palm oil mills has the potential to cause soil and water pollution due to the leaching of organic compounds, as well as to increase greenhouse gas emissions when it is left to decompose or is openly burned [7]. Such biomass burning practices also contribute to air quality degradation and pose public health risks for communities surrounding plantations and processing facilities.

This palm oil biomass waste issue shares key characteristics with the problem of plastic packaging waste both are generated in large volumes, are continuous in nature, and have not yet been effectively integrated into value-added waste management systems. Consequently, a circular economy approach that connects these two challenges holds significant strategic potential. EFB waste, which has traditionally been treated as a residual by product, can be repositioned as an alternative raw material for more sustainable packaging systems. The fibers contained in oil palm empty fruit bunches have a relatively high cellulose content, making them technically suitable for processing into pulp and fiber based materials [8]. Through appropriate extraction and material engineering processes, EFB fibers can be utilized as the base material for fiber-based beverage packaging [9]. This approach creates opportunities to substitute multilayer plastics while simultaneously reducing environmental pressure from two directions: mitigating agricultural waste and decreasing dependence on fossil-based packaging waste.

The innovation of this approach lies in the integration of large scale agricultural waste streams into functional packaging systems for everyday beverage products. Rather than merely using biomass as an alternative material, it involves designing a material system that is compatible with the requirements of the beverage industry in terms of performance, food safety, and potential integration with existing production and distribution systems. By leveraging the abundant and sustainable availability of EFB, this approach offers a rational, scalable, and long-term solution within the framework of a circular economy.

METHODS

Research Design

This study adopts a qualitative system-design and conceptual engineering methodology aimed at developing a circular packaging model for everyday beverage applications based on oil palm empty fruit bunch (EFB) waste. The research does not rely on experimental laboratory testing; instead, it integrates literature-based technical analysis, system modeling, and comparative evaluation to assess feasibility, scalability, and circular value creation. The methodological approach is structured to align with circular economy principles and industrial packaging system requirements.

Data Sources and Literature Analysis

Secondary data were collected from peer-reviewed journals, technical reports, policy documents, and industrial publications related to:

- Single-use beverage packaging systems and their environmental impacts
- Fiber-based and biomass-derived packaging materials
- Oil palm empty fruit bunch (EFB) characteristics, availability, and utilization
- Circular economy frameworks, particularly in packaging system design

These sources were used to establish baseline data on material properties, waste generation volumes, industrial practices, and sustainability performance indicators.

System Mapping and Circular Framework Development

A system-mapping approach was employed to model the proposed EFB-based circular packaging system across the entire value chain. The system was structured into key stages:

1. Raw material sourcing and collection, integrating EFB waste streams from palm oil mills

2. Fiber and cellulose extraction, using established mechanical and chemical processing principles
3. Material engineering and packaging structure design, tailored to liquid beverage requirements
4. Industrial integration, ensuring compatibility with existing filling, sealing, and distribution systems
5. End-of-life management, emphasizing fiber recycling and controlled biodegradation pathways

This mapping enabled identification of value retention, creation, and recovery mechanisms within a closed-loop system.

Comparative Assessment Approach

A qualitative comparative analysis was conducted to evaluate the proposed EFB-based packaging system against conventional multilayer plastic and conventional paper-based beverage packaging. The comparison focused on key dimensions including raw material source, material circularity, environmental footprint, recyclability, industrial compatibility, scalability, and alignment with circular economy principles. The assessment was used to highlight relative strengths, limitations, and strategic advantages of EFB-based packaging.

Business Model and Feasibility Analysis

To assess implementation realism, the Business Model Canvas (BMC) framework was applied to map stakeholders, value propositions, resource flows, and economic relationships within the proposed system. Technical feasibility was evaluated based on known material properties of EFB fibers and compatibility with existing pulp and packaging technologies, while practical feasibility considered raw material availability, supply chain integration, and industrial scalability.

Sustainability and Impact Evaluation

Environmental, economic, and social impacts were assessed qualitatively through a circular value perspective. This evaluation examined potential contributions to agricultural waste reduction, fossil resource substitution, emission mitigation, local economic development, and workforce capacity building. End-of-life considerations were embedded in the system design to avoid burden shifting and ensure long-term circular performance.

Methodological Scope and Limitations

This research is conceptual and system-oriented in nature. While it provides a robust framework for industrial application, it does not include experimental validation or pilot-scale testing. Future research is recommended to focus on material performance testing, life cycle assessment (LCA), and industrial-scale trials to quantitatively validate the proposed system.

RESULT AND DISCUSSION

Conceptual Framework of an EFB Based Circular Packaging System

The proposed circular packaging system based on oil palm empty fruit bunches (EFB) is designed as a closed-loop material system that integrates agricultural waste into the value chain of everyday beverage packaging. This conceptual framework does not position packaging as a final product that ends at the consumption stage, but rather as part of a recurring material cycle that is managed from upstream to end-of-life. Under this approach, waste is not treated as a post-production residue, but as a resource that is systematically designed to re-enter the economic cycle. The system flow begins with the collection of EFB waste generated by palm oil processing mills. At this stage, EFB previously regarded as an environmental burden is repositioned as a strategic material input. Collection is integrated into the existing logistics systems of the palm oil industry, thereby avoiding the need to create complex new supply chains. The next stage involves fiber and cellulose extraction, which represents the core of the material transformation process. Through controlled physical and chemical processes, the cellulose content of EFB is refined to produce fiber-based materials with mechanical and structural characteristics suitable for liquid packaging applications.

The extracted material is then further processed into sheets or packaging structures that meet the functional requirements of beverage products, including strength, dimensional stability, and resistance to moisture [10]. At this stage, material design is oriented toward ensuring compatibility with widely used filling, storage, and distribution systems in the beverage industry. As a result, the system does not require radical changes to downstream infrastructure, which is often a major barrier to the adoption of sustainable materials. Conceptually, the EFB based circular packaging system is built upon three interrelated dimensions. The first is material circularity, which emphasizes the substitution of fossil based virgin raw materials with renewable agricultural waste [11]. This approach not only reduces pressure on non-renewable natural resources, but also mitigates the accumulation of underutilized biomass waste. Material circularity ensures that the primary inputs of the system originate from sustainable and continuously available sources.

The second dimension is process circularity, realized through the integration of the system with existing industrial and logistical infrastructure. Rather than establishing a separate and isolated production system, this approach leverages existing facilities, distribution networks, and manufacturing capacities. Such integration enhances implementation feasibility and cost efficiency, while strengthening the potential for large-scale industrial adoption. Process circularity also encompasses the optimization of energy, water, and auxiliary materials throughout production to minimize additional environmental impacts. The third dimension is end of life circularity, which treats the post consumption phase as an integral part of system design. Packaging is intentionally designed from the outset to be responsibly managed after use, whether through fiber based recycling, controlled biodegradation, or integrated waste management systems [12]. This approach avoids shifting environmental burdens to the end of life stage and ensures that material value is retained within the economic cycle for as long as possible.

This conceptual framework demonstrates that EFB based packaging is not merely an alternative material solution, but a representation of a structured circular system design. By connecting the agricultural sector, manufacturing, and waste management within a single closed-loop flow, the system provides a strong conceptual foundation for the development of beverage packaging that is technically viable, economically realistic, and sustainable in the long term.

Innovation and Originality

The innovation offered by the circular packaging system based on oil palm empty fruit bunches (EFB) does not lie in the radical creation of a new material, but rather in a paradigm shift in how agricultural waste is perceived and positioned within industrial systems [13]. This approach reframes EFB waste not as a residue with limited utility, but as a strategic resource that can be integrated into high performance beverage packaging systems. Accordingly, the innovation developed is systemic and application oriented, rather than driven solely by technological novelty. This systemic innovation is realized through the integration of three sectors that have traditionally operated in relative isolation: agriculture, packaging manufacturing, and product consumption. EFB waste generated at the upstream stage of agro-industrial production is directly incorporated into the packaging manufacturing value chain and subsequently reintegrated into post-consumption management systems through circular economy principles. This cross sectoral integration reflects a comprehensive system design approach, in which material selection, process design, logistics, and end of life management are conceived in an integrated manner from the outset.

Table 2. Empty Content of Oil Palm Bunches

Component	Weight Percentage (%)
Sellulosa	41.3-46.5
Hemisellulosa	25.3-33.8
Lignin	27.6-32.5
Holosellulosa	60-69
Pentosan	27-29
Ekstraktif	5-8
Kelarutan dalam NaOH 1%	24-30

Source: [14][15]

The originality of this concept becomes more evident in its application context, namely packaging for liquid beverage products. Unlike the conventional use of EFB fibers in applications such as composite boards, mulch, or biomass fuel, liquid beverage packaging requires significantly more stringent performance standards. Packaging materials must exhibit adequate mechanical strength, dimensional stability, resistance to moisture, and compliance with food safety requirements. By selecting a high performance application context, this approach implicitly drives the development of more disciplined and measurable material and system designs.

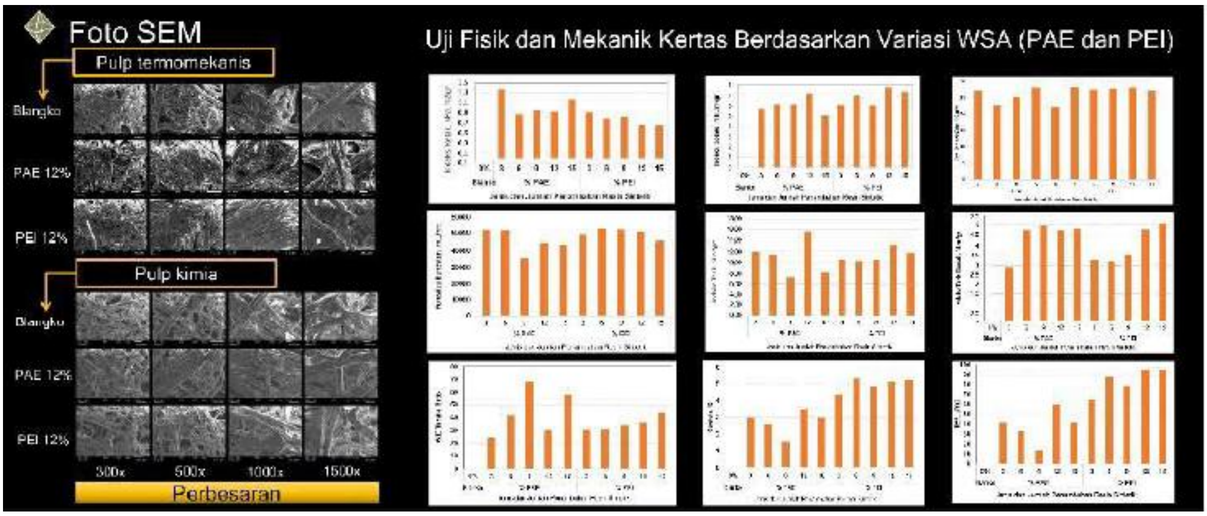

Figure 1. Physical & Mechanical Paper Testing [6]

The focus of innovation in this system is directed toward functional design and system integration, rather than the experimental exploration of material novelty. This approach emphasizes that sustainable solutions relevant to industry do not necessarily depend on the discovery of new materials, but rather on the ability to optimize existing resources through appropriate system design. By leveraging established fiber-processing technologies and adapting them to the context of beverage packaging, the system reduces adoption barriers and enhances the potential for industrial-scale implementation.

The innovation and originality of the EFB based packaging system lie in the perspective and system design it offers. By integrating large scale agricultural waste, the performance requirements of the beverage industry, and circular economy principles within a single, coherent framework, this approach provides both conceptual and practical contributions to the future development of sustainable packaging. The primary innovation of this research resides in the packaging system design model, rather than in laboratory scale material discovery. The proposed design model can be classified as a system oriented circular packaging design, an approach that treats material selection, production processes, distribution, and end-of-life management as an interconnected and unified system.

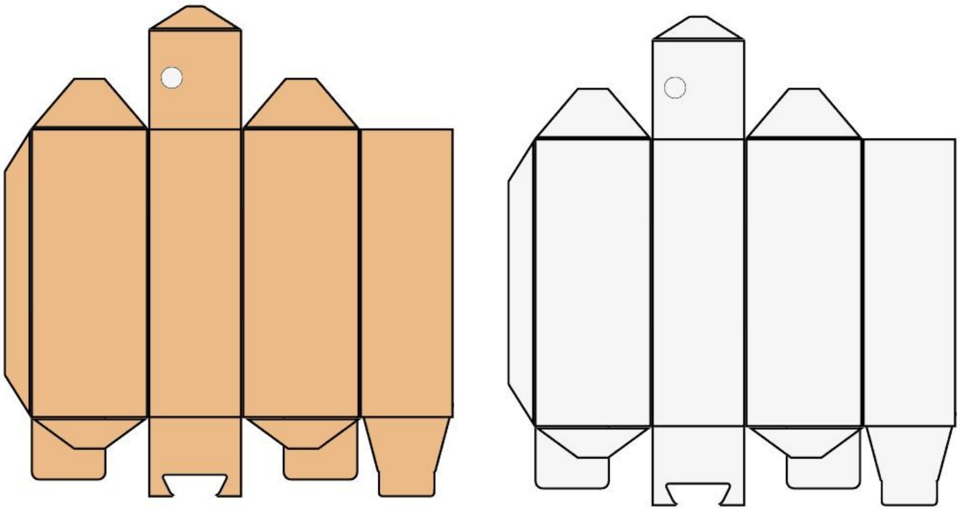

Figure 2. Packaging Design

Table 3. Comparative Assessment of Beverage Packaging Systems

Comparative Aspect	TKKS-Based Packaging (Oil Palm Waste Fibers)	Conventional Multilayer Plastic	Conventional Paper
Raw Material Source	Renewable agricultural waste (oil palm empty fruit bunches)	Fossil-based raw materials (petrochemicals)	Wood-based resources from forest systems
Material Status	Low value by product upgraded into functional material	High value primary raw material	Primary raw material competing with other uses
Availability and Continuity	High and stable year-round	Stable but dependent on fossil resource availability	Relatively stable, dependent on forest management
Material Carbon Footprint	Low to moderate, with significant reduction potential	High due to extraction and petrochemical processing	Moderate, depending on forestry and production practices
Suitability for Liquid Beverages	Specifically engineered through fiber processing and surface coating	Very high without additional modification	Limited, requires additional barrier layers
Production Line Compatibility	High, adaptable to existing fiber-based packaging systems	Very high (well established industrial systems)	High within paper based packaging infrastructure
End-of-Life Management	Fiber-based recycling or controlled waste treatment	Very limited, difficult to recycle	Relatively easy to recycle
Persistent Waste Potential	Low	High	Low
Pressure on Primary Natural Resources	Very low	High	Moderate to high
System Scalability	High, aligned with the scale of the oil palm industry	Very high	High, with resource constraints

Comparative Aspect	TKKS-Based Packaging (Oil Palm Waste Fibers)	Conventional Multilayer Plastic	Conventional Paper
Social and Economic Value Creation	High, enhancing waste valorization and local economies	Low, concentrated within petrochemical industries	Moderate
Alignment with Circular Economy Principles	High, designed across the entire value chain	Low	Moderate

Source: [16]

Business Model Canvas (BMC)

To ensure that the circular packaging system based on oil palm empty fruit bunches (EFB) is not only conceptually and technically feasible but also realistically implementable at an industrial scale, a framework is required to explain the creation, delivery, and preservation of value. In this context, the Business Model Canvas (BMC) is employed as an analytical tool to map the operational structure and inter-actor relationships within the proposed circular packaging system.

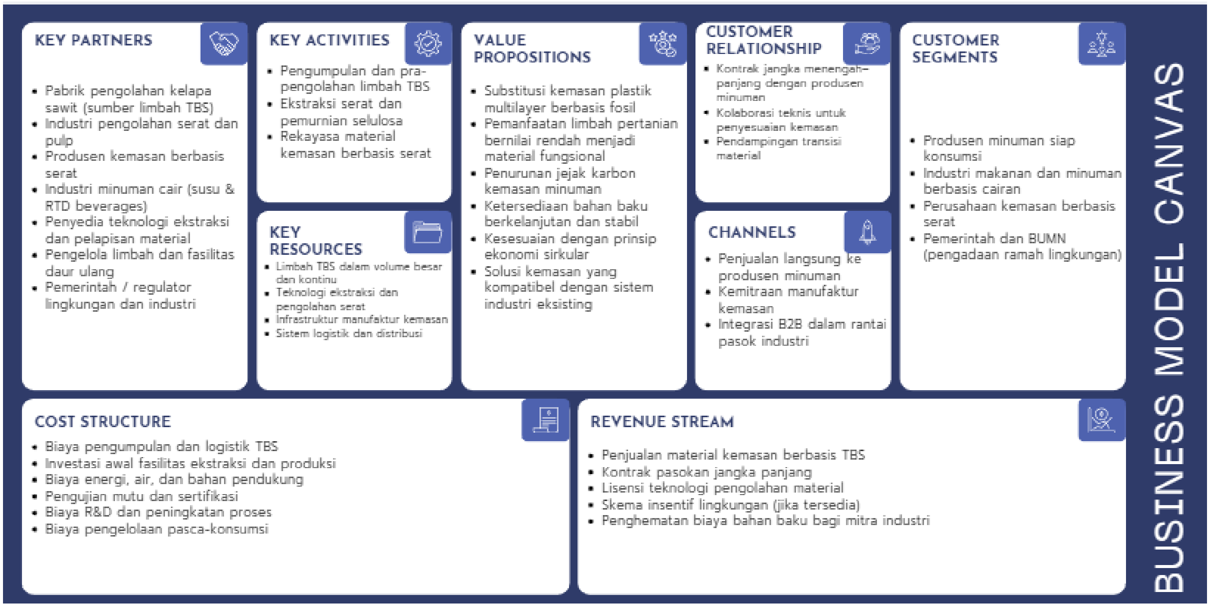

Figure 3. Business Model Canvas (BMC)

The feasibility of a circular packaging system based on oil palm empty fruit bunches (EFB) can be analyzed from two main aspects: the technical feasibility of the material and the practicality of its implementation within the beverage packaging industry. From a technical perspective, EFB is known to have a relatively high cellulose content, which fundamentally meets the prerequisites for use as a raw material in pulp and fiber based materials. The lignocellulosic fiber content of EFB allows cellulose extraction to be carried out using established methods in the pulp industry, such as controlled mechanical and chemical processes [17]. This indicates that the utilization of EFB does not require the development of radically new technologies, but rather the adaptation of existing ones.

In liquid beverage packaging applications, packaging materials are required to possess specific functional characteristics, particularly moisture resistance, mechanical strength, and dimensional stability during filling, storage, and distribution. Purified and engineered EFB fibers, processed through sheet forming and surface treatment techniques, have the potential to meet these requirements. The application of appropriate coating materials can enhance water and liquid barrier properties without compromising the fundamental characteristics of fiber-based materials. With proper material engineering, EFB based packaging can be designed to comply with applicable food safety standards, including the prevention of harmful substance migration during contact with beverages.

From a practicality perspective, the feasibility of this system is reinforced by the abundant and sustainable availability of raw materials. EFB waste is generated continuously by the palm oil industry and is concentrated at processing facilities, facilitating collection and supply control. This condition reduces dependence on imported raw materials and minimizes supply fluctuation risks that often hinder the development of alternative materials. Integrating EFB processing with existing industrial infrastructure creates opportunities for logistical efficiency and reduced operational costs. Practical implementation is also reflected in the potential adaptability of this system to existing fiber based packaging production lines. Pulp based forming, molding, and filling processes are relatively compatible with current manufacturing technologies, meaning that comprehensive changes to downstream facilities are not required. The primary challenge in implementation lies in the variability of EFB raw material characteristics, influenced by location, plantation age, and initial processing methods. However, this challenge is technical in nature and can be managed through standardized pre-treatment, raw material quality control, and the application of consistent material specifications.

Feasibility and practicality analyses indicate that EFB based packaging systems have a strong and realistic technical foundation for implementation. With disciplined process management and appropriate industrial integration, the system is not only conceptually viable but can also be gradually implemented at an industrial scale without compromising functionality or product safety. Scalability is one of the key strengths of the EFB based circular packaging system, primarily due to the large, continuous, and widely distributed supply of its raw material. Indonesia's palm oil industry generates EFB waste in volumes of tens of millions of tons per year, with relatively stable production patterns aligned with palm oil processing cycles [18]. This condition ensures long-term raw material availability and reduces the risk of supply constraints that often limit alternative material development. Unlike seasonal biomass sources, EFB is generated year-round, supporting sustainable large-scale packaging operations.

From an operational standpoint, system scalability is further supported by the potential integration with existing industrial infrastructure. EFB processing into fiber-based materials can be located near waste sources or integrated with existing pulp and packaging facilities. This approach allows production capacity to be increased incrementally without requiring the construction of entirely new systems. By leveraging existing logistics networks and manufacturing facilities, capacity expansion can be achieved through increased processing volumes and improved efficiency rather than added system complexity. From an environmental sustainability perspective, this system contributes to reducing dependence on fossil-based raw materials that currently dominate beverage packaging. Substituting conventional materials with EFB based materials has the potential to lower the product life cycle carbon footprint, particularly at upstream stages associated with raw material extraction and processing. Additionally, utilizing EFB waste as a high value raw material helps reduce the accumulation of biomass waste that could otherwise cause soil, water, and air pollution if improperly managed.

Sustainability must also be understood in economic and social terms. By utilizing abundant local resources, EFB based packaging systems can strengthen renewable resource based economies and increase the value added of agricultural waste. This approach creates opportunities for supporting industries in palm oil producing regions while reducing reliance on imported packaging materials. In the long term, supply and cost stability can enhance system resilience to market fluctuations and regulatory pressures. The combination of abundant raw material availability, integration with existing infrastructure, and environmental and economic benefits demonstrates that EFB based circular packaging systems possess high scalability and sustainability potential. With structured management and consistent governance, the system can be developed at an industrial scale without compromising environmental sustainability principles, while supporting the transition toward more circular production and consumption models.

The utilization of EFB waste as a packaging raw material generates significant environmental impacts, particularly in the context of waste management, emission reduction, and reduced pressure on ecosystems. One of the most direct impacts is the reduction in agricultural biomass waste volume that has traditionally posed environmental challenges. EFB waste is produced in large and continuous quantities and is often stockpiled, burned, or underutilized in conventional practices. Redirecting EFB into high value packaging production substantially reduces environmental burdens at the upstream stage. From a greenhouse gas emissions perspective, using EFB as a packaging material can reduce emissions through two main mechanisms. First, substituting fossil-based raw materials with renewable biomass materials reduces emissions associated with non-renewable resource extraction and processing. Second, improved EFB waste management reduces methane and carbon dioxide emissions generated by open decomposition or biomass burning. Consequently, positive impacts occur not only during packaging production but also in agricultural waste management stages that were previously suboptimal.

Another environmental benefit relates to reducing plastic packaging pollution, particularly single use beverage packaging that is difficult to recycle. EFB based packaging materials, designed under circularity principles, offer more controlled end of life pathways, either through fiber based recycling or managed biodegradation [19]. This approach helps reduce packaging waste accumulation in landfills and minimizes the risk of soil and water pollution from persistent plastic residues. However, positive environmental impacts cannot be achieved through material substitution alone. The effectiveness of this approach depends heavily on integration with adequate waste management and recycling systems. Without proper collection, sorting, and post-consumption processing systems, biomass based packaging may face challenges similar to those of conventional materials. The design of an EFB based circular packaging system must incorporate end of life management planning from the outset, including the identification of appropriate recycling or treatment pathways aligned with material characteristics.

Utilizing EFB waste as a packaging material offers comprehensive environmental contributions, ranging from agricultural waste reduction to the mitigation of packaging related pollution. Through a systemic approach that links material design, production, consumption, and waste management, the resulting environmental impacts are integrated rather than fragmented, aligning with the principles of a sustainable circular economy. The development of an EFB based packaging system also has significant social implications, particularly in terms of job creation, local economic strengthening, and human resource capacity building. Indonesia’s palm oil industry is widely distributed across rural and semi-urban regions, meaning that the utilization of EFB waste as packaging raw material has the potential to stimulate additional economic activity in producing areas. Activities such as collection, pre-processing, and fiber-based material production create new employment opportunities that are relatively inclusive, involving local labor with varying skill levels.

From a capacity development perspective, this system requires higher technical and managerial skills than conventional EFB utilization [20]. Fiber extraction, quality control, and packaging material production demand trained personnel and knowledge and technology transfer. This condition promotes human resource development in regions surrounding palm oil industries through technical training and operational skill enhancement. In the long term, such capacity building can improve social mobility and workforce quality. Beyond direct employment effects, utilizing EFB as a packaging material contributes to increased local economic value creation. Waste materials that previously had low economic value or even imposed disposal costs are transformed into valuable manufacturing inputs. This transformation creates opportunities for supporting businesses, including logistics services, biomass pre-processing, and technical service providers. As a result, the EFB based packaging system not only generates direct employment but also strengthens local economic ecosystems.

Another social impact relates to shifts in mindset and awareness regarding more responsible production and consumption practices. The use of agricultural waste based packaging materials provides a tangible example of circular economy principles in everyday life [21]. The presence of EFB based packaging products has the potential to increase public understanding of the interconnections between agriculture, industry, and the environment. Although consumer behavior change does not occur instantly, this approach can contribute to the gradual formation of social norms that support sustainability. Positive social impacts can only be fully realized if the system is managed inclusively and transparently. Community involvement, clear benefit sharing mechanisms, and the enforcement of decent labor standards are essential to ensure that the development of EFB based packaging industries does not create new social inequalities. With appropriate governance, this system has the potential to deliver long-term social benefits and strengthen the role of local communities in the transition toward a circular economy.

Economic Impact and Growth Potential

The circular packaging system based on oil palm empty fruit bunches (EFB) offers a relatively stable cost structure because it utilizes agricultural waste with low initial economic value. Unlike fossil based raw materials, which are vulnerable to global price fluctuations and supply uncertainty, EFB waste is continuously available as a by-product of the palm oil industry. This condition provides an economic advantage in the form of raw material cost predictability, which is a critical factor for long term production planning and operational risk management. The implementation of this system requires significant initial investment, particularly for the establishment or adaptation of fiber processing facilities, quality control systems, and compliance with food safety standards. These investments include costs related to equipment, energy, and human resource capacity development. However, in the medium to long term, these costs can potentially be offset through operational efficiencies and reduced dependence on conventional raw materials. As production scales up and processes are optimized, the unit cost of packaging materials can be reduced, thereby enhancing the overall economic competitiveness of the system.

The growth potential of EFB based packaging systems is driven by increasing demand for more sustainable packaging solutions. Shifts in market preferences both from producers and consumers are encouraging the adoption of packaging materials that reduce environmental impacts without compromising functionality. In addition, public policy directions that increasingly emphasize waste reduction, control of single use plastics, and the utilization of renewable resources create a regulatory environment that is conducive to the adoption of this system. Such policies not only stimulate demand but also serve as mechanisms for reducing investment risk. From an industry perspective, this system has the potential to scale gradually through a modular approach. Production can begin at a limited scale to serve specific market segments and then be expanded as processing capacity and market acceptance increase. This approach allows industry actors to manage financial risks while testing material performance under real operational conditions. Furthermore, the potential development of derivative products based on EFB fibers opens opportunities for revenue diversification and market expansion.

A clear implementation plan is a key factor in ensuring that the EFB based circular packaging system can be realized in a phased and measurable manner. The implementation roadmap is structured through logical stages, beginning with the development of packaging material prototypes, followed by technical performance testing, food safety validation, and eventual industrial-scale application. This phased approach enables early identification and mitigation of risks while allowing for iterative refinement of material design and process parameters prior to large-scale expansion. The initial stage focuses on the development and optimization of EFB fiber based material prototypes. At this phase, testing is conducted on mechanical properties, moisture resistance, and dimensional stability under operational conditions that simulate beverage filling and distribution processes. The results of these tests form the basis for refining material formulations and packaging structural designs. The subsequent stage involves food safety validation, including migration testing, material stability during contact with liquid products, and compliance with applicable standards and regulations. This validation is a critical prerequisite before the material can be widely adopted in the beverage industry.

Once technical and regulatory requirements are met, industrial scale implementation is carried out gradually through integration with existing production lines. This approach enables adoption without significant disruption to current manufacturing systems. Phased implementation also provides opportunities to evaluate material performance under real operating conditions, including production efficiency, quality consistency, and market response. Continuous evaluation at this stage plays a crucial role in determining the system's readiness for broader scale expansion. The long term sustainability of the EFB based packaging system is highly dependent on effective and consistent governance. Standardization of raw material quality and processing methods is essential to ensure stable material performance, given the inherent variability of EFB waste characteristics. In addition, alignment with national waste management policies and systems is a key prerequisite for maintaining material circularity through to the end of life stage. The system's resilience to market and regulatory changes will be determined by its ability to adapt without compromising core sustainability principles. With a clear implementation roadmap, disciplined governance, and strong integration with industrial and policy systems, the EFB based circular packaging system has strong potential to operate sustainably and remain relevant within the evolving dynamics of the packaging industry.

Table 4. Mapping of Circular Value Mechanisms and Design Decisions in EFB-Based Packaging System

Circular Value Mechanism	**Design Focus**	**Key Design Decisions**	**Value Mechanism Explanation**
Value Retention	Material Sourcing & PreProcessing	Positioning oil palm EFB as the primary raw material and applying controlled fiber and cellulose extraction processes	Retains the technical and functional value of biomass by preventing down cycling and maintaining material integrity from the upstream stage
Value Retention	Material Engineering	Limiting material degradation through selective mechanical and chemical treatment	Preserves fiber strength and cellulose quality, enabling higher-value applications compared to conventional low-grade biomass use
Value Creation	Packaging Structure Design	Engineering fiber-based structures tailored for liquid beverage containment	Creates new functional value by enabling EFB fibers to meet mechanical, moisture resistance, and form stability requirements
Value Creation	System Integration	Designing compatibility with existing filling, sealing, and distribution infrastructure	Generates economic value by minimizing disruption to established industrial systems and reducing adoption barriers

Circular Value Mechanism	**Design Focus**	**Key Design Decisions**	**Value Mechanism Explanation**
Value Creation	Value Chain Configuration	Linking agricultural waste streams with packaging manufacturing	Creates cross sector value by integrating agriculture and manufacturing into a unified circular supply chain
Value Recovery	End of Life Design	Designing mono material or fiber dominant packaging structures	Enables efficient fiber recycling and avoids material separation barriers common in multilayer packaging
Value Recovery	Post Consumption Management	Aligning material properties with pulp recycling or controlled biodegradation pathways	Recovers residual material value after use and prevents persistent waste accumulation
Value Recovery	System Closure	Incorporating post use material into existing waste and recycling systems	Ensures that material value remains within the economic system rather than exiting as unmanaged waste

Source: [16]

The core strength of this concept lies in its ability to simultaneously retain, create, and recover material value within a single, coherent system design. Value retention is achieved through the deliberate use of oil palm empty fruit bunches (EFB) as the primary material input, intentionally designed to preserve the functional value of fibers and cellulose from the earliest processing stages. Rather than degrading material quality through low-value applications or disposal, the system maintains material integrity through controlled extraction and material engineering processes, ensuring that the technical value of the biomass remains within the economic cycle at a high functional level. This approach prevents value loss at the upstream stage and sustains material utility throughout the packaging production cycle.

Value creation occurs at the system design and integration stage. Through a design for circularity approach, EFB based fibers are transformed into beverage packaging that meets performance requirements, food safety standards, and industrial compatibility. New value is generated not only in the packaging product as a physical artifact, but also through the restructuring of the value chain that connects agriculture, packaging manufacturing, and product consumption. By substituting fossil based virgin materials with renewable agricultural waste, the system delivers economic, environmental, and social value simultaneously, without increasing pressure on primary natural resources.

Value recovery is explicitly embedded through packaging designs that enable controlled post consumption management. The fiber based material structure is designed to be compatible with fiber recycling systems, integrated waste processing, or controlled biodegradation, ensuring that material value does not terminate at the use phase. By incorporating end of life scenarios into the initial design, the system avoids shifting environmental burdens to downstream stages and ensures that packaging materials continue to contribute to the economic cycle after their primary function has been fulfilled. Consequently, the EFB based packaging system does not merely reduce negative impacts, but actively orchestrates material and value flows within a comprehensive, measurable, and industrially viable circular economy framework.

Table 5. Quantification of Circular Value Mechanisms in EFB Based Packaging System

Circular Value Mechanism	Design Lever	Carbon Reduction Potential	Material Efficiency Impact	Cost Stability Impact
Value Retention	Substitution of fossil-based raw materials with EFB fibers	Reduction of upstream emissions associated with petrochemical extraction and processing (estimated low–to–moderate carbon footprint relative to multilayer plastics)	High: utilizes >70% underutilized biomass streams and reduces material loss at source	High: raw material sourced from low-value waste with stable availability
Value Retention	Controlled fiber and cellulose extraction	Avoids carbon-intensive reprocessing caused by downcycling or disposal	Medium–High: preserves fiber integrity, enabling higher functional yield per unit of biomass	Medium: process optimization reduces variability-related costs over time
Value Creation	Engineering fiber-based material for liquid packaging	Net emission reduction through replacement of carbon-intensive multilayer structures	High: single dominant material increases usable fraction of packaging mass	Medium–High: reduced reliance on volatile fossil-based material prices
Value Creation	Compatibility with existing filling and distribution systems	Indirect carbon savings by avoiding new infrastructure construction	Medium: minimizes material and energy losses from system redesign	High: lowers capital expenditure and operational disruption
Value Creation	Integration of agricultural and manufacturing value chains	Reduced transport and coordination inefficiencies through localized sourcing	Medium: tighter supply chains improve resource utilization	Medium–High: shared value creation stabilizes supplier–manufacturer relationships
Value Recovery	Fiber-dominant / mono-material packaging design	Avoids emissions from landfill accumulation and incineration	High: improves recyclability and material recovery rates	Medium: reduces long-term waste management and compliance costs
Value Recovery	Alignment with pulp recycling or controlled biodegradation	Carbon savings through material re-entry into technical or biological cycles	Medium–High: extends material life beyond single use	Medium: shifts cost from disposal to recovery-based value streams
Value Recovery	Integration with existing waste management systems	Avoids carbon-intensive parallel waste systems	Medium: increases actual recovery rates through system compatibility	Medium–High: reduces regulatory and end-of-life risk costs

Source: [22]

CONCLUSION

This study demonstrates that the environmental challenges associated with single-use beverage packaging cannot be effectively addressed through conventional recycling approaches alone. Structural limitations inherent to multilayer materials, persistent weaknesses in end-of-life management systems, and continued dependence on fossil-based raw materials collectively constrain the effectiveness of incremental recycling improvements. The findings substantiate that oil palm empty fruit bunches (EFB) possess strong technical and systemic potential as an alternative raw material for fiber-based beverage packaging, supported by their abundant and continuous availability, renewable nature, and sufficiently high cellulose content suitable for pulp and fiber applications. In terms of outcomes, the proposed EFB based circular packaging system is shown to be both conceptually robust and technically feasible for industrial-scale development. Integrating EFB into the packaging value chain enables simultaneous mitigation of agricultural biomass waste, reduction of reliance on fossil-based plastics, and improvement of end-of-life management through fiber-based recycling or controlled biodegradation pathways. Importantly, the system is designed to be compatible with existing fiber-based packaging production infrastructures, thereby lowering industrial adoption barriers and enhancing scalability without requiring disruptive changes to downstream manufacturing systems. The primary innovation of this research resides in the circular system design rather than in the discovery of a novel material. The study repositions EFB from a low-value agricultural residue into a strategic material input through a deliberately integrated circular framework linking agriculture, packaging manufacturing, and post-consumption management. This innovation is inherently systemic and application-oriented, emphasizing value retention through the preservation of fiber and cellulose functionality, value creation through engineered packaging structures tailored to liquid beverage applications, and value recovery through end-of-life design that is embedded from the outset. Collectively, these contributions advance a system-oriented model for sustainable beverage packaging that is technically viable, industrially realistic, and aligned with long-term circular economy principles.

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