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Enhancing Packaging Sustainability with Natural Fiber Reinforced Biocomposites: An outlook into the future

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Abstract. Packaging across diverse sectors like food, FMCG products, pharmaceuticals, cosmetics, and electronics predominantly relies on petroleum-based materials. These petroleum-based non-renewable resources significantly impact the environment throughout their life cycle, emitting polluting gases, demanding energy-intensive manufacturing, and causing air, water, and land pollution during disposal. These problems can be minimized by using eco-friendly materials such as materials made from natural fibres, and agricultural waste that is biodegradable in nature. Natural fibre-reinforced biocomposite materials have a high potential to be used in sustainable packaging applications due to their lower environmental impact compared to petroleum-based materials. However, the use of biocomposites is very limited in the packaging sector and growing exponentially. Recently, agriculture waste fibres have been used for the development of various biocomposites-based packaging. In this paper, prior work has been analysed to identify the impact associated with petroleum-based packaging materials, advantages and potential of natural fiber-reinforced biocomposites in the packaging sector, manufacturing techniques, recent development, challenges, and prospects have been discussed.

1 Introduction

Packaging is an essential part of product packaging. Its design should be made to protect the product from the external environment and mechanical damage, procuring the product quality for a certain period of time. Its function is also to display product information and attract consumers towards products. Packaging is classified based on various criteria such as material type, level of packaging, type of packaging, and based on application. Based on the level of packaging, there are three levels: primary, secondary, and tertiary. Primary packaging comes in direct contact with the product. Secondary packaging covers the primary packaging and makes it more secure from a protection point of view. Tertiary packaging is used for the transportation of bulk products and protection during the transport of goods. Based on raw materials, packaging can be classified into paper and board, glass, plastic, and metal. In terms of application, packaging can be broadly classified in the food industry, beverages industry, pharmaceutical industry, personal care, household, electronics, and industrial application. In terms of types of packaging, it is broadly classified into flexible and rigid types of packaging. Packaging industries are continuously growing with the increasing demand for products. A recently published report found that the global packaging market was worth more than 900 billion and has constantly evolved with more than 8 % value since 2015 [1]. The largest end-user category for plastic products is packaging. It has more than 40% of the total plastic usage in the world [2]. On average, 3 million bottles and bags are distributed worldwide every minute. Plastic packaging is non-renewable and highly unsustainable to the environment, with high energy consumption during manufacturing. It also emits greenhouse gases, harmful content in the environment during the packaging's whole life cycle. In developing countries, the recycling rate is now up to the limit to solve the environmental problem. According to published reports, microplastic pollution in soils around the world is an even more serious concern than microplastic pollution in our oceans. [3]. More than 600 Mt of packaging waste was created in 2015; only 10 % was recycled, less than 13 % was burned, and more than 75 % ended up in the environment [4]. A recently published report mentioned that more than 60 % of produced plastic ends up in open environments and creates pollution. If current trends have been followed in production and waste management, more than 10,000 Mt of plastic waste will be in landfills or in the open environment by 2050 [4]. Microplastics in soil have a variety of negative consequences, including influencing the behavior of soil fauna, such as earthworms, and spreading illness. From packaging manufacturing to burning plastic emits lots of CO_2 and harmful gases in the environment. Incineration can emit harmful content like sulfur dioxide, nitrous oxide, etc., and polluting gases [5]. More than 70% of all marine garbage is created by packaging waste. It also affects coastal tourism. Marine creatures ingest or entangle plastic waste, resulting in severe injury and death [6]. It is

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also reported that due to plastic pollution in the ocean, plastic is present in a few ocean-living species, such as fish, sea turtles, ocean species, etc. [7]. To mitigate the environmental impact on the environmental, sustainable interventions in the packaging sector are required.

2 Sustainability intervention

The environmental problems created by petroleum-based packaging can be minimized at various levels of the supply chain of packaging. It starts with selecting raw materials and ends with disposable packaging material for reuse, recycling, and biodegrading, as shown in Fig. 1. If we start intervention at the material selection phase, we need to minimize the use of petroleum-based materials using biobased materials. If the selected material is 100 % natural and biodegradable, it will make significant progress in sustainable packaging design. A package can be made more sustainable at several points along the packaging value chain. In the design phase, we can design lightweight packaging with less volume to transport the same amount of product. It will reduce fuel consumption during transportation and can carry a large volume of products. So, at every stage, we can make some changes to sustainable packaging. Using natural fibre-based materials in packaging will make it 100% biodegradable and reduce environmental impact [8].

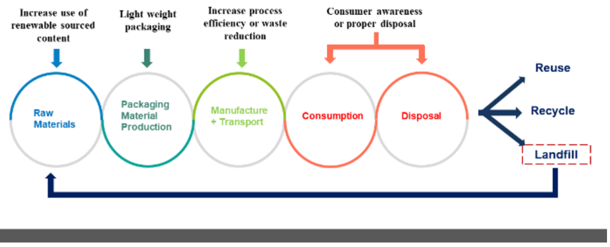

Fig. 1. The sustainability intervention in the packaging value chain.

3 Natural fibres as a reinforcing material

Geographically, most countries have access to a wide range of natural fibres, such as sisal, coir, jute, banana, bamboo, ramie, pineapple, etc., which may be used in place of synthetic fibres as reinforcement in polymer matrix composites. Natural fibres can be broadly classified into plant-based and animal-based fibres. Animal-based fibres are wool, silk, and chicken feather, which are used in various applications as reinforcing materials, such as biomedical packaging. Plant-based natural fibres such as sisal, kenaf, hemp, cotton, coir, and bamboo are used in biocomposites for products and packaging in various sectors [9-11]. Properties of natural fibres, such as high specific strength, stiffness, low density, and processing flexibility, are superior to synthetic materials. These natural fibre-based products and packaging have a lower environmental impact compared to petroleum-based materials [12]. These plant base fibres are also known as lignocellulosic fibres, extracted from the part of the plant through mechanical or chemical processes. Plant-based fibres can be further classified into seed, bast, leaf, grass, wood, and straw fibres. Seed fibres are coir, cotton, milkweed, kapok, etc. Banana, abaca, pineapple, agave, etc., are examples of leaf fibres. Grass fibres, such as sugarcane bagasse, bamboo, etc., are widely used in packaging [13-15]. Natural fibres having high potential in biocomposite have been discussed below.

3.1 Bamboo fibre

Bamboo is one of the agricultural crops that may be used to create polymer composites. Asia and South America are both home to a large bamboo population. Although bamboo is regarded as a natural engineering material, several Asian nations have not fully exploited its potential [18]. Bamboo is also made of 60 % cellulose with high content of lignin. Various bamboo fibres based biocomposites have been developed for various applications such as packaging, automobiles, etc. [19].

3.2 Jute fibre

Jute is also cellulosic fibres and is widely used in packaging materials. Jute is also used as fibre, yarn, and fabric for reinforcing material for biocomposite development. The fabrication of multilayer thermoplastic composites uses a variety of woven jute (such as plain, satin, and twill), where the fibres are strongly interconnected. Various hybrid composites blended with other fibres have been developed for improved properties [20]. PLA, PP, MAgPP materials have been used as matrix materials for jute biocomposite.

3.3 Banana fibre

Banana fibres are extracted from the pseudo-steam of the banana plant. It is a cellulosic-based fibre that consists of cellulose, hemicellulose, lignin, moisture, etc. Banana plants can be used in various applications such as flavoring, livestock feed, thickener, and micro and macronutrient sources. Among the 130 countries that farm bananas, India produces 27% of the world's total bananas. In India, Karnataka is the state where most bananas are grown. Bananas are also grown in Andhra Pradesh, Assam, Gujarat, Kerala, Maharashtra, and Tamil Nadu. Banana fibre reinforced many researchers have developed biocomposite with PLA, PP, etc. based matrices [8,16,17].

3.4 Flax fibre

Flax fibres have a high potential as a reinforcing material in biocomposite development. Flax reinforced with various thermoplastic matrix materials such as PLA, PA, and PP-based biocomposite have been developed. It was found that chemically modified flax fibre-based biocomposite has significantly improved functional properties [17, 21].

4 Natural fibre reinforced biocomposite

Biocomposites can be in the form of flexible as well as rigid forms. In packaging applications, both types of biocomposites are being used. Flexible packaging is mostly used where the barrier properties requirements are most important. In comparison, rigid packaging is used where protection from external elements is essential. We have discussed both types of biocomposite that have potential applications in the packaging sector.

4.1 Flexible packaging

Fiber-reinforced biocomposites serve as a flexible and sustainable packaging material. They combine the strength and versatility of natural fibers with biodegradable matrices, providing an eco-friendly alternative to conventional packaging materials. These biocomposites offer excellent mechanical properties, barrier performance, and can be tailored for specific packaging applications, contributing to the growing demand for environmentally friendly and innovative packaging solutions. Bamboo cellulose pulp fibre reinforced biocomposite film was developed with different fibre loading percentages from 0 % to 20 % with the solution casting method. It was observed that up to 15% fibre loading mechanical and physical properties have improved, and with further increments in fibre loading, the properties have started decreasing. Its properties meet the food packaging performance properties [22]. The developed film has potential use in the food packaging industry and is an alternative solution for nonbiodegradable packaging material. Dioscorea hispida fibers reinforced biocomposite film has been developed for packaging application. The loading of the fibre was below 9 % and is biodegradable in nature [23]. The solution casting method was used to develop arrowroot fibre 0 % to 10 % into a glycerol matrix to create thermoplastic arrowroot starch (TPAS) based biocomposite films [24]. Developed biocomposite film has high potential in food packaging applications. Rice husk fibre reinforced biocomposite was developed with multiscale fibre length through the solution casting method [25].

4.2 Rigid Packaging

Fiber-reinforced biocomposites are utilized as rigid and durable packaging materials. By combining natural fibers with biodegradable matrices, these biocomposites offer high strength and stiffness, making them suitable for protecting and preserving various goods. Their ability to resist impact and stress makes them an eco-friendly and sustainable option for rigid packaging applications, meeting the increasing demand for environmentally responsible packaging solutions. Recently, new biocomposite-based packaging materials have been developed for various levels of packaging. Cogon grass fibre reinforced thermoplastic cassava starch biocomposite was developed with compression molding for packaging application [26]. The fibre loading varied up to 5 percent. It was found that when the fibre content was increased, the functional properties such as moisture content, water solubility, and water absorption were improved. Kenaf fibre reinforced poly (lactic acid) (PLA) biocomposite was developed with an injection molding process. Fibre loading varied from zero to 20 %. It was found that mechanical properties were significantly increased [27]. The developed biocomposite has the potential for product packaging applications. Bamboo powder fibres and silica aerogel powder reinforced with modified polylactic acid (MPLA) biocomposite were developed for packaging application [28]. Fabric made from sterculia urens reinforced PLA biocomposite was developed with a hot molding process. The developed biodegradable sheet has excellent mechanical properties in food packaging applications [29]. Bamboo fabric-reinforced PLA biocomposite was developed and tested for biodegradability and recyclability. Characterizations such as physical properties, thermal properties, biodegradability in composting conditions, and weight loss determination were also performed [30]. A green biocomposite was developed by cellulosic fabric as reinforcing material and fungus mycelium as the matrix phase. Cellulosic fabric made of cotton waste fibre and hemp pith fibre was used in the development of biocomposite. The resultant biocomposite has tremendous advantages in terms of being lightweight, highly hydrophilic, and buoyant [31].

5 Challenges

There are a few problems associated with biocomposites that need to be addressed while using them in the packaging application. The addition of fibres in biocomposites increases functional properties up to a certain limit. The addition of further fibres can reduce the functional properties [22]. Besides this, natural fibre-reinforced biocomposite tends to have high moisture absorption, lower interfacial interaction with matrix material, and low durability. Natural fibres are organic, so oxidation and enzymatic produce premature biodegradation. Natural fibres high moisture absorption rates prevent them from being used in applications with high environmental exposure. Another significant drawback of natural fibres is their low fire resistance. Color, smell, and thermal deterioration of the natural fibre reinforcement may negatively influence the mechanical characteristics of the NFR biocomposite. Many NFR biocomposites may have substantial flaws because of their high fibre content and low impact strength [32].

A variety of strategies and technologies are being created and investigated to address the challenges raised above. Natural fibres inherent problems have been addressed, which has increased the use of these materials in the creation of NFR biocomposites. The performance of fibres and crop attributes is being streamlined constantly. New methods are being developed to enhance fibre matrix adherence in NFR biocomposites using biodegradable adhesives and surface-treated reinforcing fibres. When compared to other biomaterials, these biocomposites' chemical and physical characteristics can be easily tailored. It is obvious that with considerable breakthroughs in technology, NFR biocomposites are materials for the future [33].

6 Manufacturing techniques

Fibre-reinforced biocomposite can be in the form of rigid materials or the form of flexible packaging. Various conventional composite manufacturing techniques can be used in the development of rigid biocomposite packaging. The injection molding technique uses a screw-type plunger to force the materials into the mold [34]. Recently developed techniques for cellulose composites, such as all cellulose composite (ACC), can be used in the development of biocomposites [35]. Heating under a vacuum can also be used to manufacture fiber-reinforced biocomposite [36]. Resin transfer molding (RTM) and pultrusion have been used in manufacturing natural fiber-sed biocomposites [37]. Compression molding is one of the most famous biocomposite manufacturing techniques that is used to develop biocomposite for packaging applications. Compression molding is a fast and simple process compared to other types of manufacturing techniques. It was found that biocomposites developed with compression molding have better mechanical properties [38], [39]. Various short and long fibre-based biocomposites have been developed through the compression molding process [40]. As technology continuously evolves, advancements in manufacturing techniques are also increasing significantly. One of the recent developments in 3D Printing based on natural fiber-reinforced biocomposites is shown in Fig. 2 (a). Various natural fibre-reinforced biocomposites have been developed through 3D printing technology [41]. The solution casting technique can be used in the development of flexible biocomposite.

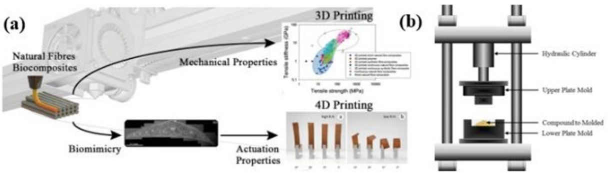

Fig. 2. (a) Natural fibre reinforced biocomposites developed through 3D printing techniques [41] (b) Compression molding technique for natural fibre reinforced biocomposite development [40].

7 Recent developments

The use of natural fibres in packaging applications is in its initial stage. Recently novel developed biocomposites have applications in flexible as well as rigid packaging applications. Natural fibre-based biocomposites have a very high potential to be used in commercial packaging applications. Few companies have taken the initiative to reduce environmental pollution created by using petroleum-based packaging materials [42]. The recently developed biocomposite in various sectors at the commercial level has been discussed below.

7.1 Pharmaceutical and personal care

Sugarcane waste fibre-based biocomposites can be used in the primary packaging of pharma industries. It provides sufficient properties that are required by pharmaceutical packaging. Jute fibre-based packaging materials can also be used as outer packaging materials for pharmaceutical and personal care items [43]. Be green packaging developed customized packaging for personal care item packaging, as shown in Fig. 2(b).

Fig. 2. (a) Pharmaceutical packaging made from sugarcane waste fibre (b) Personal care product packaging made of natural fibre-based pulp.

7.2 Electronics

In electronic packaging, bamboo-based biocomposite has been introduced by Dell. Bamboo fibre-based packaging materials have several advantages in electronic packagings, such as compostability and recyclability. A bamboo plant grows up to 2 inches in a single day. It provides good protection factors for electronic-based delicate items [44]. A company has developed a laptop casing that is made from hemp fibre reinforced PLA composite, which is biodegradable and eco-friendly in nature [45]. Be-green introduced the packaging of Chromebook made from plant fibre-based materials. It has a lightweight material and biodegradable nature. Its environmental impact is lower than previously used packaging [46]. Evocative developed mushroom-based packaging for Dell tech to eliminate petroleum-based packaging materials. It is made in an exact shape with the help of mold for a particular electronic product [47].

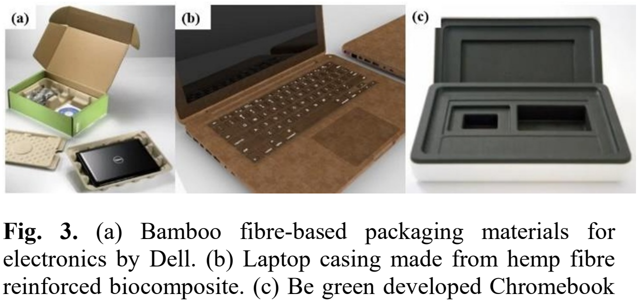

Fig. 3. (a) Bamboo fibre-based packaging materials for electronics by Dell. (b) Laptop casing made from hemp fibre reinforced biocomposite. (c) Be green developed Chromebook packaging materials made of plant-based fibre.

7.3 Food

Food packaging made from natural fibre reinforced biocomposite have several advantages in terms of biodegradability, shelf-life extension of the packed food, lightweight, high shock absorption, and high protection factor from the environment [48]. Biopolymer composites reinforced with almond shells, rice husks, and seagrass were created for food packaging. Also, barrier, mechanical, and thermal properties were investigated [49]. Enkev has recently developed COCOFORM and COCOLOK food packaging from coconut husk through compression. The developed packaging is commercially available in the market, as shown in Fig. 5(a). COCOLOK is made from coconut fibre and natural latex and can potentially use as protective food packaging [50]. Canadian sustainable packaging company developed Earthcycle biocomposite-based packaging for mushroom packaging. It is a palm fibre-reinforced biocomposite made through thermoforming process and is compostable in nature [51].

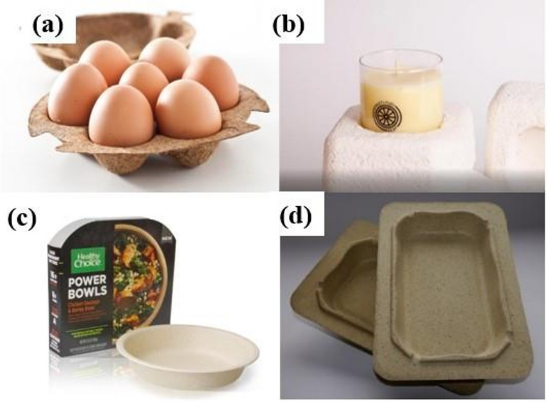

Fig. 4. (a) CCOLOK is made from coconut husk fibre and natural latex for egg packaging. (b) IKEA's usage of MyoComposite. (c) food tray made from agriculture waste-based fibre-reinforced biocomposite. (d) plant fibre-based bowl for food packaging.

IKEA has taken the initiative to reduce the environmental impact created by packaging waste by using mushroom-based packaging, "MycoComposite". It is 100 percent biobased and home-compostable [52]. Many researchers have recently developed fiber and pulp-based biocomposite material [53]. Fibres from agricultural waste are being used in food packaging applications. These fibres are converted into micro/nanoscale to make them suitable for reinforcing in the polymer matrix [54]. Congra Brands has been employing bowls made of plant-based fibre for packaging for the past three years, and they just expanded their line of goods by using their RESPONSIBOWL.

7.4 Beverages

Stora Enso and the packaging company jointly developed eco-friendly bottles and containers made from wood fibres [55]. SAS Green Gen developed a flex fibre-reinforced biocomposite for beverage applications such as beer, spirits, and wine. These eco-friendly developed bottles are potential alternatives to petroleum-based bottles shown in the figure in Fig. 5 (b). It will significantly reduce the plastic pollution created by beverage industries [56]. Carlsberg introduced eco-friendly fibre bottles for various beverage packaging. It is made of plant-based natural fibres and is fully compostable and eco-friendly [57].

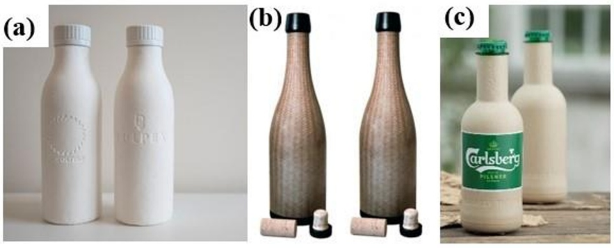

Fig. 5. (a) wood fibre pulp-based beverages bottles jointly developed by Stora Enso and Pulpex. (b) bottle made from flex fibre reinforced biocomposite for wine, beer, and spirits. (c) Carlsberg bottle made from plant-based fibres.

7.5 Cosmetics

Mycelium-based biocomposites have also been developed for cosmetics products by Ecovativ. It provides a higher protection factor compared to thin, rigid packaging material and lower weight. The packing of the cosmetics products in mycelium-based packaging is shown in the figure [58]. FS Korea is one of the companies that has taken the initiative to minimize the use of petroleum-based packaging materials in the cosmetic industry. They started using biocomposite materials made from wood-reinforced fibres. Curaua based biocosmetic has also been developed for perfume bottles. These materials have improved properties compared to previously developed packaging materials. The perfume bottles are made from 100 % natural resources and are biodegradable.

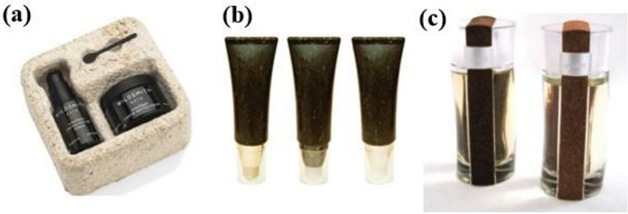

Fig. 6. (a) Mycelium based cosmetic packaging (b) perfume bottles made from curaua fibre reinforced biocomposite. (c) cosmetic bottles made from wood based biocomposites

8 Conclusion

In conclusion, the paper highlights the unsustainability and non-renewable nature of petroleum-based packaging materials, which lead to various environmental issues and public health concerns, including air, water, and land pollution. However, a promising solution lies in the adoption of biobased materials, which offer lower environmental impacts compared to traditional packaging materials. The use of natural fibers as biocomposites in the packaging industry emerges as a viable alternative that can effectively mitigate existing environmental challenges. These fiber-reinforced biocomposite-based packaging materials exhibit favorable functional properties while also being biodegradable, making them environmentally friendly and sustainable. Recent advancements have led to the successful development of several natural fiber-reinforced biocomposites that meet the functional requirements of product packaging. As the biocomposite sector is still in its nascent stage, it shows significant growth potential and exponential progress. Certain product packaging companies have already introduced biocomposite-based packaging options, paving the way for commercial adoption. The integration of biocomposites into the packaging sector holds the key to reducing environmental problems associated with conventional packaging materials. By embracing these sustainable alternatives on a broader scale, we can make substantial strides toward a greener and more eco-conscious future. It is imperative to further encourage and invest in the utilization of biocomposites in packaging to usher in positive environmental transformations and foster a circular economy.

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