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Review

Plant-Origin Feedstock Applications in Fully Green Food Packaging: The Potential for Tree-Free Paper and Plant-Origin Bio-Plastics in the Baltic Sea Region

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Abstract: Paper and plastic are the main materials used in food packaging. In the context of climate change, the importance of tree conservation and the mitigation of the negative environmental impacts caused by fossil consumption and deforestation is greater than ever before. This article reviews the potential of plant-origin feedstock from the Baltic Sea region for use in non-wood-fibre and bio-origin plastic food packaging production. It also presents a systematised literature review of the environmental impacts and applications of tree-free paper, plant-origin plastics, and natural-fibre-reinforced bio-composites in fully green food packaging. The results reveal that beneficial environmental impacts are achieved if waste or by-products are used as feedstock. While the production volumes of alternative materials in Europe are small (0.25% of paper is made of materials other than wood, and the share of bio-plastic is 0.9%), we found a large demand and potential for growth. The biggest volumes of natural fibre feedstock in Baltic Sea region countries are generated from wheat. Wheat straw, which is a by-product, has a production volume of 68.71 million tons and is potentially a significant non-wood-paper food packaging source. Agricultural waste generated from sugar beet, maize, potato, and wheat is an environmentally beneficial by-product that could be used for bio-plastic food packaging production.

Keywords: fully green food packaging; natural fibre food packaging; natural fibre applications; food packaging; sustainable packaging

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1. Introduction

Paper is the most used material in the packaging sector. Paper and board are made of pulp, for which the worldwide production capacity in 2019 was 183.0 million tons [1]. Wood is a primary raw material used for pulp and paper production. Since 2009, paper packaging production has risen annually, and in 2020, global production volumes of packaging paper and board amounted to 249 million tons [2]. The preliminary data on paper and board production in CEPI-member European countries in 2021 show that almost all paper- and board-grade production has increased, amounting to a total production of 90.2 million tons [3]. This growth has been driven by the growth of the EU economy and higher fast-moving good consumption rates. The paper packaging market in 2021 had returned to pre-pandemic levels and was expected to grow, with a forecast compounded annual growth rate (CAGR) of 4.6% over the period from 2021 to 2028 [4].

Plastic is the second most used material in the packaging sector. Globally, plastic production (not including the production of recycled plastics) reached 367 million tons in 2020. The production volume in Europe was 55 million tons [5]. Packaging, including commercial and industrial packaging, is the main plastic application sector, accounting for 40.5% of its use, amounting to 148.64 million tons. End-use plastic consumption worldwide amounts to 36% [6]. The demand in key plastic application industries (such as the food and beverage, personal care, and pharmaceutical industries) is expected to more than double plastic production in 2050, to reach 800 million tons [7].

Rising paper and plastic packaging production volumes lead to higher quantities of packaging waste. Since 2009, packaging waste in the European Union has grown annually. In 2019, the EU-27 generated 177.4 kg of packaging waste per capita [8]. In this waste stream, paper and cardboard were the main waste material, with 32.2 million tons, followed by plastic with 15.4 million tons of packaging waste [8]. Resource depletion, rising waste volumes, visual plastic pollution, and negative environmental impacts render packaging waste reduction a top priority. Special attention is being paid to the food and beverage packaging sector, where plastic waste leakage is significant. Most marine and terrestrial plastic pollutants come from food packaging, such as plastic bags, straws, cups, and food containers [9]. A total of 40% of packaging is single or very short usage food packaging which ends up in incinerators or landfills or leaks to the environment. In order to decrease the negative environmental impacts, both legislative regulations and efficient environmentally friendly food packaging made of renewable resources integrated into a circular economy are suggested. The EU's directive on single-use plastics [10] bans single-use plastic packaging such as cutlery, expanded polystyrene food containers, beverage containers and beverage cups, and plates from July 2021; however, in order to achieve long-term results, a ban of several of the most polluting kinds of packaging is not enough. Only long-term circular economy strategies and end-consumer habit changes can lead to significant changes. The Ellen MacArthur Foundation defines the circular economy as a "systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution". Food packaging in this system framework has direct (waste, pollution) and indirect (climate change, biodiversity) impacts on all aspects mentioned in this definition. The circular economy approach and the zero waste resources management hierarchy [11] highlight the importance of more efficient integration of the biological cycle with mechanical recycling streams and the need to expand mainstream food packaging to add an extra function—to capture and divert food waste from landfills. This function is dedicated to fully green compostable packaging made of renewable materials that ensures a cleaner recycling stream and supports the biological cycles of the circular economy [12].

Climate change, global warming, and resource depletion raise the importance of evaluating not only waste management but also the environmental impacts of each food packaging lifecycle stage (materials, production, transportation, usage, end of life). Many studies on the environmental impact of tree-free paper and bio-based plastics have been performed. Some studies on raw materials have indicated that the environmental factors of non-wood fibres, especially non-dedicated ones, have advantages. While dedicated crops are more energy intensive [13], agro-waste fibres already exist and can become an additional source of paper fibres instead of being wasted, with no additional land required for their production. Other researchers have highlighted energy consumption differences in the pulp production stage—the production of 1 tonne of kenaf pulp is 37% energy less intensive than softwood pulp bleached using the ECF bleaching method, but purchased energy is 50% higher. This is because wood-based mills generate more by-products that are used for energy. Chemical consumption is also important, as alternative fibres that contain a lower level of lignin require not only lower energy but also lower chemical consumption during the delignification process and milder chemicals for bleaching [13].

Many studies on the potential of bio-plastics to substitute for fossil-based plastics and comparative environmental efficiency analyses between bio-plastics and petrochemical plastics have been performed, as well as sustainability assessments of bio-plastics [14–18]. The production stage of bio-plastics has been identified as the major contributor to environmental burdens. The use of renewable energy has been suggested as a future improvement [18]. Alternative feedstocks for bio-plastic production, such as agricultural waste and by-products, as well as less energy- and chemical-intensive crops, have been identified as improved feedstocks for bio-plastic production [19]. It is important to note that there are studies that indicate only a slight improvement in the negative environmental impacts of waste product usage as a bio-plastic feedstock [20,21]. However, fossil-fuel-based resources have higher environmental impacts because they are derived from non-renewables, and bio-origin plastics can contribute to lowering greenhouse gas emissions, fossil fuel consumption, and microplastic pollution [22].

Land use, as well as seasonal aspects, especially in Baltic Sea region countries that experience four seasons, are also important factors in both paper and bio-plastic alternative material considerations [13,23]. Trees and fossil fuels are available year round, unlike dedicated fibre crops (hemp, kenaf, jute), agricultural residues (cereal, rice straw), or other plant feedstocks such as potatoes, corn, and wheat, which are harvested seasonally. Stable and regular feedstock supplies, availability and capacity, transport, and storage of raw materials result in environmental impacts and need to be identified and evaluated in each case.

The analysed literature has revealed that, in general, bio-origin materials, especially agricultural waste and by-product applications in food packaging, are environmentally favourable solutions that can benefit the biological cycle of the circular economy. Therefore, this paper aimed to discuss natural fibre feedstock that is locally available in the Baltic Sea region and its application in fully green food packaging production, focusing on three aspects: tree-free paper as a replacement for wood paper packaging, plant-origin bio-plastics as a substitute for fossil plastic food packaging, and natural-fibre-reinforced bio-composite applications in food packaging. Bio-plastics in this paper are defined as bio-origin materials made of natural fibres (plant origin), which may be biodegradable or may not be. Fully green packaging is defined as packaging made of only bio-origin materials that, at the end of life, is mechanically and/or biologically recyclable.

The main research focus was to investigate current natural fibre feedstock applications in food packaging and highlight their potential in fully green food packaging production in the Baltic Sea region.

The results of this study could be useful for packaging companies and other players in the food value chain (private companies, experts, innovators) that are considering replacing traditional wood paper and fossil packaging with fully green packaging. This study could also be useful for researchers, as it highlights several further research directions.

2. Research Method

A brief review of the raw material selection and packaging waste management stages of the packaging life cycle, as well as the role of food packaging in the overall packaging sector and its role in the circular economy, was carried out by collecting and analysing policy-based strategic documents, such as EU directives and practice-based literature (Eurostat data, Statista data, Zero Waste Europe, Ellen MacArthur Foundation data reports, and strategic documents).

As wood fibre paper and conventional plastic were identified as mainstream materials in packaging production and the packaging waste stream, further research was dedicated to wood fibre paper and conventional plastic material alternatives—tree-free paper and plant-origin bio-plastic market analysis and applications. This stage of the review defined the main alternative materials that could be used for fully green packaging production. Locally (in the Baltic Sea region), harvested materials were identified. At the next stage, non-wood fibre and plant-origin bio-plastic applications in food packaging were analysed.

Lastly, alternative materials (non-wood fibre paper and plant-based plastics) and feedstock availability in Baltic Sea region countries (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, and Sweden) were identified.

The academic database desk research and scientific literature review on alternative material applications covers a ten-year time span, starting from 2012. Strategic documents, statistical data, and data reports cover from 2019 to 2022. An explicative flowchart of the presented literature review process is provided in Figure 1.

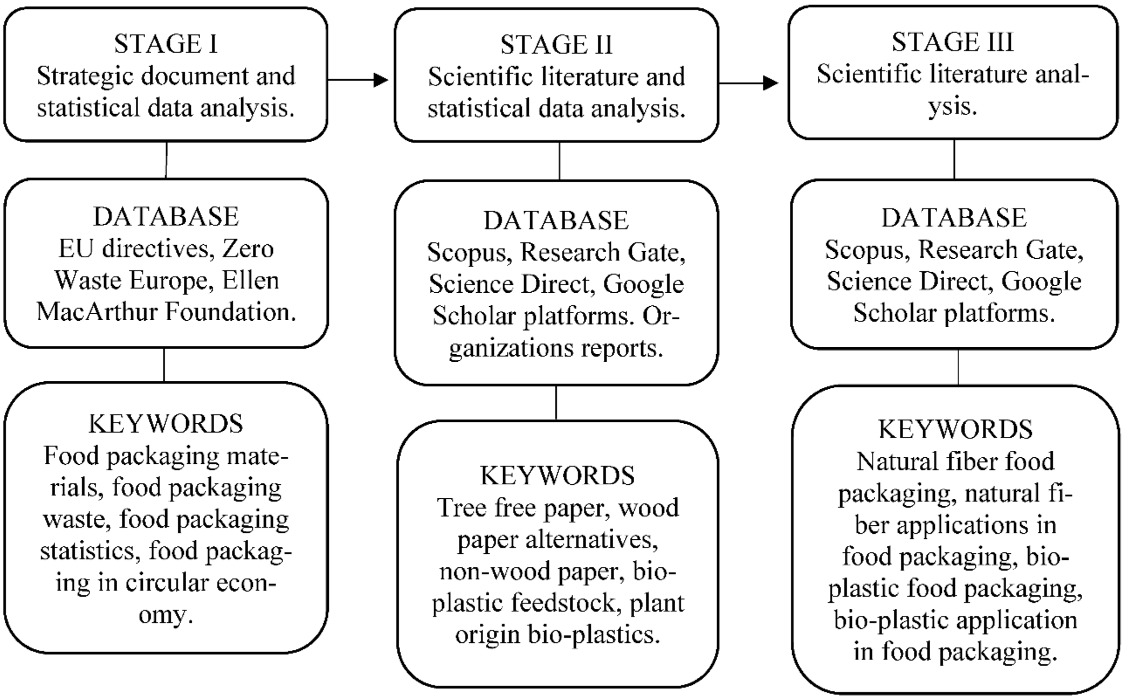

Figure 1. Methodological framework flowchart.

3. Results and Discussion

3.1. Alternative Bio-Origin Feedstock

3.1.1. Tree-Free Paper

Paper and board can be made of only wood pulp, 100% non-wood pulp, or a blend of different fibres. Pulp can be made of virgin fibres (primary pulp) or produced by repulping paper for recycling (secondary pulp). Out of a total of 36.190 million tonnes of pulp produced in Europe (EU-27 countries plus Norway, Switzerland, and the United Kingdom), only 0.25% is produced from fibres other than wood, such as sugar cane bagasse, wheat straw, kenaf, cotton rags, and hemp [1]. Although the non-wood fibre market is small, demand for plant fibre paper production is growing. Many environmentalists, researchers, and technologists are working on non-wood fibre paper and trying to find feasible and appropriate forest fibre alternatives. It is interesting to note that 150 years ago, 90% of pulp was produced from non-wood fibres, such as cotton and flax rags and cereal straw [24].

Fibre chemical composition varies depending on the plant source and manufacturing technology [25]. The end-use paper grade and properties depend on the treatment method, fibre source, fibre composition, and fibre properties [26]. The International Association of Wood Anatomists provides fibre classification depending on the fibre length: medium-length (0.91–1.60 mm), moderately long (1.61–2.20 mm), and very long (2.21–3.00 mm) [27]. The most common fibre length for paper production is 1–2 mm, with a diameter of approximately 25 µm [26]. The length of cereal straw fibre is 1.5 mm with a 23 µm width, corn straw is 1.5 mm with an 18 µm width, wheat straw is 1.4 mm with a 15 µm width, rice straw is 1.5 mm with an 8 µm width, coniferous wood fibres are 4.1 mm with a 25 µm width, and deciduous wood is 1.2 mm with a 30 µm width [13]. Bamboo fibre lengths vary between 2 mm and 4 mm based on species and are quite similar to some wood species, with a fibre width ranging from 14.22 µm to 19.97 µm [28].

Cellulose fibres are the main constituent of paper pulp. The other two major chemical components of woody materials are hemicellulose and lignin. Chemical composition (%) of wood and non-wood materials is provided in Table 1. Cellulose, hemicellulose, and lignin content indicate plant suitability for papermaking and affect the pulping and paper manufacturing conditions. Plants with high cellulose and low lignin content are the most suitable for paper production. Different treatment methods have different effects on the fibre chemical composition. For example, NaOH treatment can increase the cellulose content in agricultural waste, such as hemp and wheat bran [29,30].

Table 1. Chemical composition (%) of wood and non-wood materials.

Material	Cellulose	Hemicellulose	Lignin	Reference
Wood	50	20–25	30–35	[31]
Hard wood	40–44	15–35	18–25	[32]
Soft wood	40–44	20–32	25–35	[32]
Willow	50	19	25	[32]
Thermo-mechanical pulp (TMP)	56	22.15	25.6	[25]
Chemical thermo-mechanical pulp (CTMP)	52	24.51	16.33	[25]
Bleached softwood kraft pulp (BSKP)	87	16.07	1	[25]
Unbleached softwood kraft pulp (UBSKP)	87	16.94	2.6	[25]
Hemp fibre (USO 31)	78.4–81.7	5.7–6.4	10–13	[33]
Hemp fibre (Fedora 17)	65.6–84.9	6–8.1	2.7–4.5	[33]
Hemp fibre (Felina 34)	64–83	11–15	1–4	[33]
Hemp fibre (Fibrimon 56)	53.2	6.9	5	[33]
Hemp hurds (untreated)	44.5	32.78	21.03	[30]
Hemp hurds (treated NaOH)	53.87	12.06	27.27	[30]
Hemp hurds (treated EDTA)	45.7	31.05	24.22	[30]
Hemp hurds (treated $Ca(OH)_2$)	45.75	28.88	23.98	[30]
Flax	62.21–74.01	13.91–22.30	2.56–7.96	[34]
Wheat straw	28–39	23–24	16–25	[35]
Wheat bran (untreated)	8.56–11.1	27.3–33	3–4.1	[29]
Wheat bran (treated NaOH)	29.6	24.9	-	[29]
Wheat bran (treated H_2SO_4)	35	6.83	-	[29]
Rice straw *	30–45	20–25	15–20	[36]
Bamboo *	73.8	12.5	10.1	[37]
Sugarcane bagasse *	32–34	19–24	25–32	[38]

* Imported feedstock that is not locally available in the Baltic Sea region.

In many cases, alternative plant fibres can complement forest fibres. Blending non-wood fibres into wood pulp (10–15%) can improve paper properties without any disruption to the papermaking process [24]. Hemp and flax harvested in the Baltic Sea region have a high cellulose content and are great wood fibre alternatives. Paper products made of 100% non-wood fibres, such as moulded food containers, are a growing wood alternative fibre market segment.

3.1.2. Plant-Origin Plastics

The bio-based polymer market is still in an early development stage. A German Nova-Institute report [39] indicated that the bio-based polymer market share in 2021 was less than 1% of global plastic production, which is 2.41 million tonnes. The bio-plastic market is expected to triple by 2026, reaching approximately 7.59 million tonnes [40]. The European bio-plastic market share in 2019 was 25%, amounting to 0.53 million tonnes of the global bio-plastic market. The global plastic market in 2019 was 368 million tonnes, with 57.9 million tonnes of production based in Europe [40]. In the European market, the bio-plastics share, compared with conventional plastics, was 0.9%.

Only natural origin (biodegradable and non-biodegradable) plastics are covered in this article. Bio-based plastics defined by Spierling et al. as "man-made or man-processed organic macromolecules derived from biological resources and for plastic and fibre applications (without paper and board)" are often excluded from the category of plastics.

Bio-based plastics that have a unique chemical structure are called novel plastics. Drop-in plastics, such as bio-PET, bio-PE, and bio-PP, have an identical chemical structure to fossil-origin PET, PE, and PP [41] and can be integrated into existing plastic production and recycling streams. The bio-plastics share, by material type of total production, is provided in Figure 2.

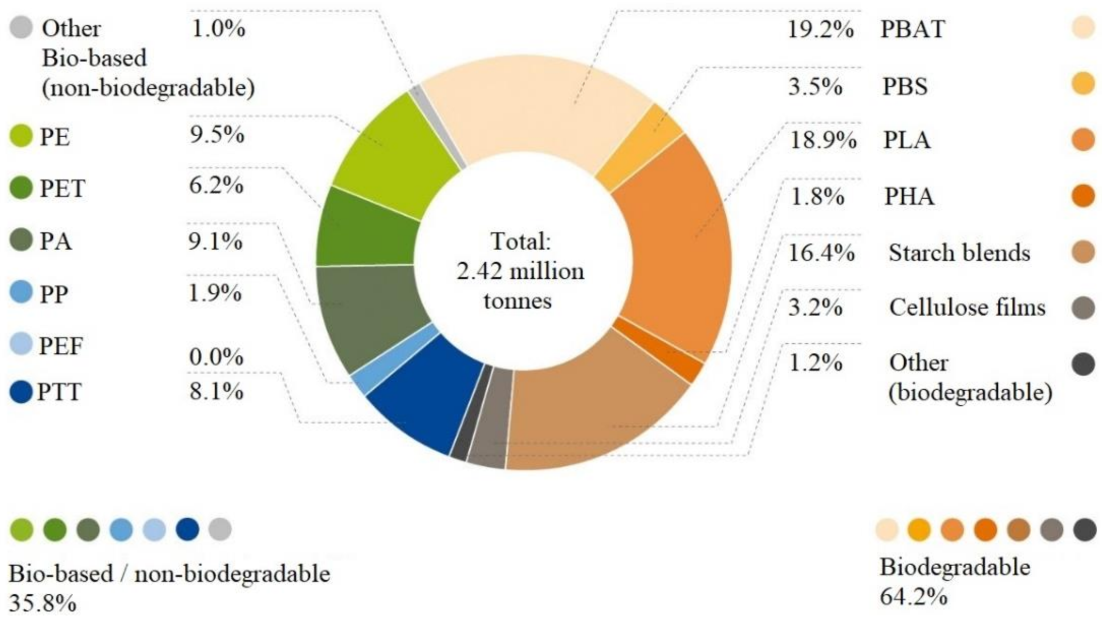

Figure 2. Global production capacity of bio-plastics in 2021 by material type (European Bioplastics, 2021).

The major bio-based polymer production feedstock is biogenic by-products (46%), especially the by-product glycerol from biodiesel production. Other than glycerol, materials come from residues and bio-waste, forestry, agriculture, and other sources. Significant plant feedstocks for bio-based material production by polymer type are [41]:

- Sugarcane *. PLA, PHAs, bio-PBS(A), bio-PET, bio-PE, PEF, bio-PP, bio-PAs, PTT;
- Sugar beet. PLA, PHAs, bio-PBS(A), bio-PET, bio-PE, PEF, bio-PP, bio-PAs, PTT;
- Corn. PLA, PHAs, starch blends, bio-PBS(A), bio-PE, PEF, bio-PP, bio-PAs, PTT;
- Potato. PLA, PHAs, starch blends, bio-PBS(A), bio-PE, PEF, bio-PP, bio-PAs, PTT;
- Wheat. PLA, PHAs starch blends, bio-PBS(A), bio-PE, PEF, bio-PP, bio-PAs, PTT.

* Imported feedstock that is not locally available in the Baltic Sea region.

Siracusa and Blanco [42] provided the development stages of bio-based polymers. Some, such as PEF (PEF is an aromatic polyester made of ethylene glycol and is a chemical analogue of polyethylene terephthalate (PET)), bio-PP, and bio-PA (6 and 6.6), are in the R&D stage. Others, such as PLA, plastic from starch, bio-PA (11), partial bio-PTT, and partial bio-PA (11), are at the large stage development stage. Plastics from cellulose and alkyd resins have already been commercialised.

Development stage, potential, economic, and environmental aspects should be considered overall. Bio-origin plastics are more expensive because of lower production volumes and required investments in new production technologies.

3.1.3. Natural-Fibre-Reinforced Bio-Composites

Composite materials are made of at least two distinctly different materials—the matrix and filler. This combination provides an engineering performance that exceeds that of any individual component [43]. Bio-composites are natural-fibre-reinforced biopolymers [44]. The above-reviewed natural plant fibres are potential fillers for natural-fibre-reinforced bio-composites. Non-wood natural fibres, provided in Table 1, can not only be used as wood fibre alternative in paper production but also as low-cost fillers in bio-composite materials and are gaining popularity. All fibres—short, medium, and long—can be used in thermoplastic polymers, and up to 80% of the composite mass can constitute cellulosic material [45]; however, the optimal matrix:filler ratio varies depending on the required properties [46]. Natural fibre composites can be fully green composites or partly green composites. Fully green composites are made of a renewable matrix (in food packaging, this is a polymer matrix) and natural fibre fillers. A partly green composite matrix has a petrochemical origin [47].

Bio-composites are renewable, and they are also lightweight, cheaper, have good sound insulation and thermal properties, are less energy intensive to make, and are biodegradable [48]. These features make bio-composite materials an attractive alternative to fossil materials, and they are already being applied in many sectors, including building and construction, transportation, and packaging. As shown in Figure 2, PLA has the biggest (18.9%) market share of bio-based plastics (PBAT is a fossil-based bio-plastic). Natural fibres available in the Baltic Sea region, such as hemp, and other plant fibres that are more common in tropical and subtropical regions, such as rice straw, abaca, ramie, kenaf, jute, bamboo, and rice husks, are used to improve PLA's mechanical properties [46]. For instance, hermoplastic starch reinforced with sisal and hemp fibres has demonstrated both tensile and flexural strength improvement [49].

3.2. Fully Green Food Packaging

3.2.1. Paper Applications in the Food Sector

There are more than 3000 types of paper and board that can be classified into four main categories [39]:

- Graphical paper, which is mainly used for newsprint and also covers a variety of writing, copy, printing, map, envelope, etc., papers;
- Specialty paper made for special purposes, such as filter paper, spinning paper, and condenser paper, and papers with tailored characteristics such as anti-rust, anti-tarnish, etc.;
- Tissue paper or hygienic paper used for bathroom and facial tissue, kitchen towels, serviettes, diaper production;
- Packaging paper and board, which covers a wide range of paper sorts, such as craft liner and folding boxboard, which are used for secondary and tertiary packaging, and a variety of papers that are used for direct food contact, such as greaseproof (meat and butter packaging), vegetable parchment, which is waterproof and, if covered with silicon, can be used as backing paper, and grease-resistant but not waterproof glassine, which is used as wrapping paper.

Packaging paper is one of the most advanced paper products and can be shaped and moulded depending on product shape and size, as well as be modified for sensitive foods or liquids packaging. However, uncoated paper applications in the food and beverage sector are limited because of the low oxygen and vapour barrier properties, low mechanical strength, and high material hydrophilicity. Uncoated paper is not sealable [50]. Therefore, it is usually used for only dry food and groceries that are not oxygen and vapour sensitive.

In order to increase oil, grease, and water resistance, food packaging [51] paper is coated with a variety of polymer barrier coatings, such as polyolefins, waxes, ethylene vinyl alcohol (EVOH), and polyvinylidene chloride (PVDC) [52]. Even though synthetic and fossil-based coatings provide the required barrier properties, they limit the mechanical recycling possibilities and, in the case of fossil-based microplastic pollution, eliminate biological recycling possibilities. Paper coated with bio-origin coatings such as chitosan nanocomposite [53], gelatine-based [54] and starch-based films, or coatings made of corn, cassava, banana starch, or potato are commercially viable, demonstrate good mechanical properties [55], and could be used in fully green compostable food packaging.

3.2.2. Bio-Plastic Applications in the Food Sector

Depending on the polymer, bio-based polymers can be used widely in the automotive and transport sector, building and construction sector, and textile sector. The packaging sector applications share in 2019 was 24%, with 13% flexible packaging (mainly starch-containing polymer compounds, bio-PE) and 11% rigid packaging, including service-ware (mainly bio-PET, PLA) [39]. Global production capacities of bio-plastics in 2021 by market segment are provided in Figure 3.

Plastics usage in the food and beverage packaging sector brings undoubtable benefits because of plastic's low cost, versatility, ease of design and manufacture, high oxygen and vapour barrier properties, and durability [56,57]. Today, it is almost possible to produce bio-based packaging with nearly the same or even the same properties and performance as conventional plastic materials. Production does not require any specific processing technologies, and the packaging can be processed with existing machinery [5]. PLA is the most famous biopolymer implemented in food packaging applications. Its physical and mechanical properties have been widely analysed [58,59], and the most efficient applications in food packaging have been revealed; this polymer has been successfully applied in rigid (trays, cups) food packaging and in flexible (clear food films) food packaging production. PHA is suitable for large food containers, while starch blends are used for pouch outer packaging, films, and bag production [60].

Drop-in plastics (bio-PET and bio-PE) are mainly used for rigid packaging production. These materials are fit for sparkling and non-sparkling liquids. Bio-PET is also used for flexible packaging but in smaller production volumes. Bio-PE applications for flexible packaging are approximately twice as common as rigid packaging, but the leading position among renewable feedstock used for flexible packaging belongs to starch blends [5].

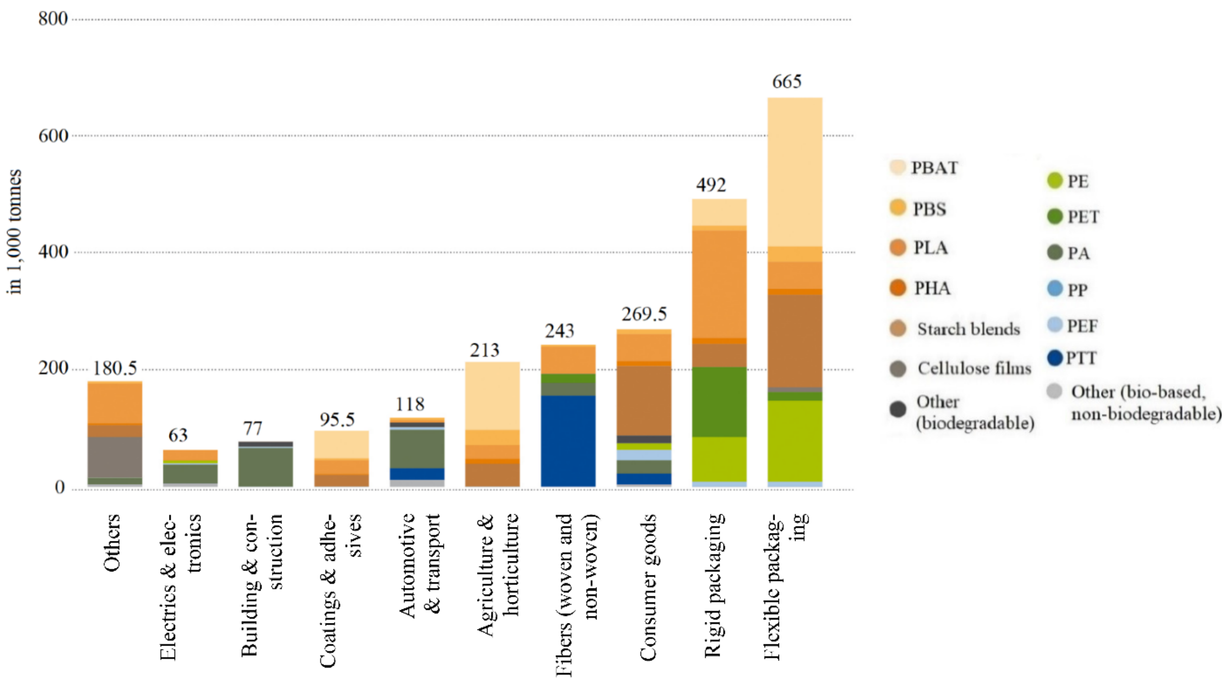

Figure 3. Global production capacities of bio-plastics in 2021 by market segment [61].

Bio-plastic films are used for carrier bags and are suitable for confectionary wrapping, as well as wrapping for fresh food. Bio-plastic films and trays give fresh food, such as fruits, vegetables, and meat, a longer shelf life. Bio-origin novel plastics (these plastics have a chemical structure unlike other plastics, e.g., PLA, starch blends) are used in food service packaging (cups, caps, plates, food containers, cutlery) as more sustainable organically recyclable alternatives to single-use products that cannot be mechanically recycled or when mechanical recycling is not feasible.

3.2.3. Natural-Fibre-Reinforced Bio-Composite Applications in Food Packaging

Many researchers have indicated that bio-origin composites reinforced with natural fibres are cheaper, lighter, more environmentally friendly, and have better thermal and mechanical properties. Although natural fibres can acquire the applicable mechanical properties, hydrophilicity is an issue. Sensitivity to moisture and water absorption limit green composite applications for food packaging [45,62]. In most food packaging, moisture absorption is not treated as an advantage of green composites in food packaging production and is not yet widespread.

The improvement of fully green bio-composites is an ongoing process. Research data show that customised composite material requirements for food packaging can be achieved by selecting the proper natural fillers (fibres), bio-based polymer matrix, and additives, such as green coupling agent (GCA) obtained from virgin coconut oil [63], as well as using appropriate manufacturing technology [62]. However, further enhancement of the performance properties is still needed. One feasible food packaging example is moulded PLA matrix and sugarcane bagasse and bamboo fibre filler green composite with the food-safe additive AKD, which demonstrates good mechanical properties and increased hydrophobicity. Moreover, this moulded pulp tableware is biodegradable and has lower CO_2 emissions than PS plastic products [64]. Another research project conducted by Fieschi and Pretato (2018) [16] confirmed that the use of biodegradable and compostable tableware with organic recycling at the end of product life is a preferable option for fast food and takeaway foods. The results of this study show a significant reduction in carbon, water, and the resource footprint.

3.3. The Potential for Tree-Free Paper and Plant-Origin Bio-Plastics in the Baltic Sea Region

The global agricultural land area in 2019 was 4.8 billion hectares (ha). Europe, with 19% of the available agricultural land, is the third biggest area [65]. The total land in Baltic Sea region countries used to harvest potential wood fibre alternatives and plant-origin plastic feedstock in 2020 was 7.3 million hectares. The detailed split of each country per feedstock item is provided in Tables 2 and 3.

Table 2. Wood fibre alternative feedstock in Baltic Sea region countries, 2020.

Baltic Sea Region Country	Wood Fibre Alternative Feedstock					
	Flax Fibre and Tow		Hemp Tow Waste		Wheat Straw *	
	Yield (ha)	Production (t)	Yield (ha)	Production (t)	Yield (ha)	Production (t)
Denmark	-	-	-	-	80,987	5,495,054
Estonia	-	-	-	-	50,019	1,134,702
Finland	-	-	-	-	34,538	926,937
Germany	-	-	-	-	78,195	29,932,335
Latvia	20,000	200	-	-	53,384	3,590,460
Lithuania	-	-	10,756	2420	53,931	6,505,313
Poland	30,385	790	60,295	14,290	52,388	16,784,834
Sweden	-	-	-	-	71,561	4,339,305
TOTAL:	50,385	990	71,051	16,710	475,003	68,708,939

Source: FAOSTAT [66]. Crops and livestock products data. * Calculated by authors. The average yield of wheat straw depending on climate and agronomic factors is 1.3–1.4 kg of straw per kg of wheat grain [67].

Table 3. Plant-origin plastic feedstock in Baltic Sea region countries, 2020.

Baltic Sea Region Country	Plant-Origin Plastic Feedstock							
	Maize/Corn		Potato		Sugar Beet		Wheat	
	Yield (ha)	Production (t)	Yield (ha)	Production (t)	Yield (ha)	Production (t)	Yield (ha)	Production (t)
Denmark	62,484	38,740	439,952	2,762,900	770,663	2,558,600	80,987	4,070,410
Estonia	-	-	261,509	88,390	-	-	50,019	840,520
Finland	-	-	301,643	624,400	383,182	421,500	34,538	686,620
Germany	95,874	4,020,000	428,340	11,715,100	741,402	28,618,100	78,195	22,172,100
Latvia	-	-	213,059	181,100	-	-	53,384	2,659,600
Lithuania	70,144	141,690	157,255	296,740	677,970	948,480	53,931	4,818,750
Poland	70,763	6,694,650	347,683	7,848,600	576,266	14,171,540	52,388	12,433,210
Sweden	67,568	12,500	364,437	877,200	681,378	2,027,100	71,561	3214,300
TOTAL:	366,833	10,907,580	2,513,878	24,394,430	3,830,861	48,745,320	475,003	50,895,510

Source: FAOSTAT. Crops and livestock products data.

A total of 68.726 million tonnes of total flax fibre and tow, hemp tow, and wheat straw was produced in Baltic Sea region countries in 2020. Flax production volumes are 990 tons per year. The main flax applications are textiles (the oldest known textile application), oilseed, and paper/pulp [68]. Hemp feedstock production was 16,710 tons in 2020. Hemp is used in food and beverages, cosmetics, building and construction, textiles, bio-fuel, and the paper industry [69]. The biggest volumes of non-wood fibre material are generated from wheat production. Wheat straw, which is the by-product obtained after harvesting of wheat grains, accounts for 99.97% of all non-wood fibre alternative stock, reaching 68.708 million tonnes of production volume. Wheat straw utilisation by producing cellulosic pulp is an economically justified solution [70]. Agro-industrial waste, such as wheat and other grain straws and sugarcane, as well as bagasse, are the cheapest raw materials [71]. Besides economic feasibility, wheat straw as a by-product is attractive because of high production volumes; these agricultural waste fibres already exist and can become additional sources for paper fibres instead of being wasted, with no additional land required for their production.

Wheat and potatoes are agricultural products that are produced in all of the analysed Baltic Sea region countries. Wheat is produced in the highest production volumes, amounting to almost 51 million tonnes, followed by sugar beet with more than 47 million tonnes, requiring 3.8 million hectares of land. In comparison, the wheat yield, with similar production volumes, requires almost ten times less land use.

When it comes to polymer production from food crops and other agricultural products, food/feed and polymer production competition, as well as land conversion to biomass production from forest and grassland, should be considered. Currently, land used for bio-plastic biomass growth is less than 0.02% of the total available land, covering around 0.82 million hectares, and it is expected that no big changes will occur in the next five years [72].

In order to avoid negative impacts such as habitat destruction or significantly increased land usage for biomass in the future, alternatives, such as biomass production from waste or use of degraded cropland, should be prioritised. Firstly, plastics made of fermentable sugars and sugar beet are preferable to cereal crops [22]. Secondly, by-products or agricultural wastes should be used, as in this case, there is no competition with food and/or feed production (maize, potato, sugar beet, wheat). Moreover, bio-plastics made of agricultural waste have environmental advantages, as when the by-products are used for other purposes, part of the environmental impact is allocated to those purposes [22].

- Definitions used in Tables 2 and 3: Flax fibre and tow, item code (FAO)—773. Broken, scutched, hackled, etc., but not spun. Traditionally, FAO has used this commodity to identify production in its raw state [66].
- Hemp tow waste, item code (FAO)—777. Cannabis sativa. This plant is cultivated for seed, as well as for fibre. The fibre is obtained from the stem of the plant. Trade data include raw, retted, scutched, combed fibre, tow, and waste [66].
- Maize, item code (FAO)—56. Zea mays corn, Indian corn, mealies. A grain with a high germ content. At the national level, hybrid and ordinary maize should be reported separately, owing to widely different yields and uses. Used largely for animal feed and commercial starch production [66].
- Potatoes, item code (FAO)—116. Solanum tuberosum Irish potato. A seasonal crop grown in temperate zones all over the world, but primarily in the northern hemisphere [66].
- Sugar beet, item code (FAO)—157. Beta vulgaris var. altissima. In some producing countries, marginal quantities are consumed, either directly as food or in the preparation of jams [66].
- Wheat, item code (FAO)—15. *Triticum* spp.: common (*T. aestivum*), durum (*T. durum*), spelt (*T. spelta*). Common and durum wheat are the main types. Among common wheat, the main varieties are spring and winter, hard and soft, and red and white. At the national level, different varieties should be reported separately, reflecting their different uses. Used mainly for human food [66].

- Wheat straw—a by-product obtained after harvesting of wheat grains (Kapoor et al., 2016) [73].

4. Conclusions

4.1. Environmental Footprint and Circular Bio-Economy

Most of the research conducted on plant-origin feedstock applications in food packaging (and other sectors) highlights the importance of this feedstock being renewable and having a lower environmental footprint, especially if waste or by-products are used. At the same time, researchers have noted the importance of LCA, as not only the raw-material stage but also the end-of-life stage play significant roles in the food packaging life cycle. Plant-origin plastic drop-ins can be (and already are) integrated into existing plastic production and recycling streams. Non-recyclable plant-origin packaging (for example, food packaging contaminated with food leftovers and/or grease and oils), if designed to be compostable, brings co-benefits in the circular economy by playing a significant part in cleaning waste streams and supporting biological cycles.

4.2. Natural Fibre and Plant-Origin Feedstock Potential

The current European market situation indicates a very small scale of these alternative materials—out of total 36.190 million tonnes of pulp production in Europe, only 0.25% was produced from fibres other than wood, and the bio-based polymer market share in 2021 was less than 1% of global plastic production. Both the tree-free paper and bio-plastic markets are expected to grow, meaning higher demand for fully green packaging in the food sector. There is a range of natural fibre feedstocks available in the Baltic Sea region for tree-free paper (hemp, flax, wheat) and plant-origin plastic (wheat, sugar beet, corn, potato) production, and the concrete stock availability and commercial viability should be further systemised.

4.3. Tree-Free Paper Applications in Fully Green Food Packaging

Paper (wood and non-wood fibre) applications in fully green packaging are still limited (can only be used for dry food and groceries that are not oxygen and vapour sensitive and do not require a long shelf life) because of the barrier properties requirements. Plant-based barrier coatings remain an ongoing field of research. Promising examples include chitosan nanocomposite coatings, gelatine-based edible coatings, and starch-based coatings. Natural barrier coatings are an important research topic, as fully green compostable packaging can significantly support the biological circular economy cycle and reduce visual and microplastic pollution. Further research into each natural coating's effect on paper recyclability must be conducted in order to design fully green paper packaging that meets circular economy requirements. Packaging designed as recyclable would be directed to mechanical recycling streams and, accordingly, packaging designed as compostable directed to biological recycling.

4.4. Plant-Origin Bio-Plastics Applications in Fully Green Food Packaging

Today, it is almost possible to produce bio-based packaging with nearly the same or even the same properties and performance as conventional plastic materials. At a small scale of production, bio-plastic applications in food packaging have been successfully implemented in all food packaging types—flexible (pouches, films, bags, labels) and rigid (bottles, trays, cups, caps, cutlery). PLA is applied to clear food films, trays, and cups; PHA is suitable for large food containers; starch blends are used for pouches, films, and bag production; and bio-PE and bio-PET drop-ins are analogues for fossil-based PE and PET and have the barrier properties required for the packaging and beverages product group. Bio-origin novel plastics (these plastics have a chemical structure unlike other plastics, e.g., PLA, starch blends) are used in food service packaging (cups, plates, food containers, cutlery) as more sustainable, organically recyclable alternatives for single-use products that cannot be mechanically recycled, or when mechanical recycling is not feasible.

4.5. Natural-Fibre-Reinforced Bio-Composite Applications in Fully Green Food Packaging

Bio-origin composites reinforced with natural fibres are cheaper, lighter, more environmentally friendly, and have better thermal and mechanical properties. Although natural fibres can acquire the applicable mechanical properties, hydrophilicity is still an issue. This explains why natural-fibre-reinforced bio-composite application in food packaging is still limited—it is mainly used in single-use tableware production. The improvement of fully green bio-composites is an ongoing process.

4.6. The Potential of Tree-Free Paper and Plant-Origin Bio-Plastics in the Baltic Sea Region

The biggest volumes of natural fibre feedstock in Baltic Sea region countries are generated from wheat. Wheat production's share of agricultural products that can be used as plant-origin plastic feedstock is 37.72%, or almost 51 million tonnes. Wheat straw, which is the by-product obtained after harvesting wheat grains, accounts for 99.97% of all non-wood fibre alternative stock, reaching 68.71 million tonnes of production volume. Considering food crops and other agricultural products as sources of non-wood fibres and bio-origin plastics with food and/or feed competition, wheat straw as a by-product seems to have the greatest potential. As a by-product, it does not require any additional land, and in comparison with other agricultural products, its production volumes are high and its land usage is small. Bio-plastics made of fermentable sugars and sugar beet are preferable to cereal crops, and if by-products or agricultural wastes are used, no competition with food and/or feed occurs and environmental advantages are achieved.

5. Future Research

The presented article notes the small scale of production and growing potential of the application of tree-free paper, bio-plastics, and natural-fibre-reinforced bio-composites in fully green food packaging production. It also notes the wheat straw and agricultural waste application potential. Further analysis and the need for a holistic approach that covers all fully green packaging life cycle stages is needed. The choice of alternative materials plays a major role in the product and packaging life cycle; therefore, clear alternative material application classification based on food packaging type and end-of-life scenarios is needed. Natural fibre agricultural waste availability that could be used in fully green packaging production in the Baltic Sea region should also be further evaluated.

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