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Parameters Proposed for Sustainability Assessment of Biocomposite Based Rigid Packaging

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Abstract
The sustainability of rigid packaging can be increased by using biocomposites in packaging. Existing frameworks have some limitations such as are made to assess a few aspects, conventional packaging parameters are considered, etc. Biocomposite has a slightly different scenario at various life cycle stages, like the end-of-life cycle process. To assess the sustainability of biocomposite rigid packaging, we must consider parameters related to the biocomposite-based rigid packaging materials life cycle. These are categorised into different aspects of sustainability and life cycle phases.

Keywords: life cycle assessment (LCA), sustainability, sustainability parameters, packaging

1. Introduction

Packaging is necessary for preserving, transporting, and presenting various items. Its structural design should be strong to prevent product damage during shipping or storage. It should also contain information and be aesthetically beautiful to pique the consumer's interest in the product. Packaging is classified as flexible, rigid, glass, paper, and others based on the material utilized. Packaging can also be classified according to its use, such as food, drinks, medicines, personal and domestic, and electronics packaging (Campbell et al., 2015). Rigid packaging is typically more expensive than other types of packaging since it employs traditional solid materials such as plastics, metals, and glass.
Synthetic plastic materials are used in the conventional rigid packaging industry for bottles, soft drinks, packed water, juice, beer, liquid wash, jars, energy drinks, and microwavable friendly trays (Siracusa et al.,2008). Rigid packaging has a higher protection factor than flexible packaging. However, rigid packaging has a more considerable environmental impact than flexible packaging. The ecological effect of packaging is caused by the feedstock sourcing, the manufacturing of polymers and packaging, and the end-of-life behaviour of these materials. At any of these stages, pollutant emissions in the open environment can cause negative environmental effects such climate change, water and air pollution, acidification, etc. As populational increases with time, the consumer base for the FMCG also increases, which is expected high growth of the rigid packaging. Rigid plastic packaging offers distinct advantages such as high impact strength, stiffness, and barrier qualities, all of which have contributed to the growth of the rigid plastic packaging market in recent years (Mordor Intelligence, Industry Report (2019). Rigid packaging, glass, and metal packaging cover around 44 % of the total market segment in global packaging demand. According to research, one-third of all thrown plastic winds up in the soil or waters (Food print Issue, 2021). In research it was found that synthetic microparticle (synthetic plastic particle below five millimetres) contamination in soils worldwide is an even more severe problem than the plastic pollution in our waters, ranging from four to twenty three times more severe depending on the region. Plastic is a fossil fuel product manufactured from the molecules taken from oil feedstocks.

However, according to the current study, around 4% of world oil output is utilized as plastic raw materials, with another 4% required for energy to run plastic plants. Plastic packaging contains additives such as stabilizers, fire retardants, and UV stabilizers to attain good final package qualities. These chemicals have the potential to be harmful to human health (Qualman, 2017). Nonetheless, leftover plastic in landfills is eventually burnt to create room for fresh rubbish. When plastic is burnt, toxic chemicals and irritants are discharged into the air. Reducing the amount of plastic garbage disposed of in landfills will dramatically improve global air quality.

The environmental impact of conventional packaging can be reduced in packaging at different levels of the packaging value chain, starting from raw material production to end of life. For example, at the level of the material, we can use biocomposite materials, recyclable materials. At the consumer level, we can put it in the right dustbin to be recycled or composted. At the raw material selection stage, renewable material-based biocomposite can be an alternative solution. For example, bio-based biocomposite packaging materials decomposes under composting conditions over a certain duration of time, and they have lower carbon footprint on the environment. So, these problems can be solved by using eco-friendly materials in the packaging sector. Recently, natural fibre-based biocomposites for sustainable rigid packaging have been reviewed (Srivastava et al., 2022). Various sustainability assessment framework has been developed to assess the environmental impact and different aspect of sustainability (Azzi et al., 2012). Sustainability frameworks are used to assess the different aspects of sustainability, such as environmental, economic, and social. Existing frameworks related to sustainable packaging materials have various limitations, such as they considered few aspects of sustainability or made for specific application or assessment based on limited parameters (Singh et al., 2018 and Grönman et al., 2013). Parameters used in the sustainability assessment framework of packaging do not include all the aspects of the biocomposites-based rigid packaging such as functional parameters package including compressibility, the strength of fibre-reinforced biocomposite, and environmental parameters like degradation time, water consumption in the cultivation of fibres, etc. To assess the sustainability of biocomposites-based rigid packaging, we need to consider a holistic list of parameters related to the life cycle of biocomposites-based rigid packaging materials. In this article, sustainability assessment parameters have been identified through critical literature survey and life cycle stages of biocomposite-based rigid packaging. These parameters are further categorised into economical, performance, functional, environmental aspects, and life cycle phases of packaging.

2. Advantages of Biocomposites in the packaging application

The renewable fibres used to form biocomposite-based materials for rigid packaging applications would lessen reliability on fossil-based plastics. Furthermore, items manufactured from these materials are biodegradable or compostable at the end of their life, providing more disposal alternatives than synthetic plastic-based products. It would also allow for a reduction in the quantity of microplastic contamination that ultimately ended up in the waters. Biocomposites derived from natural fibres are a new class of useful biodegradable materials capable of meeting long-term, stringent packaging requirements.

Biocomposite packaging degrades much faster than traditional packing. There is the formation of carbon dioxide, water vapor, and organic molecules. It has the potential to lessen the negative environmental impact of plastic pollution. Biocomposites have the potential to remove considerable volumes of waste packaging materials from landfills while also serving as a helpful soil supplement for agricultural production in the long run (Sustainable Packaging Coalition's SPC Bioplastics Converge 2017). Compost serves various purposes as an agrarian supplement, including enriching the soil with critical nutrients for growth and development, improving soil structure, and establishing a more stable soil equilibrium. Compost-enriched soil can help prevent disease and pest infestation in plants by reducing erosion, alleviating soil compaction, and reducing soil compaction (Composting biodegradable plastics: A technical review, 2019).

During the growth of a plant, it consumes carbon dioxide through photosynthesis. As a result, biocomposites have a smaller carbon footprint than petroleum based plastics (Lamberti et al., 2020). The excellent biodegradability of specific fibres, in addition, makes them a more ecologically sustainable material. Biodegradable polymers are more energy-efficient than conventional polymers (Bohlmann, 2004). Natural fillers, on average, outperform glass fibres in terms of environmental performance. Notably, natural fibres are light in weight than glass fibres (David et al., 2021). Floor panels made of synthetic and plant fibre harm the environment. The results reveal that plant fibre panels have a lesser environmental impact than other panels (Lorite et al., 2017). According to LCA findings, natural fibres are more environmentally friendly than synthetic fibres as composite reinforcement. LCA studies of fibre-reinforced biocomposite in comparison to the conventional petrochemical polymer. Compared to traditional petrochemical polymers, fibre-reinforced biocomposite has a better environmental impact at each life cycle stage (shen et al., 2008).

3. Environmental impact assessment of packaging

3.1. Conventional packaging

Several studies related to the environmental impact assessment of the packaging have been performed. Environmental impact assessment of milk packaging in Canada was conducted where only two parameters were considered. The first one is the production parameter of raw materials and packaging. The second one is the end of life, and assessment was done by analysing embodied energy, carbon dioxide equivalent GHG, and water consumption in each step (Sun et al., 2021).

In the process of formation of multi-walled carbon nanotubes from the waste of the flexible plastic and its environmental impact has been assessed. Climate change, fossil depletion, human toxicity, ionizing radiation potential, freshwater ecotoxicity, and marine ecotoxicity are all factors considered in this study. (Ahamed et al., 2020). The Life Cycle Assessment method was used to compare the present Extended Producer Responsibility System (EPRS) to the new DRS system. Even if the DRS reaches a value of 90 percent for the package return index, the new system EPRS is more environment friendly (Abejón, 2020). According to CarloIngrao et al., LCA was done on foamy polystyrene (PS) trays used for fresh meat packing. PS-granule manufacture and power usage had the most significant environmental implications. EI may be reduced to 14 percent using renewable energy sources (Ingrao et al., 2015). Suwanmanee et al. compared the environmental effect of bio-based Vs. Petroleum-based plastics for single-use boxes using Cradle to Consumer Gate LCA, concentrating on PS, PLA, and PLA/starch. The observations imply that the PS box has a smaller environmental effect than PLA and PLA/starch boxes. (Suwanmanee et al., 2012).

Packaging made of biobased materials have lower environmental effect than traditional packaging materials, according to Mendes et al. It was also advised that environmental implications, as well as integrated climatic and environmental impacts, be taken into account (Mendes et al., 2021). Guo et al. conducted an environmental impact assessment of biopolymer cool boxes and cardboard recycling. When compared to a pure AD biopolymer cool box, it was recommended that mechanical and biological treatment (anaerobic digestion (AD) of the biopolymer + recycling of the cardboard) is a more ecologically friendly option (Guo et al., 2011). Singh et al., proposed a framework for measuring 16 environmental impact assessment factors. Using this methodology, the environmental impact of packaging using alternative packaging materials can be examined. Another study by Williams showed that packaging minimizes food waste and proposed a crucial technique for lowering the total environmental effect, even if the packaging itself has an increased impact (Williams et al., 2011). Gabriela et al. assessed the environmental implications of products from the cradle to the grave. However, they left out the marketing and use of these products and transit between the two stages (Lorite et al., 2017).

3.2. Biocomposites based packaging

Plastic pallets are the most often used rigid packing material in industrial settings. Using an injection moulding technique, Korol et al., 2016 presented a comparative evaluation of several biocomposites made from polypropylene (PP), glass fibres (GF), and natural fibres - cotton fibres (CF), jute fibres (JF), and kenaf fibres (KF). A lifecycle assessment of the biocomposite production systems was conducted using SimaPro 8 software and the Ecoinvent database 3.1. Cotton fibre reinforcement depicted the most significant environmental impact, whereas kenaf and jute fibre reinforcement had the lowest environmental impact. Cotton industrialization on a massive scale may be responsible for this problem. Molins etal. studied the biocomposite material prepared from PLA and chicken feathers (CF). Two CF

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stabilisation techniques, autoclave and surfactant were studied and compared to decide which one to prioritize from an environmental standpoint. The result observed that the autoclave stabilization method had a lower environmental impact than the surfactant stabilisation process, owing to lower electricity and water requirements and lower pollution loads in the generated effluent (Molins et al., 2017). The takeout food container is a widely used packaging material in a restaurant chain. Salwa performed a lifecycle assessment of sugar Palm Fibre Reinforced-Sago Biopolymer Composite. The research focuses on the overall product system's damage assessment, including end of scenarios for the food container made of sugar palm fibre based biocomposite. The goal of the study was to predict how the cradle-to-grave method will affect the environment. The findings indicate that the total human health harm was 2.63 ×10 -5 DALY, while the ecosystem damage was 9.46× 10 -8 species, according to the findings per kilogramme of containers each year (Salwa et al., 2020). David et al. compared the life cycle assessment of a rigid tray made of virgin PHBV, PLA, or PP reinforced with vine shoots to a rigid tray made of virgin PHBV, PLA, or PP reinforced with vine shoots. The results reveal that composite trays had a lower impact than virgin plastic trays, ranging from 5% vol percent for PHBV or PLA to 20% vol percent for PP (David et al., 2021).

4. Existing framework in sustainable packaging design

Grönman et al., 2013 presented a framework for designing environmentally friendly food packaging. They represented a framework based on the complete life cycle of product packaging, focusing on food loss prevention and packaging design with a lower environmental impact. Economical, functional, technical, and environmental based various parameters were considered. Five aspects were considered in a conceptual framework for packaging design: design for product safety, design for environmental sustainability, communication, logistics, etc. Environmental sustainability factors such as material selection, the weight of the packaging material, reusability of the packaging, waste reduction, minimization of hazardous substances was also reviewed (Azzi et al., 2012).

Effectiveness (fit for purpose), efficiency (energy required, efficient use of materials and water used), life cyclic material flows of materials (compostable, recyclable, etc.), and safety are the four design concepts that guide packaging design (non-polluting and non-toxic). The framework considered the following factors- 1. environmental protection; 2. use and conservation of natural capital; 3. cost of environmental protection; 4. material, energy, and water use; 5. solid waste and pollution; 6. implications for product and service life cycle and 7. performance in comparison to industry best practices (Verghese et al., 2012).

Afif et al., 2021 proposed a conceptual framework for sustainable packaging in which environmental, economic, and social performance were considered. Material consumption, reuse, recycling, and recovery factors were considered in the environmental performance section. Relevant important factors were studied and identified such as resources used and their environmental impact, cost, consumer demand, regulatory pressure, etc. In environmental performance, only material consumption, reuse, recycling, and recovery measurement were considered. Colwill et al., 2012 proposed a sustainable packaging design framework for biopolymer. It supports comparative analysis of the biopolymer or pack concept made from a biopolymer. Only factors relevant to the comparison of a biobased packaging with a conventional polymer packaging were considered. In environmental impact assessment, the only raw material (finite resources or renewable resources, land and water use, emission (GHG, air quality, climate change, and health), and production parameters (energy use) and EOL (landfill and incineration, and litter) were considered. Singh et al., 2018 proposed a parameter-based framework for environmental impact assessment of product packaging. In this study life cycle was divided into four steps: pre-production, production, usage, end of life. The framework was validated through cool beverage cane case studies. With the help of this framework, we can also design a quantified comparison of the alternative packaging.

5. Design Parameters of biocomposite materials for packaging

Parameters that can help to assess the environmental and other aspects of sustainability of the biocomposites are considered. In this study, the whole life cycle starting from harvesting to end of life was studied. As per the literature survey, we found that parameters used in the assessment of conventional

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packaging do not include all the aspects of the packaging of the biocomposites-based rigid packaging such as functional parameters (package compressibility, the strength of materials, etc.). Biocomposite life cycles have a slightly different route than fossil-based packaging at the end of life, raw material production, etc., as shown in figure 1. It can be made from fossil-based polymer or renewable resource-based polymer in the matrix phase. Renewable natural fibres are used as reinforcement, as shown in figure 1. In the life cycle of the biocomposites-based rigid packaging, different stages starting from harvesting or raw material extraction to end of life are taken into consideration for sustainability assessment. Also, based on the literature survey, a few are taken from existing frameworks to the assessment of biocomposites rigid packaging sustainability (Singh et al., 2014 and Grönman et al., 2013). Biocomposite can be made with synthetic and renewable polymers and natural fibres as reinforcing materials. In this section, renewable polymers as matrix and fibres as reinforcing materials have been considered. Parameters that are considered are divided into two broad categories first environmental-related and the second one is related to performance, economic and material properties during the whole life cycle.

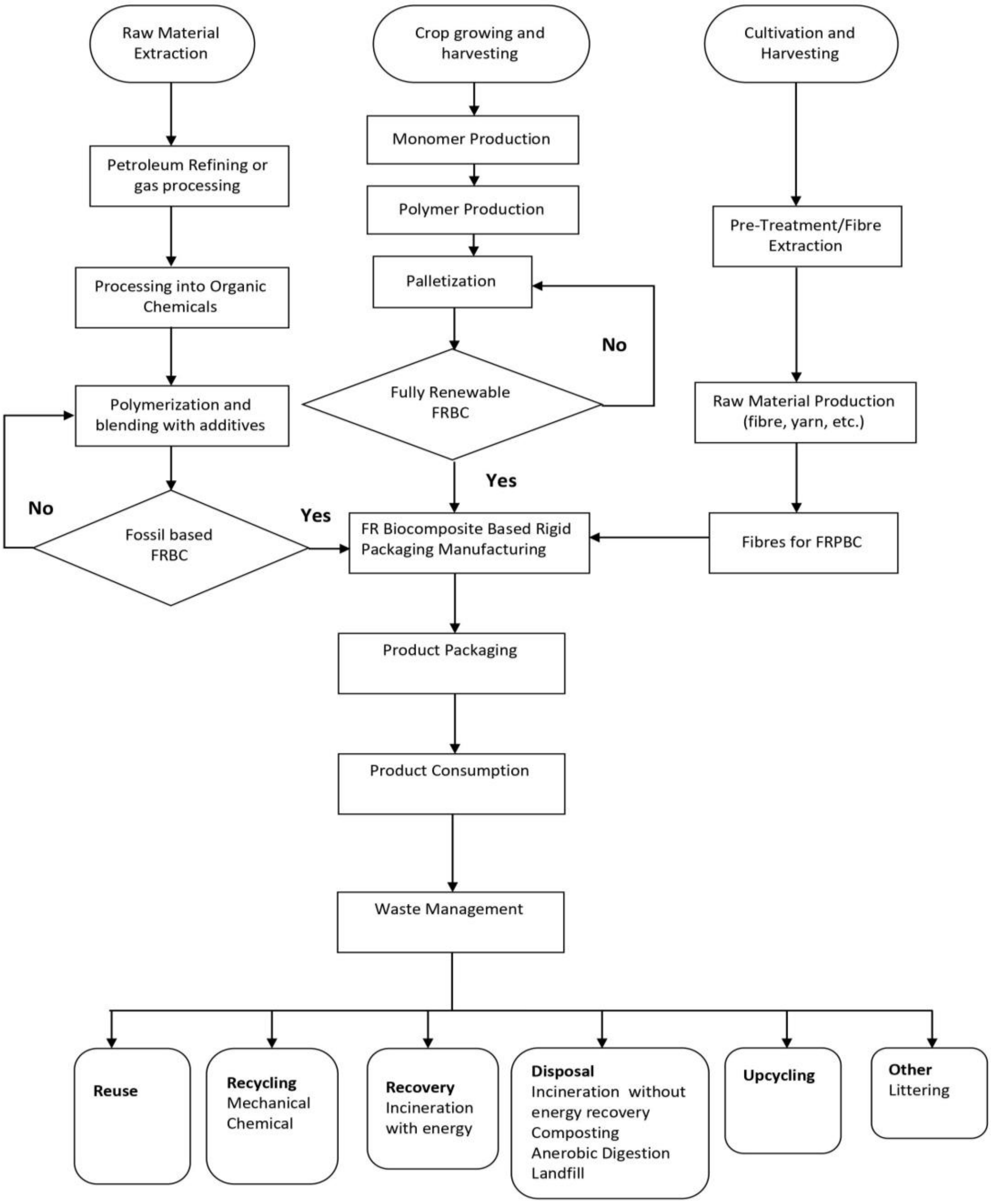

Figure 1. Life cycle stages of the biocomposite based packaging

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5.1. Lile cycle stages

Biocomposite can be made from fossil-based polymer or renewable-based polymerase, a matrix material. Natural fibres in the form of fibre yarn fabric are used as reinforcing material for biocomposite manufacturing. Natural fibre or polymer production has various parameters such as freshwater consumption, the energy required to grow the plants, etc., that can be used in the assessment of sustainability. In the assessment of biocomposite-based packaging, considering the harvesting and cultivation phases can give us a more accurate value of sustainability. In the life cycle phases, various steps such as pre-treatment, monomer, and polymer production have a considerable impact, such as hazardous chemicals used, waste generation, and pollutions emissions. Subsequently, in the packaging production stage, environmental, performance, and economic parameters are also important. Product packaging and consumptions stage, most of the similar parameters are considered as suggested by Grönman, Kaisa et al. used in the food packaging framework. Moreover, properties such as mechanical, physical, barrier, etc., are also important. At the end of life, parameters such as degradation time, recycling, recovery, reuse. So, parameters related to these aspects are considered. The whole life cycle of packaging is shown in figure -1.

5.2. Proposed parameters with life cycle phase

Parameters are broadly classified into two groups. The first is economical, performance, and functional, and the second is environmental parameters phases of sustainability. Along with life cycle stages, the important and related to biocomposite rigid packaging parameters are considered. The list of parameters is shown in table 1.

5.2.1. Harvesting and cultivation

In this stage, environmental parameters such as freshwater consumption, fertilizer use, energy consumption, pollution emission, etc., have a larger share of overall environmental impact. Parameters related to soil fertility, crop efficiency, the total cost can also be considered to assess the overall sustainability of the packaging. For example, high pollution emissions in the environment will increase global warming, and low crop efficiency will lead to high crop costs.

5.2.2. Pre-treatment/fibre extraction

Pre-treatment of the fibres or monomer production involves heavy machinery, so energy, pollution, and waste generation are the major environmental impact shareholders. For example, the use of heavy machinery will consume a huge amount of fuel. The burning of fossil fuels will also generate air-polluting gases. In another category, cost, self-life, machine efficiency is considered to assess the overall sustainability of the packaging.

5.2.3. Packaging manufacturing

It is also an energy-intensive process and has a large share of environmental impact. As a result, parameters such as waste creation, energy consumption, pollutants emitted during manufacturing, and the use of a hazardous chemical are considered. For example, waste generation will lead to land, water, and air pollution. Packaging properties play a vital role in this section to check the overall performance of the packaging. Packaging with poor mechanical qualities might cause product damage. Transportation cost, machine efficiency, etc., are also considered to assess the overall sustainability of the packaging.

5.2.4. Product Packaging and consumption

Environmental-related parameters such as the material used, waste generation, energy used to transport product and packaging, pollution released during use, etc., are considered. For example, high energy will consume a high amount of fossil fuel. Burning fossil fuels will generate air pollution. Parameters such as physical parameters size, shape, weight, protection factor, aesthetics of the package are considered.

5.2.5. End of life

Biocomposite made from fully renewable resources is biodegradable in nature. The biodegradability rate depends upon reinforced and matrix materials. So, the end the life scenario of the biocomposite packaging is significantly different compared to conventional packaging materials. So, parameters such as degradation time, types of composting, incineration with energy, etc., are considered. Other parameters such as easy to unpack from the product, percentage of materials recovery, reuse, recycled, and the waste cost is considered to assess the overall sustainability of the packaging.

Table 1. Parameters required for assessment of biocomposite based rigid packaging

Life Cycle	Economical, performance and functional Parameters	Environmental Parameters
Harvesting and cultivation of the crop	Quality of raw material produced	Waste Generation
	Required Human resources and machinery	Energy Consumption
	Cultivation cost	Land Use
	Soil fertility	Freshwater consumption
	crop efficiency	Pollution (air, water, land)
	crop cycle time	Effect of used fertilizer on environment
Preproduction	Process cost (machine, materials, human resource)	Hazardous Chemical used
	Transportation cost (Land to pre-production unit)	Material used
	self-life of raw material	Energy used
	Quality of raw material produced	Process water use
	Number of the process involved	Waste Generation
	Machine efficiency	Pollution (air, water, land)
Biocomposite Packaging manufacturing	Physical properties of the package (size, shape, weight, thickness, uniformity, etc.)	Material used
	Mechanical properties (compression, tear, puncture, shearing, bursting, etc.)	Energy used
	Barrier properties (moisture, gas, water, permeability, etc.)	Waste Generation
	transportation cost (pre-production to packaging manufacturing)	Hazardous Chemical used
	Machine efficiency, cost of packaging	Pollution (air, water, land)
Product packaging and consumptions	Pack size	Waste generation
	shelf life	Energy used
	Aesthetics	Material used
	Protection	Pollution (air, water, land)
	Transportation cost	
	Ratio to Product volume to packaging volume	
End of Life	Easy to unpack of product from packaging	The energy required to reuse, recycle, recover
	% of material reuse, recycle, recover	Landfill or disposal
	Easy to short and composting	Biodegradation time
	waste cost	Incineration with energy recovery
		Home composting or Industrial composting
		Pollution (air, water, land)

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6. Conclusion

Conventional rigid packaging materials have a higher impact on the environment due to the use of fossil fuel-based ingredients. Natural-based biopolymers and fibres are found eco-friendly in nature and have various advantages such as renewability, eco-friendly, lightweight, and inexpensive. Biocomposites should be preferred over rigid packing materials because of their environmental sustainability. Biocomposite-based packaging has slightly different scenarios in the life cycle phases than conventional packaging, such as harvesting and cultivation stage in biocomposite manufacturing and refinery in synthetic packaging. For a better sustainability assessment, different parameters have been identified and proposed from different stages of the biocomposite lifecycle. These parameters are further classified in different aspects of sustainability such as environmental, functional, economic, and performance. To assess the sustainability of the rigid packaging made of biocomposite, we can use these suggested parameters starting from harvesting to end of life of biocomposite. Based on these environmental, functional, economic, and performance parameters, we can compare the sustainability of the biocomposite-based rigid packaging. The proposed parameters form a framework that can offer manufacturers, designers, and engineers recommendations for designing and developing sustainable rigid packaging at various levels.

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