Evaluating Bubble Wrap and Proposing Post-consumer Textile Waste as Alternative Material: A Review

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Abstract: Packaging is an important part of practically every business, sector, and supply chain. The main objective of packaging is to protect the product from its surroundings which can be achieved in a sustainable manner. Effective packaging is necessary to avoid product loss and, at the same time, reduce environmental effects. Ecommerce has intensified the problem, as the products purchased online need to deliver to consumers sans damages and breakage, thus finding excessive usage for bubble wrap as a protective packaging material. Bubble wrap, one of the most widely used protective inner packaging materials in e-commerce, has been irreplaceable for most of its functions in packaging for consuming less space, being featherweight, and its shock absorption abilities. With the intensifying environmental impacts of consumption and disposal in the e-commerce-driven world, it has become pertinent to evaluate bubble wrap's sustainability quotient and identify alternative material which could provide protective and sustainable packaging solutions. By addressing this important issue, in this study, an extensive literature review was conducted to evaluate bubble wrap as a protective packaging material on sustainable packaging principles. The study also included comparison of bubble wrap and other alternative packaging material identified, on these principles. Additionally, the review helped in examining post-consumer textile as an alternate material by mapping suitable textile techniques that facilitate the production of protective textile-based packaging material. The paper proposes the potential to develop a novel approach and future research directions for inclusion of post-consumer textiles in protective packaging material production, as this would encourage recycling and address landfill issue.

Keywords: Protective packaging, Bubble wrap, Sustainable packaging principles, textile manufacturing techniques, Post-consumer textile waste

Paper Type: Review Paper

1. Introduction

Packaging refers to the act of wrapping or covering an item or group of items. Packaging is a coordinated system made up of materials of any nature to be used to prepare goods for containment, protection, transport, handling, distribution, delivery, and presentation (Helano et al., 2019). Packaging materials account for about 65 percent of the world's solid waste. About 380 million tons of plastic are produced annually worldwide (as of 2018), and a total of about 6.3 billion tons of plastic have been produced over the past 68 years (FutureBridge, 2020). Of the 6.3 billion tons of plastic, only an estimated 9 percent is recycled, 12 percent is incinerated, and the rest remains as pollution, contaminating the land and the oceans. Cellophane, paper, textile, glass, fabric, and metal are among the various different kinds of materials used for packaging. Generally, there are three levels of packaging (Cardenas, 2019). Primary packaging is used to contain and protect the product until it is consumed and, in some cases, while being consumed, e.g., a plastic bag, bottle, or carton. It also contains information for the consumer and helps to market the product. Secondary packaging is used to protect and unitize multiple units of a product, e.g., a cardboard box, cardboard tray, or shrink film overwrap. This facilitates transport and storage. Tertiary, transport, or distribution packaging is used to secure and unitize products for transport and storage, e.g., a pallet, shrink or stretch film. Protective materials such as packing peanuts, dividers, die-cut foam, and bubble wrap find primary use both at the secondary and tertiary packaging levels.

The booming e-commerce sector has spurred the demand for protective bubble wrap packaging in the recent past. The global bubble wrap packaging market is expected to reach US$ 3.8 billion by 2029, growing at a CAGR of 3.4 percent between 2022 and 2029 (Future Market Insights, 2019). Bubble wrap is lightweight, takes little space, and protects fragile items, making it one of the most commonly used protective packaging, especially in e-commerce. It consists of air bubbles that are soft and compressible and act as shock absorbers to slow down the impact on the product in case of a sudden collision (Jalan, 2019). They are made from low-density polyethylene (LDPE), a non-renewable polymer derived from petroleum and natural gas. Biodegradable alternatives for bubble wrap are available, but with limitations of availability and higher prices. The widely used standard wrap is made of plastic and significantly pollutes the environment through air, soil, and water pollution. Slow decomposition, lack of reusability, flammability, and recycling difficulties are other problems associated with bubble wrap. E-commerce packages typically use paper bills, envelopes, cardboard boxes, plastic bags, woven bags, tape, and an excessive amount of buffering materials such as bubble wrap and packing peanuts. Customers typically throw these materials away after receiving the package. The expansion of e-commerce has encouraged the use of bubble wrap, increasing its consequences.

The massive amount of plastic waste impacts the environment on land as well as in the ocean. The need for sustainable packaging has become extremely critical. Sustainable packaging includes the design and use of alternative packaging material involving innovative materials (compostable, bio-degradable, plant-based, recycled, etc.), packaging design advancements, distribution, and use-phase period and end-of-life processing improvements (FutureBridge, 2020). Sustainable packaging can be defined as packaging which endorses the four principles given by Sustainable Packaging Alliance (SPA) namely effective, efficient, cyclic and safe (James et al, 2005; Sustainable Packaging Alliance, 2010). Problems associated with plastic-based packaging materials have pushed various sectors to focus on manufacturing and start using its alternatives. There are various alternatives, either of a similar or different form, but having the same usage as bubble wraps available in the market e.g., tessle wrap, protega paper cushions, 3D folded kraft paper, wool bubble, cellulose wadding wrap, eco-friendly air pillows, green bubble wrap, etc., however, some of them have not been scaled to be used commercially or still lie in the prototype stage.

A step towards sustainability direction is to use post-consumer material into making bubble wrap like protective packaging. One such post-consumer material found in abundance is the textile waste. Post-consumer textile waste holds significant potential to be transformed into packaging material, which can be directly linked to sustainability implications. The fashion industry accounts for 10 percent of global carbon emissions and remains the second largest industrial polluter after the oil industry (Conca, 2015). Post-consumer textile waste occupies a significant portion of landfills, which is why the fashion industry has acquired a poor reputation over the years regarding environmental issues (Bauck, 2021). Of the textile waste generated, 66 percent is sent to landfills, 19 percent is incinerated with energy recovery, and only 15 percent is recycled (Devoy et al., 2021). Since waste generation is not adequately controlled, recycling these wastes is gaining importance; therefore, designers and engineers are investigating ways to make new products from these wastes (Enis et al., 2019). Some of the textile fabrics are similar in structure, shape, and cushioning to bubble wrap. Hence, as a determined step towards sustainable packaging, utilizing post-consumer textile waste can prove to be a creative and impactful act.

This study evaluates bubble wrap according to sustainable packaging principles to derive the valuable characteristics that can be used to develop alternative protective packaging material. The study further explores the possibility of using post-consumer textiles as an alternative material by mapping various techniques for producing textiles that provide cushioning and similar properties to bubble wrap.

2. Research Methodology

This study is a review work aimed at proposing post-consumer textiles as a sustainable material for developing protective packaging. It begins with evaluating bubble wrap according to sustainable packaging principles to derive valuable characteristics. The study further explores post-consumer textiles as an alternative sustainable material by identifying suitable textile techniques that facilitate the production of protective textile-based packaging material.

An extensive literature review of concepts related to the theme was conducted using Google scholar, Scopus, and WOS databases. The keywords used and their combinations were protective packaging, characteristics of protective packaging, sustainable packaging, bubble wrap, fabric manipulation, textile techniques, and post-consumer textile waste. Other web sources such as news articles, e-commerce websites, and blogs were also referred to. The broad web search included about 23 articles from Google Scholar, Scopus, and WOS, about 20 news articles, blogs, and about 12 e-commerce websites.

The review was carried out in different phases. In the first phase, a literature review was conducted on the types of packaging materials, the characteristics of protective packaging, sustainable packaging, and sustainable packaging principles. Based on phase 1 of the literature review, bubble wrap was chosen as the unit of analysis because it is widely used as a generic packaging material. The literature review was conducted to understand the characteristics and issues of bubble wrap. Alternatives to bubble wrap were identified. Based on the literature review and the authors' comprehension, bubble wrap was evaluated in terms of sustainable packaging principles. The identified alternative protective packaging materials were also compared to bubble wrap based on the parameters of sustainable packaging principles. Further, the possibility of using post-consumer textiles as an alternative material was explored by evaluating different techniques for producing textiles that provide cushioning and similar properties to bubble wrap. In the final phase, key findings, conclusions, and future research directions were proposed.

3. Literature Review

A. Packaging and its menace

Globalization allows the free movement of goods and services and the opening of national borders thanks to the growth of multinational companies, which positively impacts the development of the packaging industry (Kozik, 2020). Packaging protects the environmental and economic investment in products and contributes to economic development and social well-being by facilitating the distribution and delivery of products to the marketplace. Besides logistics requirements, the packaging industry is driven by social consumption and trends and the growth of other businesses requiring packaging. Packaging is done in different levels; each level performing specific functions. Generally, there are three levels of packaging (Cardenas, 2019). Primary packaging refers to the materials that are in direct contact with the final product as well as all the packaging that surrounds it when the consumer buys it. Primary packaging refers to all the packaging which eventually finds its way into the domestic waste stream, once the product is used up (Pongrácz, 2007). Secondary packaging is the material used to group packs together for easy handling and is intended to protect the primary ones. Inner packaging materials are the secondary-level packaging materials used within the outer packaging to minimize the movement of the product and protect it from sudden movement during warehousing and logistics (Sustainable Packaging Coalition and Green Blue Institute, 2006). Tertiary packaging intends to collate secondary packs for a more efficient transportation (Perez Espinoza, 2012). In terms of raw materials for the packaging industry, plastics are widely used worldwide. Being light-weight, durable and flexible it reduces transportation costs and greenhouse gas emissions. In addition to plastics, paper products are used extensively in the packaging industry. They are used to produce envelopes, labels, individual packaging, and mainly transport packaging (Kozik, 2020).

Packaging waste is a significant issue. Plastics, particularly packaging based on PET, account for a significant portion of marine waste, representing about 85 percent of all waste collected. Hundreds of millions of tons of packaging are produced each year, requiring solutions that significantly reduce environmental impact (Rossi et al., 2020). The ecological implications of increasing online purchases and e-commerce shopping trends have received much attention in recent years. New manufacturing techniques can help improve the volume and shape of the packaging and enable more sustainable production with lower emissions of pollutants and more efficient use of materials (Escursell et al., 2021). Manufacturers are developing unique biodegradable packaging materials and using renewable or recycled raw materials to adapt the industry to current demands and advances (Kozik, 2020). Traditional packaging materials such as plastic, paper, glass, and metal can also meet the criteria for sustainable packaging if their life cycles are examined and certain parts of their production, use or disposal are considered (Kozik, 2020). The world continues to rely on environmentally questionable packaging solutions such as single-use plastics and multilayer packaging. On the other hand, end users' use and disposal of packaging place additional demands on the ecosystem (Meherishi et al., 2019). There are research initiatives for innovative ways to improve packaging already on the market and adapt it to the current state and changing demands of the market, society, and the environment. Innovative materials and technologies that allow existing materials to adapt to changes and new applicable standards are critical (Kozik, 2020).

B. Sustainable packaging

Sustainable packaging is packaging that is conscious and encourages innovation, transformation, and optimization. The Sustainable Packaging Coalition[1] provides holistic criteria that define the essential aspects of sustainable packaging. According to the criteria, Sustainable Packaging (a) is beneficial, safe & healthy for individuals and communities throughout its life cycle, (b) meets market criteria for performance and cost, (c) is sourced, manufactured, transported, and recycled using renewable energy, (d) optimizes the use of renewable or recycled source materials, (e) is manufactured using clean production technologies, and best practices, (f) is made from materials healthy throughout the life cycle, (g) is physically designed to optimize materials and energy, and (h) is effectively recovered and utilized in biological and/or industrial closed loop cycles (Gustavo et al., 2018; Sustainable Packaging Coalition, 2019).

Sustainable packaging has to strike the right balance between business objectives and environmental concerns throughout the lifecycle of packaging. Sustainable packaging promotes best and responsible practices in the context of materials used, manufacturing processes, and recycling opportunities. Some of the major benefits of sustainable packaging are that it remains safe for individuals and communities throughout its lifecycle, reduces the overall carbon footprint, is easily disposable and bio-degradable, is versatile and flexible, improves storage space, reduces the use of resources significantly, and impacts the brand image (Ryan, 2010). Sustainable packaging calls for innovative approaches to developing, using, and recycling/reusing packaging materials that bio-degrade and decompose. A wide range of innovative materials are being currently used to develop sustainable packaging, which includes paper- and plant-based materials, seaweed, edible material, plantable material, etc. (FutureBridge, 2020).

The Sustainable Packaging Alliance (SPA)[2] defines sustainable packaging as packaging that is useful, safe, and healthy throughout its life cycle for individuals and society as a whole (Sustainable Packaging Alliance, 2010; Kozik, 2020); meets market efficiency and cost criteria; is sourced, produced, transported, and recycled using renewable energy; maximizes the use of renewable or recycled feedstocks; and is manufactured using clean production technologies and processes (Kozik, 2020). Sustainable packaging aims at providing significant benefits to society

[1] The Sustainable Packaging Coalition (SPC), founded by non-profit sustainability institute GreenBlue, is an industry group that supports sustainable packaging initiatives by conducting research, sharing best practices, and advocating for environmentally-friendly packaging

[2] The Sustainable Packaging Alliance (SPA, www.sustainablepack.org) is a alliance between three Melbourne (Australia)-based organizations: the Centre for Design (CfD) at RMIT University, the Packaging and Polymer Research Unit at Victoria University and Birubi Innovation in 2002 to develop an integrated, supply chain focused, multi-dimensional approach to research, education and training (James et al., 2005)

by effectively protecting products throughout the supply chain and facilitating conscious and responsible consumption. Sustainable packaging is designed to use materials and energy throughout its life cycle efficiently and poses no health or environmental risks (Sustainable Packaging Alliance, 2010). Lewis et al. (2007) pointed out that sustainable packaging is a complicated concept that requires a systems approach and critical thinking. SPA first established four principles of sustainable packaging under the labels "Effective," "Efficient," "Cyclical," and "Safe" (James et al, 2005; Sustainable Packaging Alliance, 2010). Packaging that meets these principles will be instrumental in sustainable development. The four principles are provided in Figure 1.

Figure1. Sustainable packaging principles

Effective: Adds economic and social value • Reduces product waste • Improves functionality • Prevents over-packaging • Reduces business costs • Achieves satisfactory return on Investment (ROI	**Efficient: Minimum use of material and energy** • Improves product / packaging ratio • Improves efficiency of logistics • Improves energy efficiency (embodied energy) • Improves materials efficiency (total amount of material used) • Improves water efficiency (embodied water) • Increases recycled content • Reduces waste to landfill
Cyclic: Recyclable or compostable • Returnable • Reusable (alternative purpose) • Recyclable (technically recyclable and system exists for collection and reprocessing) • Biodegradable	**Safe** • Reduces airborne emissions • Reduces waterborne emissions • Reduces greenhouse gas emissions • Reduces toxicity • Reduces litter impacts

Source: Authors' Compilation adapted from James et al., 2005 and Sustainable Packaging Alliance, 2010

C. Protective packaging

Protective packaging is the additional layer of packaging to protect and buffer a product from potential damage or destruction during shipping or warehousing (Dube, 2021). Protective packaging may form the main component of a product's packaging or may be present as a secondary form of packaging, depending upon the product type and the packaging purpose. A variety of materials are considered to design protective packaging, including bagging, flexible films, shrink packaging, shipping protection, air pillow carded packaging - blister packs, clamshells, skin packs, shipping protection (air pillows), bubble wrap, etc. (Caleb, 2013).

As the issue of sustainability has gained prominence in the packaging industry, vendors in the market are investing significantly in research and development to develop environment-friendly and sustainable packaging solutions (Berg, 2020). Growing concern about the impact of plastics on the environment has led to the development of eco-friendly, flexible protective packaging, such as biodegradable bubble wrap for the packaging. This is a significant trend observed in the bubble wrap packaging market (Future Market Insights, 2019). Packaging industry has become adaptive to the use of eco-friendly packaging material; less expensive alternatives to bubble wrap, such as recycled paper and foam packaging are gaining acceptance in the marketplace. However, most of these developments are not yet suitable for commercial use or are still in the prototype stage.

D. Bubble wrap

Bubble wrap is one of the most widely used protective packaging due to its efficiency in offering unprecedented protection both as shock absorber and as abrasion resistant. Bubble wrap is also very flexible and lightweight. With the changing face of retail and consumption, bubble wrap has found massive use as a packaging material, especially in e-commerce (Spolarich and Gray, 2020). It meets all the conditions required for excellent packaging to function, i.e., lightweight, offers flexibility (can be wrapped around items, regardless of their size and to some extent their shape), requires less material. It consumes less space, has a cushioning effect, and provides sufficient protection against pressure marks, is impact resistant, moderately transparent, suitable as a sealing medium, a good water vapor barrier, a poor gas barrier, easy to mold or extrude, and has a waxy surface (Safe Packaging, 2021). Bubble wraps are manufactured using polyethylene (PE) and polyethylene terephthalate (PET). Low-density polyethylene (LDPE) keeps it lightweight. It has a density of 0.017 $g/cm^{3.}$ Lighter packaging is easier to distribute and handle which reduces the likelihood of impact damage from dropping and reduces transportation costs (Forte, 2005). As the name implies, bubble wrap consists of soft and compressible air bubbles ranging from ¼" to 1" in diameter (King, 2017), a GSM range of 40-140, and a height of 4mm (Safe packaging, 2021), which absorb impact and reduce the impact on the product in the event of a sudden force (Kelley, 2020; Kelly et. al, 2016). The change in GSM value is due to the thickness of the bubble wrap, while the size of the bubble wrap remains the same (Hazzard, 2015). When more protection is needed, bubble wrap with large air bubbles is used to reduce the number of wraps around the product (Safe Packaging, 2021). Although bubble wrap is not used directly to contain liquids, it is waterproof (Verghese et al., 2012) and protects the product from spills, dirt, dust, and moisture (Safe Packaging, 2021). Bubble wrap typically comes in sheets, bags, and rolls (Rogers, 2017) with a perforated tear line at a specific spacing (12") (Safe Packaging, 2021) for ease of manual handling. The commonly used standard bubble wrap is transparent and allows light to pass through (Verghese et al., 2012). However, it is also available in different colors, and these colors represent specific types of bubble wrap. For example, green bubble wraps are biodegradable and recyclable, while pink bubble wraps are antistatic and prevent the buildup of static electricity (Safe Packaging, 2021); other categories include cohesive, adhesive, and flame-resistant bubble wraps. For electronics packaging, some bubble wraps provide cushioning for transport and protect metal and electronic parts from corrosion during storage (King, 2017).

Despite its immense usability, bubble wrap has some negative aspects. Plastic bubble wrap causes significant environmental damage and has adverse health aspects, including non-biodegradability, end-life disposal, and fire hazards (Rogers, 2017). Amazon alone generated 465 million pounds of plastic packaging waste in 2019, including air pillows, bubble wrap, and other plastic packaging, of which 22.44 million pounds of waste entered and polluted global freshwater and marine ecosystems (Spolarich and Gray, 2020). The carbon footprint of plastic (LDPE or PET) is about 6 kg of CO_2 per kg of plastic (Verghese et al., 2012). Non-renewable thermoplastics derived from fossil raw materials have some significant environmental impacts, such as depletion due to the use of non-renewable resources as raw materials, emission of harmful gases during the refining and cracking process, and some by-products or emissions are carcinogenic, e.g., vinyl chloride monomer and styrene monomer (Verghese et al., 2012). Bubble wraps tend to catch fire more easily than other forms of flexible protective packaging, mainly because of the plastic and air mixture. (Future Market Insights, 2019).

E. Post-consumer textiles: An emerging issue

With growing population and increased purchasing power, consumers are not only consuming but also generating more waste than ever before. The linear approach to textile manufacturing and the increasing shift to fast fashion have resulted in more textiles being produced and consumed. At the same time, the low reuse and recycling of these textiles have also led to higher waste generation. This has, directly and indirectly, led to increased consumption of land, water, and fossil fuels, as well as increased air, water, and soil pollution. Nearly 5 percent of all landfills are taken up by textile waste (Aishwariya and Jaisri, 2020).

Post-consumer textiles have increasingly become a global problem over the past decade, especially synthetic textiles, due to their non-biodegradability, toxicity and ever-increasing production volumes (Dissanayake, 2018). The lack of appropriate waste management facilities and technologies poses environmental and social challenges to textile waste management. Multi-material systems further increase the complexity of textile recycling (Stone et al., 2019). 45 percent of post-consumer textile waste can be worn as second-hand clothing, 30 percent can be cut up and used as industrial rags, 20 percent can be biodegraded after landfilling, and 5 percent is incinerated (Ryder and Morley, 2012). The increasing waste generation is necessitating a higher level of recycling accompanied by designing and engineering initiatives for conscious products (Enis et al., 2019). While markets for the sale of used clothing are thriving, markets for low-quality garments unsuitable for resale are generally mature or declining. Combined with competition from better virgin fiber substitutes, this results in very low prices for low-quality garment grades, typically below the cost of collecting and sorting the clothing - sometimes well below (Ryder and Morley, 2012). Available markets include wipers for the engineering and printing industries, flocking for mattresses, fibers for shoddy manufacturing, and nonwovens for automotive soundproofing (Fashion for Good, Sattva Consulting, Reverse Resources and Saahas Zero Waste, 2022). Hence, environmental and commercial interests are working together to find new markets for these recycled grades.

4. Analysis and findings

This part presents the analysis and findings for the two objectives of the research. It is organized into 3 sections.

A. This section presents the evaluation of bubble wrap against sustainable packaging principles. The characteristics of bubble wrap were mapped to the four principles of sustainable packaging (ref. Figure 1) on the basis of author's interpretation of available publications. The mapping is presented in Table1. The characteristics of bubble wrap that emerged on the basis of mapping are summarized below-

- Effective:

The material was found to be effective while serving as a generic packaging material suitable for a wide variety of products and uses. A good compressive strength, a thickness of 4 mm, air cushioning, a minimum distance between bubbles and a 12" tear line make it an effective packaging material. It benefits society by properly confining and safeguarding items as they move through the supply chain.

- Efficient:

Bubble wrap is an efficient protective packaging material as it is affordable ($0.025-0.0375/ m^2). It has a GSM between 40 and 200, occupies less space, and has low material consumption.

- Cyclic:

Bubble wrap, as a packaging material, falls short of this parameter of cyclability as it is non-recyclable and non-biodegradable. It reduces finite resources and does not support reuse.

- Safe:

Bubble wrap is toxic and releases carcinogenic emissions. Thus it does not satisfy the safety criteria.

To summarize, bubble wrap is found to be effective and efficient, but it is not cyclic and safe because of the associated environmental risks. The characteristics of bubble wrap mapped on sustainable packaging principles are shown in Table 1. The major elements constituting each principle are depicted and are rated on a scale of 0-5 (0 depicting lack of information available for the particular element, 1 depicting extremely insignificant similitude between the element and bubble wrap characteristics, while 5 depicting extreme similitude). On the basis of extensive scanning of literature sources, the most relevant cell from 0 to 5 was highlighted. The elements rated as 0, signify gaps in research.

Table 1. Characteristics of bubble wrap vs. sustainable packaging principles

Effective: Adds economic and social value						
• Reduces product waste	0	1	2	3	4	**5**
• Improves functionality	0	1	2	3	4	**5**
• Prevents over-packaging	0	1	2	3	4	**5**
• Reduces business costs	0	1	2	3	4	**5**
• Achieves satisfactory Return on Investment	**0**	1	2	3	4	5
Efficient: Minimum use of material and energy						
• Improves product / packaging ratio	0	1	2	3	4	**5**
• Improves efficiency of logistics	0	1	2	3	4	**5**
• Improves energy efficiency (embodied energy)						

- Improves materials efficiency (total amount of material used)
- Improves water efficiency (embodied water)
- Increases recycled content
- Reduces waste to landfill

0	1	2	3	4	5
0	1	2	3	4	5
0	1	2	3	**4**	5
0	1	2	3	4	5
0	**1**	2	3	4	5
0	**1**	2	3	4	5

Cyclic: Recyclable or compostable

- Returnable
- Reusable (alternative purpose)
- Recyclable (technically recyclable and system exists for collection and reprocessing)
- Biodegradable

0	1	2	3	4	5
0	**1**	2	3	4	5
0	1	2	3	**4**	5
0	**1**	2	3	4	5
0	**1**	2	3	4	5

Safe

- Reduces airborne emissions
- Reduces waterborne emissions
- Reduces greenhouse gas emissions
- Reduces toxicity
- Reduces litter impacts

0	1	2	3	4	5
0	**1**	2	3	4	5
0	1	2	3	4	5
0	**1**	2	3	4	5
0	**1**	2	3	4	5
0	**1**	2	3	4	5

Source: Authors' compilation

B. The second section identified alternative packaging materials that can be protective as well as sustainable. An extensive web search was undertaken. The aim was to select material that could satisfy the two-fold purpose of being sustainable and having bubble wrap-like characteristics. In all, 14 alternatives were identified. Table 2 presents the description of these alternative packaging materials in details of raw material used, structure, uses, functioning, post-disposal handling, advantages and disadvantages.

Table 2. Alternative sustainable and protective packaging materials

Packaging Material	Image	Features
Tessle wrap or paper bubble wrap (Packaging connection, 2006)		• Kraft paper, Interleaf tissue, recycled paper used as raw material • Die cut honeycomb structure • Recyclable and biodegradable • Usually utilized in Sharp objects, electronics packaging • Slit formed angled cells provide interlocked packaging without the use of tapes • Aesthetical, used in small quantities,

		commercially used, known as eco-friendly paper bubble wrap • Limited width of paper, costlier than bubble wrap, may leave scratches on product without tissue
Protega paper cushions (Protega global, 2021)		• Recycled paper is used as raw material • Air filled crushed paper bag with unique folds structure • Biodegradable, compostable, recyclable, decompose in ocean • Usually utilized in case of fragile glass items, cosmetics • Crushed structure of paper acts as shock absorber prevents breakages and locks the product inside the box • Retains structure for long distances, eco-friendly version to plastic air bag, restricts movement of product within packaging • Lacks strength, excess material is required
3D folded kraft paper (Forte, 2019)		• Kraft paper is used as raw material • Folded chevron structure • Recyclable and biodegradable • Ideal usage is for shaped products like wine bottles etc. • The chevron structure allows absorption of shock from all directions • Multidirectional shock absorption, molded in different shapes, aesthetically pleasing, strength • Expensive
Bubble Wool (Woola, 2019)		• Waste wool is used as raw material • Similar to Bubble wrap • Biodegradable and recyclable • Currently utilized as wool envelops and bottle sleeve • Indented structure provide protection to the products • Durable and can be reused multiple times. Company setting up a Returns System to keep the precious material in the loop. Light-weight, protective, reusable • Limited raw material

Cellulose wadding Wrap (Thieblesson et al., 2017)		• Recycled newspapers , cuts of newspaper from the printing industry used as raw material • Multilayers of soft-papers • Biodegradable and recyclable • Furniture wrapping, moving domestic goods • Cellulose fibers act as an absorbent for any leakages from fluid products besides providing cushioning • Can be used for oily and greasy product, shapeable • Shed dusty particles, expensive, limited uses, use of excess material
Eco-friendly air pillows (Protega Global, 2020)		• FSC-compliant papers, Bio polymer inner sealing is used as raw material • Packets filled with air structure • Compostable, decay when exposed • Utilized for fragile and sensitive products • Non-abrasive, so don't affect product with scratches • Expensive, use of excess material
Green bubble wrap (Caleb et al., 2013)		• d2w® compound used as raw material • Similar to Bubble wrap • Decompose under heat, sunlight and water • Decompose under heat, sunlight and water • Generic packaging • Beneficial to soil and plants • Might not degrade if conditions are not fulfilled
Cell-O air cushions **(Transpack, 2021)**		• Patent compound and cellophane is used as raw material • Perforated cushions filled with air structure • Disintegrate in presence of microorganisms (1-5 years) • Usually used in packaging of small items and delicate items • Protects sensitive goods in transit from vibration by blocking the products in carton • Eco-friendly • Uncertain degradation, use of excess material

Shredded crinkle Paper (Shredders India, 2021)		• Any waste paper • Shredded paper with crimped style folds like an accordion • Biodegradable and eco-friendly if paper doesn’t contain toxins • Generic packaging • Prevents the products from shifting in the box • Cheaper, protect the product by restricting its movement • Excess material use, lack of reuses, messy appearance
Saran wrap and cotton ball packet prototype (Kelley, 2020)		• Recycled cotton, bee’s wrap is used as raw material • Wrapped and sewn cotton balls structure • Biodegradable • Generic packaging • Friction between packets will ensure that the product does not shift to one side of the box while minimizing overall material • Eco-friendly alternative • Expensive, use of excess material, unsuitable for sharp objects
Plastic rings (hollow sphere prototype) (Kelley, 2020)		• Cut plastic bottles are used as raw material • Rings of plastic in a hollow sphere shape ; Can be reshaped • Non-biodegradable • Suitable for non-delicate items • The force would compress the spheres a little on one side of the package and expand on the other to compensate for the shock • Low cost, uses less material to manufacture • Large quantity of packaging material, no reuse, may cause abrasion
Packing peanuts (Kelley, 2020)		• Styrofoam is used as raw material • Popcorn like structure • Non-biodegradable • Generic packaging • Shaped to interlock when compressed and free flow when not compressed • Aesthetically pleasing, inexpensive • Limited uses, excess use of material, no reuse, uneasy to use

Packaging foam (Flexipack, 2020) (Epsole, 2020)		• Thermocol is used as raw material. • Can be in different shapes : mostly elongated bars of foam • Non-biodegradable • Custom packaging • Provides stiff protection by restricting product's movement • Completely secure the product, cheaper • Dense and large in size
Plastic air cushions (AirPackagingMachine, 2022)		• High Density Poly-ethylene (HDPE) is the raw material • Square/Rectangle pillow like structure • Non-biodegradable • Generic packaging • Air filled packets provides compression to sensitive goods in transit from vibration by blocking the products in carton • Satisfy the packaging demand, cost effective, light in weight, saves space • Easy to tear

Source: Authors' compilation

Further, the identified alternative protective packaging materials were compared with bubble wrap on parameters of sustainable packaging principles. Table 3 presents the comparison. A tick mark (✔) shows the presence of the particular property in the respective packaging material alternative.

Table 3. Comparison of alternate packaging materials and bubble wrap on parameters of sustainable packaging principles

Packaging	Biodegradable	Minimum material usage	Form: Sheet	Re-uses	Generic packaging	Recyclable	Made from waste
Bubble Wrap		✓	✓		✓		
Tessel wrap	✓		✓			✓	✓
Protega paper	✓	✓				✓	✓
3D folded paper	✓					✓	
Bubble Wool	✓	✓	✓	✓		✓	✓
Cellulose wadding wrap	✓	✓				✓	✓
Eco-friendly air pillow	✓	✓					
Green bubble wrap	✓		✓		✓		✓

Cell O air cushions	✓	✓					✓
Shredded wrinkle paper	✓	✓			✓		✓
Saran cotton wrap	✓	✓			✓		✓
Plastic rings		✓			✓		
Packaging peanuts		✓			✓		
Plastic foam		✓	✓				
Plastic air cushions					✓		

Source: Authors' compilation

Out of fourteen inner packaging materials studied, only bubble wool qualified for reuse. Of the total materials, six were made of paper, four were made of non-recyclable plastic, and the others were made using patent materials. Materials with smaller separate units, such as packaging peanuts, air-cushions, shreds, etc., take up more space and result in excessive material consumption, whereas sheet-like materials, such as tessel wrap and green bubble wrap, use material while providing the same level of protection. There were only three generic packaging materials that were biodegradable. Saran wrap was in the prototype stage. Green bubble wrap was not entirely practical, while the shredded, wrinkled paper was not very appealing due to poor aesthetics. Other than bubble wool and green bubble wrap, there were no other general internal packaging materials that were either biodegradable or reusable and had minimal material consumption.

To summarize, most alternative materials could meet at most four parameters out of the seven parameters. Bubble wool, a textile-based alternative, met the maximum number of six criteria, thus emphasizing the possibility and potential of textile material in producing protective packaging. After bubble wool, green bubble wrap met the most parameters, i.e., five.

C. In the third section, examination of the post-consumer textiles as an alternate material was done by mapping suitable textile techniques that facilitate the production of protective textile-based packaging material. Some of the textile fabrics resemble in structure, shape, cushioning, and form to bubble wrap, one of the most generic packaging. One way to manufacture sustainable packaging materials could be when they are produced from discarded or waste materials that ultimately contribute a significant portion to the landfills around the globe. Upscaling of post-consumer textile waste can be done using certain techniques that render cushioning features. The identified textile techniques, appropriate for this purpose and their description are provided in Table 4 below.

Table 4. Potential textile manufacturing techniques providing cushioning

Air bubble stitch	Air bubble stitch is also known as bubble stitch or hand knitting. The structure resembles bubble wrap, and is made using the knitting technique, purl, and skip stitches (McDonnell, 2017). The hollow 3D design can flatten when stretched. Unlike bubble wrap, the knit structure would open when cut and pulled, but the sizes can be customized because it is handmade. The bubbles are made using the knit stitches between the skip stitches; the more rows of knit stitches in between, the larger the bubble will be (McDonnell, 2017). Compact and stiff bubbles increase the weight of the fabric, and also the cushioning. When made of acrylic and absorbent cotton, the structure is more voluminous.
Puff Stitch	The puff stitch has thread pockets as 5-11 yarn passes are used to make a puff. These yarns trap air and look puffy (Johanson, 2020; Shelagh, 1983). When these pockets are crocheted close together, the result is a stable wrap knit structure that does not deform much under stress. This bulky stitch yields a cushion-like surface with same look on both sides (Johanson, 2020). This product is handmade, and the sizes can be customized.
Sujani Weave	Sujani is a hand weave from the 1860s (Tailor, 2018), and has chequered geometric patterns with small pockets woven on the loom and filled with cotton, making it puffy. The raw material is mainly cotton (Trivedi, 1967). A throw shuttle loom (8 shafts and two sets of 8 paddles) is used as the primary tool. After wrapping and sizing the yarns, weaving is done on the loom with the warp threads arranged in blocks in two layers: front and back. The cotton is stuffed into square pockets (Sharma et al., 2015) and interlocked on the loom. Since it is a type of quilt, it will be more voluminous, and reducing the weight per unit area would require changing the filling material and composition of yarns for warp and weft.
Popcorn Knits	This hand-knitting technique is the opposite of bubble knit in production, as it also involves knitting the stitches in reverse order and skipping them. It is more like popcorn scattered over the surface. Knitting this structure is time-consuming; however, efficient with semi-automatic knitting machines (Guagliumi, 2018). With increased number of popcorn on the surface, the fabric becomes even more voluminous and expensive. These knits are available on the market with a GSM range of 120 to 200 and are generally made of wool and Lycra. In hand knitting, resizing is possible.
Waffle quilt	The waffle quilt is a hand-woven quilt. The surface has honeycomb-raised structures evenly distributed over the entire surface but not high or thick enough to provide any cushioning. It is usually made from long-staple Turkish cotton, but cheaper versions are made from polyester and elastane with a GSM range of 300 to 400 (Purushothama, 2016). The fabric is very absorbent and dries quickly.

Bubble quilt	In quilting, the sewing machine sews the cotton fibers between the thin panels of fabric in a circular motion, creating raised structures on the surface. The bubbles that form on the surface are more significant, resulting in an uneven surface. Smaller and more densely arranged bubbles increase the weight and manufacturing time of the fabric. Thickness and distance between the two bubbles determines the cushioning effect. The product made by this process has a GSM of 200 to 350 when the wool yarn is used.
3D embossed microfiber	3D embossed microfiber is a fabric with a design higher than the material's surface, like embossed bubbles on the fabric. It is made with an embossing machine. The 100 percent polyester microfiber woven fabric is fed to the roller of an embossing machine, which forms the fabric by heat. It is a lightweight material with a GSM value of 65 to 135 (Purushothama, 2016; Changxing Dingqiang textiles, n.d.). The fabric is commonly produced for home textiles. When the pattern with raised dots is used for rollers, the fabric can look like bubble wrap with one side raised and the other pressed in.
Seesucker honeycomb knit	This is a Chinese warp knitted fabric of GSM 220 when spandex yarn is used (made-in-china, n.d.). It has a small honeycomb-like surface that is not significantly raised and thus provides mild cushioning.
Bubble Microfiber hobby lobby fleece	This smooth fabric has a design of raised dots on one side and is smooth on the other. The raised dots are not hollow but a compressed bag of fibers with good thickness and pillow-like texture. It is a knitted microfiber fleece fabric that is heat pressed to obtain such a raised structure. It has a GSM of 100 to 350 when made from recycled polyester and polyester yarns.
Bubble Fabric	This is a patent fabric from Ocean Textiles in China. It has a raised surface and is made of polyester and chiffon with a GSM of 200-290 (Ocean, 2017). The hollow raised structure appears to be perforated unevenly across the fabric and provides mild cushioning.
Velvet bubble fabric	The fabric is made in China with an automatic quilting machine. The raised bubbles are sewn as hollow structures resulting in a stretchiness of the fabric. This voluminous velvet fabric has a GSM range of 200 to 340. The velvet fabric is transformed into hollow structure using a fabric manipulation technique, only possible for materials with greater fluidity (Joann, 2021).
Manipulated Bubble Fabric	Fabric manipulation is one of the methods to transform 2D fabrics into a 3D structure. This technique is similar to embossing and is a manual process in which a lightweight material is either hand-tied or shaped and then heated to give the structure a permanent form. The raised structure is hollow, weak, and has an uneven thickness. Through various techniques of fabric manipulation, the GSM of the fabric can be changed from 100 to 450. The hollow space can be filled with cotton, thermocol balls, foam, or a biodegradable cushioning material - algae foam from Algae bloom

	(MaterialDistrict, 2018).
3D shell woven fabric	The 3D shell fabric is made with a weaving technique that uses a roller to create a raised structure during weaving and is removed when the bump is closed; leaving a hollow raised 3D structure of the fabric without cutting and sewing. GSM of material increases with the number of shells. The fabric is bulky with a GSM greater than 250 (Chen et al., 2011).
Wool Paper (Non-woven)	Non-woven structure can be made using both post and pre-consumer textile waste (Asare and Yeboah, 2013).

5. Conclusion and Future Research Directions

Packaging is a menace but at the same time, an indispensable element in commercial activities. With the rise of e-commerce, the use and quick disposal of packaging material proliferated to great extents. As it is quintessential to safeguard products in transit and storage during supply chain activities and deliver them to the customer without tampering and damage, the use of reliable and protective packaging is being emphasized more than ever before. This is leading to quick and massive disposal of packaging material, increasing the landfills woes. Bubble wrap is being used extensively for a wide range of products and purposes, as a protective packaging material. Although bubble wrap is an effective and efficient packaging material, it is not recyclable and safe. With the aggravating plastic disposal issue, the design and use of sustainable packaging alternatives are of paramount urgency. A very conscious and apt move could be the incorporation of waste material in making new packaging that is more environmentally friendly; thus a two-way solution of waste reduction and producing less-impactful packaging material. Post-consumer textiles are available aplenty across the globe and some innovative textile techniques can upscale and transform them into a more useful and sustainable, protective packaging material alternative.

The research findings provide some very practical and relevant future directions. As a future research direction, criterions and specifications for developing bubble wrap like structure, deploying appropriate textile manufacturing techniques could be identified, keeping in view the sustainable packaging principles. Further, the exact nature of raw material (different textile composition) that would increase the sustainability quotient of textile-based protective packaging could be studied. This could lead to an investigation of how different segregation methods can be designed for post-consumer textiles in order to sort the types most suitable for protective packaging development. Since Bubble wool, a textile-based product, was found to qualify the maximum number of comparison parameters, there is massive scope of research in upscaling of textile waste into packaging material. Future research can also be conducted in the direction of addressing the gaps identified in the mapping process of bubble wrap characteristics against the sustainable packaging principles. Bubble wrap is a widely used packaging material; it is critical to research in the direction of making it less environmentally impactful. A dearth of research was found in context of evaluating bubble wrap on aspects of sustainability principles or innovative approaches towards making the use of bubble wrap more sustainable. The current research identified specific gaps amongst the sub-parameters of the sustainable packaging principles indicating scope a research in some extremely significant areas such as finding the effectiveness of bubble wrap of return on investment (economic sustainability), evaluating / improving energy and water efficiency in manufacture, use or disposal of bubble wrap (environmental sustainability), and making bubble wrap more safe by reducing waterborne emissions (environmental and social sustainability). Use of packaging material is inescapable, however introducing consciousness and sensitiveness in this process can be a crucial step towards sustainability.

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