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Valorizing Food Waste into Functional Bio-Composite Façade Cladding: A Circular Approach to Sustainable Construction Materials

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Abstract

Façades account for approximately 15–20% of a building's embodied carbon, making them a key target for material decarbonization. While bio-composites are increasingly explored for façade insulation, cladding systems remain dominated by carbon-intensive materials such as aluminum and fiber-reinforced polymers (FRPs). This paper presents findings from a study investigating the use of food-waste-derived bulk fillers in bio-composite materials for façade cladding applications. Several food-waste streams, including hazelnut and pistachio shells, date seeds, avocado and mango pits, tea leaves, and brewing waste, were processed into fine powders (<0.125 µm) and combined with a furan-based biobased thermoset resin to produce flat composite sheets. The samples were evaluated through mechanical testing (flexural strength, stiffness, and impact resistance), water absorption, freeze–thaw durability, and optical microscopy to assess microstructural characteristics before and after testing. The results reveal substantial performance differences between waste streams. In particular, hazelnut and pistachio shell fillers produced bio-composites suitable for façade cladding, achieving flexural strengths of 62.6 MPa and 53.6 MPa and impact strengths of 3.42 kJ/m^2 and 1.39 kJ/m^2, respectively. These findings demonstrate the potential of food-waste-based bio-composites as low-carbon façade cladding materials and highlight future opportunities for optimization of processing, supply chains, and material design.

Keywords: bio-composite materials; façade cladding; food-waste valorization; low-carbon materials; thermosets

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1. Introduction

The need to reduce the consumption of natural resources, fossil fuels, and carbon emissions in construction and retrofitting has been widely acknowledged [1]. The European Climate Law established a target of achieving net carbon neutrality by 2050 with a reduction goal of at least 55% by 2030 [2]. The building sector was identified as key area for climate mitigation [3], with the use of low-carbon bio-based construction materials becoming essential for reducing the environmental impact of buildings [4,5]. However, using bio-based construction materials for the renovation of building stocks may require significant land use for biomass growth [6,7]. Land competition can lead to rising food prices [8] and increased demand for arable land, which often replaces forests or jungles with farmland [9]. Crop-based resources may also contribute to water resource depletion, biodiversity loss, and reduced ecosystem quality [10].

On the other hand, around 500 million tons of waste are generated globally every year in the agri-food sector [11]. The 2024 United Nations (UN) Food Waste Index Report defines food as "any substance-whether processed, semi-processed or raw- that is intended for human consumption," and food waste as "food and the associated inedible parts removed from the human food supply chain" [12]. Food waste can occur at different stages of the supply chain, including primary production, processing and manufacturing, retail, distribution, and consumption, both "in- and out-of-home" [13]. According to the UN report, an estimated 1.05 billion tons of food were discarded globally in 2022 across retail, food service, and household settings [12]. This corresponds to about 132 kg of wasted food per person each year, with households alone responsible for 79 kg per capita. In financial terms, this means that more than US $1 trillion worth of edible food is thrown away annually [12].

Managing food waste can significantly harm the environment. When biodegradable materials are sent to landfills, they break down and generate gases, mainly methane, which is far more powerful than carbon dioxide in driving long-term global warming, possessing roughly 34 times its warming effect over a century [14]. There are at least four waste management pathways: minimization, conservation, segregation, and utilization [15]. The latter embodies a more circular, zero-waste approach as it not only reduces waste in the food sector but may also reduce waste in the mining sector by replacing raw material resources with food waste [16]. Integrating food-waste into new low-carbon bio-based construction materials would therefore significantly reduce waste and its environmental footprint while offering plausible low-carbon alternatives to conventional carbon-intensive, extractive materials. This is further supported by European Union (EU) regulations such as the 2011 *Roadmap for moving towards a competitive low carbon economy in 2050* and the 2012 plan for *Innovating for sustainable growth—a bioeconomy for Europe*.

The use of agro-industrial waste in producing construction materials is becoming increasingly widespread, driven not only by practical needs but also by engineering innovations that enable these wastes to be transformed into useful, high-value products [17]. Several studies indicate that products made of agri-food waste can deliver equal or superior performance compared to conventional materials [18]. But are these products well suited for demanding building applications like façades?

This study focuses specifically on the use of food-waste-derived bio-composites for façade cladding. Façades account for at least 15–20% of a building's embodied carbon [19], meaning that shifting to sustainable, biobased materials could significantly reduce their carbon footprint. In Europe alone, more than 50 materials suitable for façade applications have been catalogued [20]. While research on biobased materials often focuses on insulation—such as flax, hemp, or sheep's' wool due to their low density and thermal conductivity [21,22]—façade cladding remains dominated by materials like ceramics, aluminium, and FRPs. Cladding systems must meet multiple performance criteria, including load bearing capacity, fire and water resistance, and aesthetics [22,23].

Nevertheless, an emergent body of research on bio-composite materials opens new possibilities for façade cladding [23,24]. Using either plant fibers or organic fillers combined with partially or fully biobased polymers, these materials can offer properties comparable to conventional façade cladding materials but with a significantly smaller material and energy footprint [25–27]. The choice of resin is crucial, as it influences both fabrication methods and end-of-life scenarios. Natural fibers and particulate fillers derived from agricultural and food-processing waste, such as walnut, pistachio, and chestnut shells, have demonstrated improvements in stiffness, impact behavior, and environmental performance when properly integrated into polymer matrices [26,28–30]. In addition, bio-composites have been explored for non-structural architectural applications, including interior façades and partitions, where benefits such as improved indoor air quality and reduced material toxicity are emphasized [24]. Several of these new bio-composites rely solely on bulk filler and resin, limiting or eliminating the use of fibers [28–30]. Despite these advances, challenges remain related to filler–matrix compatibility, moisture sensitivity, durability, and large-scale standardization, which continue to shape current research directions [27].

This research is driven by the need to develop bio-composite materials that are both technically robust and systemically feasible for construction applications. It focuses on fiber-free bio-composite formulations based exclusively on granular bulk fillers, reducing material complexity, simplifying processing workflows, and enabling lower-cost, lower-carbon composite solutions. Food-waste-derived granular fillers are prioritized as value-generating resources that simultaneously address material performance and waste reduction. Building on a research line initiated in 2024 that demonstrated the mechanical feasibility, improved workability, and reduced embodied carbon of granular food-waste-based fillers [31–33], this study extends beyond material optimization toward system integration. By combining the mapping of food-waste flows in The Netherlands with the technical evaluation of selected waste streams for bio-composite façade cladding applications, the research links laboratory-scale performance with considerations of resource availability, consistency, scalability, and integration into existing waste and construction systems, thereby contributing to the advancement of bio-composites within a circular-economy framework.

2. Materials and Methods

2.1. Setting the Scene: Identifying Food Waste Streams in The Netherlands

The Netherlands is a country has a large import–export economy and is the second-largest exporter in the European Union [34], facilitated by the Port of Rotterdam, Europe's largest seaport [35]. Many imported goods are processed and redistributed across Europe [35], while the country is also responsible for a substantial share of agricultural production in the European Union [36]. As a result, large streams of food waste are available throughout the country [37].

In 2017, nearly half of all industrial waste in The Netherlands (14.7 billion kg) consisted of animal and vegetal waste from the food, beverage, and tobacco industry, of which 99% was recycled [38]. The types of food-waste streams resulting from *food production* vary greatly from province to province. Noord Brabant has the largest total utilized agricultural area, while Groningen produces larger quantities of potatoes, grains, and sugar beets. Livestock is most prevalent in Gelderland (largest number of cattle), and Noord Brabant (largest number of housed animals) [39]. Further along the food industry chain, waste occurs due to *food processing*, distribution and retail, totaling 55,500 tons of material per year in The Netherlands. This waste is primarily used as cattle feed, with a smaller proportion used to produce biogas [40]. Additional waste is generated during *food consumption*, both in food service and in Dutch households. The highest concentration of Dutch food service establishments is in North Holland and South Holland [41]. Household waste amounts to 493 kg per person per year [38], of which 33 kg is food waste -approximately 9% of all purchased food [42]. In total, household consumption generates 55,400 tons of waste per year [43]. Most of these streams are collected as organic waste and processed into compost and biogas [44].

The 2021 European Environmental Agency report highlights The Netherlands' efforts to prioritize food waste reduction [45,46]. Nevertheless, resources classified legally as waste cannot be used for consumption nor freely imported or exported [47], complicating their potential use in other applications [40]. Current processes therefore focus on the lower levels of the Moerman's Ladder [48]. Logistics and storage challenges add further complications: transportation alone can account for up to 16% of total emissions in construction [49], and seasonal materials require large storage facilities that become underutilized over time. For effective stockpiling, materials must undergo immediate processing to ensure shelf stability, such as decomposition prevention, cleaning, sorting, and drying [40].

During the early months of the project, 24 companies and organizations were identified and contacted. These were selected based on the availability of food waste generated resources relevant to the project scope, their location (preference was given to companies located in South Holland), their scale of operations, and the consistency of their food waste streams. Where possible, price and seasonal variability were also considered. Animal-based food waste was excluded due to additional legal requirements and building regulations.

Most companies represented the fruit and vegetable sector, known for generating significant volumes of waste such as peels, rinds, seeds, cores, stones, pods, vines, skins, and pomaces [50]. Waste management companies were also included (20 companies currently process organic waste in The Netherlands [51]). Ultimately, limited feedback from companies prompted the team to expand the mapping effort to include circular hubs (e.g., Blue City), regional governance entities (e.g., the Province of South Holland), and findings from earlier TU Delft research focused on North Holland [40].

2.2. Selecting the Resources for Plausible Filler Material

This search yielded a total of seven food-waste streams as potential filler material varying in kind (pits, shells, spent grains) and in origin (food processing waste, household waste). The selected materials were mango teguments and kernels, avocado pits, hazelnut and pistachio shells, beer brewing waste (BBW), tea leaves and date seeds.

2.2.1. Mango Teguments & Kernels

Mango (*Mangifera indica* L.) is the most prevalent tropical fruit in the world, with a production of 41 million tons in 2020 [52]. Mango processing generates 35–60% (w/w) agro-industrial waste, while its inappropriate disposal can cause environmental contamination [53]. Mango teguments and kernels are discarded as waste from processing industries. Even though mango trees are not grown in The Netherlands, mangos are largely imported and consumed either as fruit or as a primary resource for juices and they can also be retrieved in household waste.

2.2.2. Avocado Pits

Avocado (*Persea americana* Mill.) crop is cultivated globally, and its industrial processing generates seeds accounting for 13% to 17% of fruit mass [54]. In 2020, Dutch avocado imports grew by 19% with The Netherlands responsible for 63% of all EU imports of non-EU avocados, 9% of which remain in the domestic market [55]. Recent research indicates that 5–6% of these avocados are wasted due to oversupply (wholesalers importing more avocados than they could manage efficiently), inadequate storage capacity, and poor temperature control, impacting avocado quality and shelf life [56].

2.2.3. Hazelnut Shells

Although hazelnuts are native to The Netherlands, domestic production has always been limited [57], with most hazelnuts imported from Turkey and re-exported to other European countries [58]. Hazelnut shells account for 50% of fruit weight and possess lignocellulosic composition, high calorific power, homogeneous particle size, and low ash content. These characteristics support their use as biomass for biofuel, though they are also composted or processed into snacks [59]. Powdered hazelnut shells have previously been used as reinforcement in agro-cement composites [60], motivating their selection here for this research.

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2.2.4. Pistachio Shells

Pistachio (*Pistacia vera* L.) is the only pistachio species producing edible nuts of commercial size [61]. Just like with hazelnuts, The Netherlands serves as a major trade hub for pistachios in Europe, re-exporting around 80% of imported quantities [62]. Previous research demonstrates that pistachio shells show excellent mechanical properties when processed into filler material, making them a promising alternative to traditional reinforcement materials [29,63].

2.2.5. Beer-Brewing Waste

The Netherlands is a major beer exporter, with nearly 800 breweries nationwide, including 110 in South Holland [64]. Beer brewing generates substantial by-products, the main ones being brewer's spent grain (BSG), hot trub, and residual yeast [65]. BSG represents 85% of brewing waste and is currently used in food, animal feed, biofuel production, and composite packaging materials [66]. This broad utility positions brewery waste as a promising circular-economy resource [67].

2.2.6. Spent Tea Leaves

The Netherlands is the fifth-largest tea-consuming country in Europe, with black and green tea most commonly consumed [68]. Most consumers (60%) dispose of compostable tea bags in organic waste (when tea bags are compostable), while the rest (38%) discard them in residual waste [51]. Spent tea leaf powder has been used in bio-composite films [69] and in bio-composites materials reinforced with jute and cotton [70].

2.2.7. Date Seeds

Dates, the fruit of the date palm tree (*Phoenix dactylifera*), are native to the Middle East and North Africa [71,72]. The Netherlands functions mainly as a re-exporter, with low domestic consumption [71]. Date seeds (approximately 10% of fruit weight) are by-products of processing and have economic potential in food and feed industries [73]. In The Netherlands, date seeds are also used as a caffeine-free coffee alternative [74]. In construction, date seeds have been used as filler in bricks (with clay and straw) and in insulation boards (with Polylactic Acid (PLA)-based polymers) [75].

2.3. Preparing the Filler Materials

2.3.1. Pre-Processing (Cleaning & Preparation)

Because of their different material characteristics, raw food-waste material resources require individual preparation methods to allow processing with the available machinery. For further processing, the resulting material should contain less than 2% moisture.

Avocado pits, as well as mango teguments and kernels, were collected from fresh fruits. Cleaning was performed by placing the collected pits and teguments in an 85 L mortar tub filled halfway with water. Two soft-bristle brush attachments were mounted on drills using extension bits to prevent contact with water. The drills were operated at high speed, causing the seeds to collide with the brushes and with each other. This process was repeated until all remaining pulp was removed.

Clean avocado pits were cut in half to remove the membrane surrounding the kernel. Mango teguments were split open to remove the kernel, and membranes were removed from both pits and kernels. The kernels were bisected along their natural split. Halved pits and kernels were oven-dried, at 90 °C for 8 h. The process was carried out once using seeds collected from local restaurants and again at a large-scale using fresh fruits procured from local markets. Although effective, the process was time-consuming and labor-intensive but could likely be automated for up-scaling.

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The average weight of avocado seeds collected from restaurants was 35 g before drying, and 8 g after oven drying. A total of 150 avocados were processed yielding 1215 g of dried seeds. Mango kernels averaged 39 g wet weight and 10 g after drying. Processing 150 mangos resulted in 1220 g of dry material. Notably, both avocado and mango kernels were not heated to the target moisture content at this stage, resulting in a lower overall dry weight.

Spent tea leaves were spread on baking trays and left to sun-dry, until dry to the touch. The tea bags were cut open, and the leaves were dried again at 90 °C for 8 h. Final moisture reduction was achieved through oven drying at 115 °C, yielding 380 g of material. However, this was insufficient to produce a meaningful number of samples, and the resulting composite was brittle and showed no promise. Therefore, tea leaves were not included in subsequent steps.

Beer brewing waste was collected in a cotton cloth, tied, and hung outdoors until dripping ceased. The material was then transferred to a container to sun-dry. Once it reached a dough-like consistency, it was moved to baking trays and oven-dried at 90 °C for 8 h. This process produced a uniform, brittle mass that crumbled easily. Final moisture content was achieved through drying at 115 °C, producing approximately 1200 g of material. Starting from about 5 kg, this represents a 76% weight reduction.

Hazelnut shells, date seeds, and pistachio shells were procured from external companies (De Hazelnotenboer (Almelo, The Netherlands) for the first and Bio-powder.com (Birkirkara, Malta) for the other two and required no preparation at this stage.

2.3.2. Milling

Coarse milling of dried materials was necessary to prepare them for the fine milling machinery, which requires particle sizes smaller than 25 mm. Only avocado and mango seeds required coarse milling, performed using a Retsch SM300 cutting mill (Retsch GmbH, Haan, Germany). Due to clogging, feed quantities were kept small (150 cm^3), and the machine required cleaning after approximately every 10 feeds.

Fine milling was then performed to achieve particle sizes smaller than 0.125 µm, since the smallest grain sizes ($\leq$0.125 µm) exhibit the highest impact strengths [33]. A Herzog manual vibratory disk mill (Herzog Automation Corp., Strongsville, OH, US) was used for this purpose. Milling intervals averaged 6 s, though some tougher materials required 10-s intervals. Each interval was followed by a 30–60 s cooldown. After 10–15 min of process time (including cooldown periods), a full machine cooldown and cleaning of the vessel were necessary to prevent clumping.

Although the machine was able to mill most materials effectively, processing was slow. Milling and sieving were therefore run in parallel to improve workflow efficiency. PPE was required due to dust and noise generation.

2.3.3. Sieving

Sieving was conducted using an EML Digital Plus T test sieve shaker (NEXOPART GmbH, Oelde, Germany). After each sieving cycle, particles retained in larger sieves were returned to the mill. When optimized, the workflow alternated between milling and sieving; while one batch was being sieved, the next batch was milled, and vice versa. Manual sieving supplemented machine sieving to improve the output. A minimum of 800 g of material was needed for efficient operation.

An attempt to enhance the performance of the sieve tower involved adding 15 mm, 4 g rubber ball weights to the sample. However, these compacted the material instead of improving separation, rendering the method ineffective.

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2.4. Additional Bio-Composite Components

2.4.1. Furan Resin

Furan resin—supplied by TransFurans Chemicals (Geel, Belgium)—was used as the matrix material in this study. Furan resins are based on 2-furaldehyde [76] and are widely used in applications requiring high durability and chemical resistance, such as industrial coatings, sand binders for metal casting, and foundry cores [77]. There are multiple reasons for choosing furan: firstly, it is derived from renewable biomass, it is resistant to moisture, it withstands thermal degradation, and it shows strong fire resistance.

Furan is a thermoset resin that forms three-dimensional, non-reversable networks [78]. It cures at ambient indoor temperature, with curing speed increasing at higher temperatures. The resin can withstand continuous exposure 150 °C without deterioration [78]. Furan resins are dark in color, form strong chemical bonds, and penetrate porous surfaces effectively.

2.4.2. Functional Fillers

Furan curing typically requires heat, radiation, light (photoinitiation), moisture, activators, or catalysts. In this study, the catalyst HM1448 (a 2-hydroxyethyl ammonium nitrate) was used and mixed with the resin at a 1:20 weight ratio. Linseed oil was used as a release agent and applied to the mold to facilitate demolding.

2.5. Preparing the Samples—Composition Parameters

The production of samples involves two steps: first, the bio-composite ingredients are combined into a dough-like material (Bulk Molding Compound, BMC) where all composite components are mixed and pre-cured. This is followed by a full curing of the BMC under pressure in a heated press, to form flat sheet samples (Table 1).

Table 1. Sampling recipes.

		Composition	
Component	**Description**	**Recipe 1—45% Filler**	**Recipe 2—55%**
Resin–Catalyst	Furan + HM1448	Hazelnut, Pistachio, BBW, Dates: 52%	Avocado: 41.81% Mango: 44.53%
Filler	Food-Waste	Hazelnut, Pistachio, BBW, Dates: 45%	Avocado: 56.88% Mango: 54.07%
Releasing agent	Linseed oil	1.68%	1.31%

2.5.1. Mixing/Kneading

Mixing was carried out using a Linden Type K Double-Z-Kneader (Linden, Marienheide, Germany) heated to 95 °C. Resin, catalyst and filler were added sequentially, allowing excess moisture to evaporate before adding the filler powder. Following the research by Neuhaus [33] and Wiersma [79], a filler-to-resin volume fraction of approximately 45–55% was selected as optimal for mechanical strength for most fillers except for avocado and mango where the ratio was reversed (55–45%). Two samples were produced per filler type, with a standard plate thickness of 4.2 mm.

2.5.2. Pressing

Pressing was performed using a Bucher KHB hydraulic press (Bucher Hydraulics, Klettgau, Germany) at 6 MPa and 150 °C for 15 min. The resulting flat sheets (4.2 mm thickness) were cooled at ambient temperature (21 ± 2 °C) and humidity (55 ± 5%).

2.6. Testing Protocols

Flat sheets were milled into test specimens measuring 80 mm by 15 mm, 80 mm by 10 mm, and 50 mm by 50 mm for the three-point bending, the Charpy impact testing, the water absorption, and the freeze-thaw cycling testing, respectively (Table 2). This study also examined processing behavior and visual appearance of fillers and composites under a digital microscope (Keyence VHX-7000, Mechelen, Belgium). UV degradation, resistance to atmospheric pollutants, and fatigue performance were not considered in this study.

Table 2. Testing types, with number and size of specimens and the required standard.

Test	No of Specimens	Specimen Size	Standard
Three-point bending	6	80 × 15	ISO 14125:1998 [80]
Charpy Impact	10	80 × 10	ISO 179 1:2023 [81]
Water absorption	3	50 × 50	Submersion for 28 days with weight measurements every 24 h
Freeze/Thaw cycling	3	50 × 50	10 cycles of freezing and thawing

3. Results

This section presents the main results of all tests indicated in Table 2 as well as several observations made during the filler processing, sieving, and mixing stages.

3.1. Optical Microscopy

All filler materials and specimens were analyzed using a Japanese-made Keyence VHX-7000 digital microscope (Keyence, Mechelen, Belgium) equipped with a 50×–400× lens.

3.1.1. Powdered Fillers (<0.125 µm)

The fillers exhibited different characteristics and agglomeration behaviors. Particles of beer brewing waste powder showed lumpiness and clustering (Figure 1). The particles in this case also varied in size, and there were not enough small particles to fill the voids created by the larger particle clusters. Date seed filler displayed local impurities with darker, clove-shaped particles that, although limited in mass, contributed to the filler inhomogeneity. Pistachio shell powder also showed some lumpiness but had better consistency, with small black particles evenly distributed throughout.

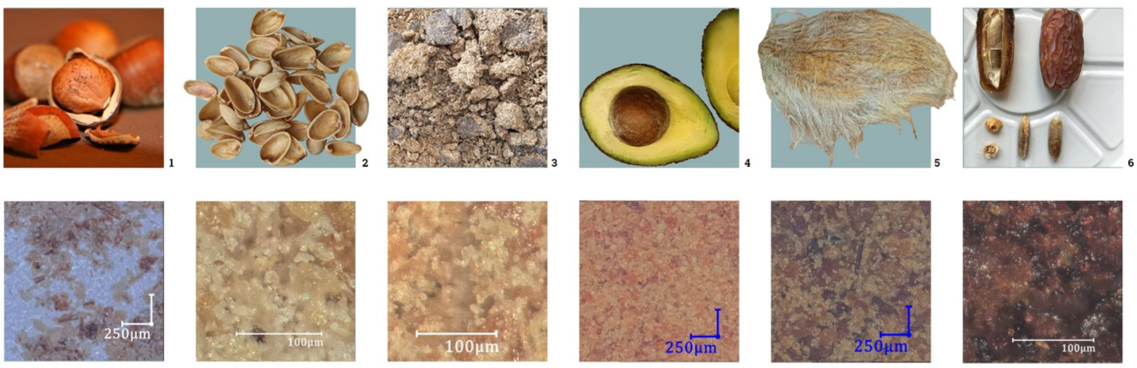

Figure 1. Images of all food-waste resources tested (**row above**) and enlarged images after milling (**row below**). Left to right: (1) Hazelnut (250 µm), (2) Pistachio (100 µm), (3) Beer Brewing Waste (100 µm), (4) Avocado (250 µm), (5) Mango (250 µm), and (6) Dates (100 µm).

3.1.2. Sample Specimens

The seven samples varied in surface quality and color. Hazelnut specimens showed no surface defects, while mango specimens appeared significantly shinier. Under the microscope (Figure 2), mango kernel, brewer's spent grain, and date seed specimens showed relatively smooth, flat surfaces, with protrusions measured at 17.40 µm, 29.0 µm,

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and 37.46 µm respectively. Mango kernel samples further displayed a homogeneous, coral-like network structure. Pistachio shell specimens showed surface craters with maximum protrusions of 52.95 µm, comparable to hazelnut specimens (54.50 µm).

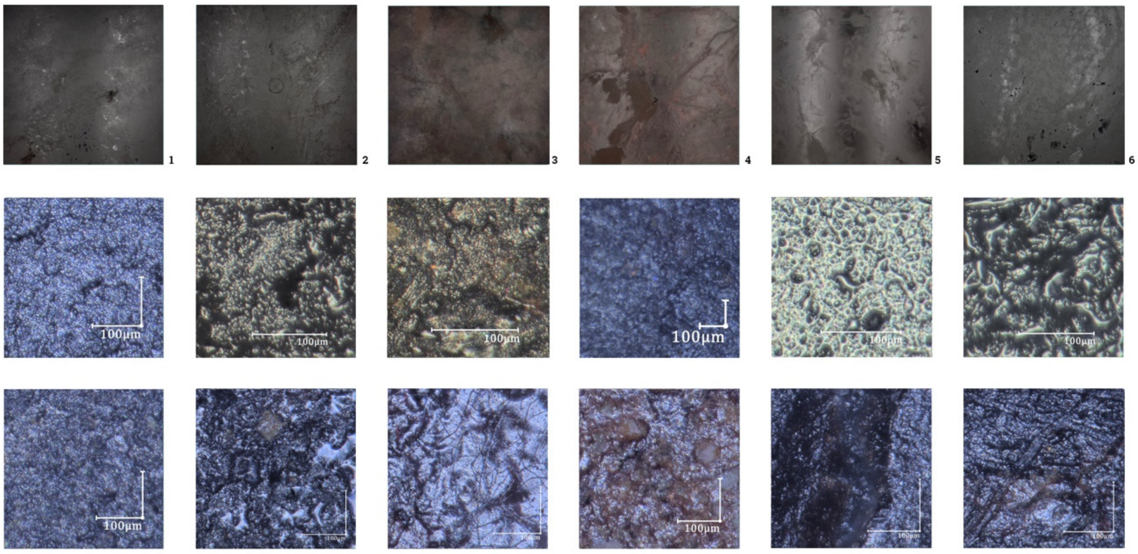

Figure 2. Images of all sample plates (**row above**) enlarged plate images (**row middle**) and enlarged images of specimens after freezing and thawing (**row below**). From left to right: (1) Hazelnut (100 µm), (2) Pistachio (100 µm), (3) Beer Brewing Waste (100 µm), (4) Avocado (100 µm), (5) Mango (100 µm), and (6) Dates (100 µm).

3.1.3. Sample Specimens After Freezing/Thawing

Hazelnut shells and date seeds specimens showed no significant changes after freeze-thaw cycling and retained homogeneous shapes (Figure 2). In the case of hazelnut samples, the resin appeared thinner than the filler. In contrast, beer brewing waste specimens developed a blister-like substructure. This effect was more pronounced in avocado and pistachio samples, which showed morphological deformation and chemical changes in material structure. The mango specimen exhibited a large crack, with holes around the crack area approximately 50 µm in diameter, likely associated with the damage.

3.2. Three-Point Bending & Charpy Testing

The results of the three-point bending and Charpy impact tests for all six bio-composite variants are presented in Table 3 and further illustrated in Figures 3 and 4, respectively. Mean flexural strength values ranged from 12.8 MPa for date seed composites to 62.6 MPa for hazelnut shell composites. The mean flexural modulus varied from 1.62 GPa for avocado pit composites to 5.62 GPa for hazelnut shell composites. Finally, mean impact strength ranged from 1.17 kJ/m^2 for avocado pit composites to 3.42 kJ/m^2 for hazelnut shell composites. The relative ranking of the materials was consistent across both bending and impact performance.

Table 3. Overall performance of specimens for three-point bending and Charpy testing.

No	Filler Material	Flexural Strength		Flexural Modulus		Charpy Impact Resistance	
		Mean [MPa]	Std Dev [MPa]	Mean [GPa]	Std Dev [GPa]	Mean [kJ/m^2]	Std Dev [kJ/m^2]
1	Hazelnut shells	62.6	11.91	5.62	0.72	3.42	0.27
2	Pistachio shells	53.9	9.02	5.24	0.15	1.39	0.24
3	Beer brewing waste	17.7	4.40	2.20	0.11	1.34	0.24

Table 3. *Cont.*

No	Filler Material	Flexural Strength		Flexural Modulus		Charpy Impact Resistance	
		Mean [MPa]	Std Dev [MPa]	Mean [GPa]	Std Dev [GPa]	Mean [kJ/m^2]	Std Dev [kJ/m^2]
4	Avocado pits	14.2	2.55	1.62	0.10	1.17	0.19
5	Mango kernels	35.7	5.13	3.84	0.24	1.4	0.32
6	Date seeds	12.8	1.05	1.79	0.16	1.28	0.30

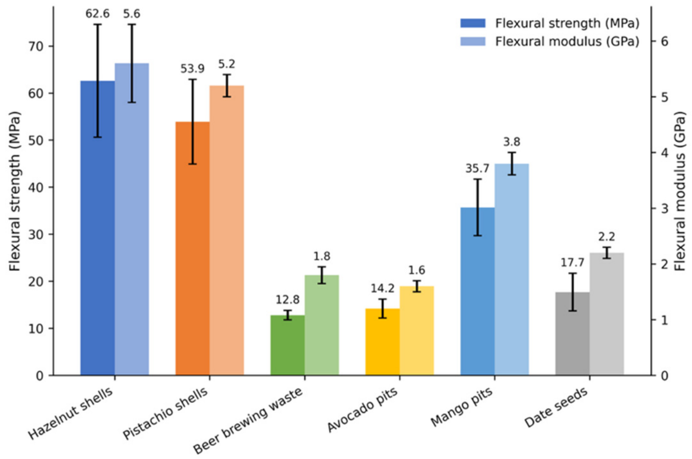

Figure 3. Flexural strength (in MPa) and flexural modulus (in GPa) of the six bio-composite variants. Error Bars indicate the standard deviation.

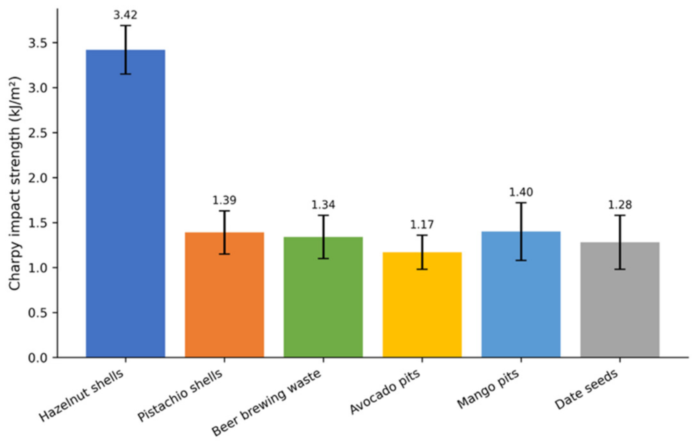

Figure 4. Impact strength of bio-composites variants of the six filler types (in kJ/m^2). Error Bars indicate the standard deviation.

3.3. Water Absorption

The bio-composites exhibited significant variation in water uptake (Table 4). Avocado specimens absorbed substantially more water than any other filler type within the first 24 h and peaked after approximately 10 days (Figure 5). After this peak, the specimens exhibited weight loss. This trend was also observed for beer brewing waste and date seed specimens.

In contrast, pistachio, hazelnut, and mango specimens continued absorbing water throughout the 28-day test period, though at different rates, without losing weight. Mango specimens exhibited modest absorption within the first 24 h, followed by a steep increase over the next 27 days, reaching 17.45%.

Table 4. Water absorption after 24 h and 28 days.

Filler	24 h [wt%]	28 Days [wt%]
Hazelnut	3.13%	4.18%
Pistachio	2.31%	5.80%
Beer Brewing Waste	3.63%	10.55%
Avocado	12.26%	30.07%
Mango	2.75%	17.45%
Dates	2.90%	3.57%

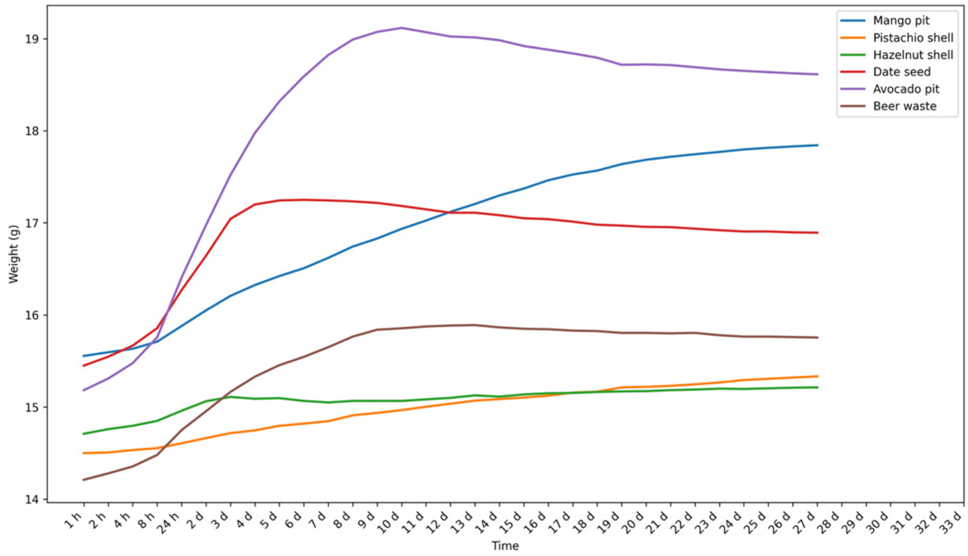

Figure 5. Water uptake of all bio-composites over the 28-day period (authors' data).

3.4. Filler Processibility

3.4.1. Milling

Several observations were made during milling: date seeds tended to clump due to heat. Allowing full machine cooldown between intervals prevented clumping. If clumps formed, they were manually broken after cooling; hazelnut shells required repeated intervals of up to 10 s (minimum five cycles) to reach the desired particle size, unlike other materials; mango and avocado pits milled smoothly but still produced large particles even at longer intervals, necessitating more frequent sieving. To reduce delays, larger quantities of raw material were prepared so milling could proceed continuously while sieving occurred in parallel; lastly, most samples generated noticeable airborne particles, whereas avocado pit and date seed powders produced relatively stronger odors.

3.4.2. Sieving

Hazelnut shells and date seeds sieved easily to the desired particle size. For date seeds, heat-clumped material needed manual crushing before sieving.

Beer brewing waste, avocado, and mango powders interacted statically with the sieve mesh. Automated sieving did not perform well for these samples; the fine particles formed a solid layer on the sieve surface, with larger particles trapped above. As a result, automated sieving was ineffective; larger particles had to be manually separated, while remaining material was brushed through the sieve using a round, soft-bristle brush. This behavior may be related to residual moisture and might be mitigated through enhanced material dehydration.

3.5. Filler Content

The original 45–55% filler–resin ratio was maintained for hazelnut, pistachio, date, and beer brewing waste samples. In avocado and mango composites, the viscosity of the resin–filler mixture was too low, requiring an increase in filler content. For the mango samples, 420 g of resin and catalyst were used (44.53%); another 13.2 g of the releasing agent (1.40%); and 510 g of filler (54.07%). For the avocado samples, 367.5 g of resin were used (41.81%) with 11.55 g of releasing agent (1.31%), and 500 g of filler (56.88%).

3.6. Density

The measured bulk densities of the bio-composite specimens ranged from approximately 1256 kg/m^3 (beer brewing waste) to 1391 kg/m^3 (hazelnut shells), with relatively low standard deviations, indicating good repeatability across specimens (Table 5).

Table 5. Average bulk density of bio-composite specimens by filler type.

Filler Resource	Mean Density (kg/m^3)	Standard Deviation (kg/m^3)	No of Specimens
Hazelnut shells	1391	54	5
Pistachio shells	1379	45	6
Beer brewing waste	1256	18	6
Avocado pits	1368	23	6
Mango pits	1361	18	6
Date seeds	1330	17	6

4. Discussion

4.1. Food-Waste Information Retrieval and Data Uncertainty

Following the FoWaBa-Bio project's planned activities, a workshop with waste management company representatives was organized early in the project to identify potential food-waste streams. However, only four representatives attended, and the meeting produced limited insights, as participants were reluctant to share relevant information. Retrieving reliable information about food-waste streams therefore proved more difficult than expected. Companies involved in waste management or material supply do not readily disclose such data.

As a result, most potential filler materials were identified through a combination of scientific literature and validated statistical data, primarily sourced from databases such as Centraal Bureau voor de Statistiek (CBS). The limited quantities required for experimentation were subsequently collected directly from food-processing or waste-processing facilities or procured independently in small batches. This approach enabled exploratory material testing but did not allow for systematic control over variability in source quality or supply consistency.

The scarcity of available data inevitably introduces a degree of uncertainty into research of this kind. While some of the selected resources are well documented in scientific studies, others have not been thoroughly examined in the context of polymeric bio-composites. Consequently, the selection of food-waste resources for processing and testing remains partly speculative and must be interpreted as an initial screening rather than a comprehensive assessment.

Further complicating material selection, many of the filler resources investigated in this study are already utilized in other applications, including biofuels, food or cosmetic oil extraction, and animal feed. Determining the most effective use of biomass is therefore not straightforward, as priorities differ depending on perspective, methodology, and local context [82].

4.2. Interpretation of Material Performance Results

The experimental results demonstrate that food-waste-derived bulk fillers exhibit markedly different processing behavior and composite performance, despite being processed under identical conditions. Mechanical testing revealed a clear hierarchy among the investigated fillers, with hazelnut and pistachio shells consistently outperforming the other food-waste streams in terms of flexural strength, stiffness, and impact resistance. In contrast, date seeds, beer brewing waste, avocado pits, and mango kernels showed substantially lower mechanical performance and, in some cases, pronounced sensitivity to moisture and freeze–thaw cycling.

These differences can be directly linked to filler homogeneity, lignocellulosic structure, and moisture affinity. Fillers with relatively uniform particle morphology and lower hygroscopicity formed denser, more coherent composites, as confirmed by optical microscopy. Hazelnut and pistachio shell composites exhibited limited void formation, good filler–matrix bonding, and stable microstructures after durability testing, which explains their superior mechanical behavior. Conversely, fillers characterized by heterogeneous particle size distributions, residual impurities, or higher moisture uptake showed localized defects, blistering, or cracking, which translated into reduced strength and durability. Together, these findings indicate that food-waste fillers cannot be treated as interchangeable resources, but must be selected based on their combined microstructural, hygroscopic, and processing characteristics.

Fillers associated with higher mechanical performance, hazelnut and pistachio shell exhibited densities in the upper range of the tested materials. Although bulk density varied across filler types, the results demonstrate that mechanical performance and moisture resistance are governed primarily by microstructural homogeneity and filler–matrix compatibility rather than density alone.

4.3. Processing Behavior and Implications for Composite Design

Beyond mechanical performance, the results highlight the strong influence of processing requirements on material suitability. Several fillers required extensive pre-treatment, including prolonged drying, repeated milling, or manual sieving, which affected both material consistency and process efficiency. The need to adjust filler–resin ratios for avocado and mango fillers further indicates limited compatibility with the chosen resin system. These findings suggest that technical performance alone is insufficient as a selection criterion; processability and stability during fabrication are equally decisive for façade applications.

The observed correlation between processing ease, microstructural homogeneity, and composite performance underscores the importance of integrating material science considerations early in the selection of food-waste resources. From a façade engineering perspective, fillers that enable stable, repeatable processing are more likely to support scalable production and consistent product quality.

4.4. Scalability and Systemic Considerations

With estimated prices of approximately €0.10–0.30 per kilogram, food-waste fillers are relatively inexpensive compared to fiber reinforcement; however, transportation, drying, and pre-processing costs may significantly increase overall material cost, particularly when these steps are not yet automated. Table 6 provides a preliminary, qualitative comparison of the two most promising filler resources in terms of estimated availability, cost, and processability within the Dutch context. The processability score represents a qualitative assessment based on drying requirements, grindability, particle-size control, and material heterogeneity, where high processability indicates minimal preprocessing requirements. Under conservative assumptions (45 vol% filler content), the estimated annual availability of hazelnut shells alone could theoretically support more than 8 million m^2 of façade cladding tiles. This rough estimate is based on 400 mm × 400 mm × 4.2 mm tiles, a composite density of 1250 kg/m^3, and an average yield of approximately 0.423 m^2 per kg of filler, without accounting for processing losses. While indicative rather than exhaustive, this comparison highlights the relative scalability potential of hazelnut and pistachio shells, as well as the constraints that must be addressed to enable industrial upscaling.

Table 6. Anticipated availability, cost and processability score for hazelnut and pistachio shells.

Filler Resource	Estimated Cost (€/kg)	Estimated Availability (kt/year, NL)	Processability Score
Hazelnut shells	0.10–0.30	20–30	High
Pistachio shells	0.15–0.30	5–10	High

Assessing the potential value of food-waste-based bio-composites requires consideration of both intrinsic and extrinsic factors. Intrinsically, properties such as particle granulometry, mechanical performance, and compatibility with the matrix resin are critical determinants of composite quality [63]. Extrinsically, factors such as availability, logistics, and processing effort strongly influence scalability. While this study demonstrates the technical feasibility of using food-waste-derived bulk fillers in bio-composite façade cladding, it also illustrates that successful implementation depends on coordinated technical, logistical, and organizational strategies. Integrating food waste into construction products such as façade cladding tiles therefore requires a broader, systemic approach that extends beyond material development alone.

Such an approach would likely involve not only large industrial actors but also smaller stakeholders, including restaurants and households, whose waste handling practices directly affect material quality. Manufacturers, in turn, would need to develop supply networks and scalable processing workflows capable of delivering consistent material properties. Processing stages need to also be revisited and automated where possible to avoid delays and to guarantee a constant and consistent resource flow.

5. Conclusions

This study confirms that food-waste-derived bulk fillers can be successfully incorporated into polymeric bio-composites for façade cladding applications, provided that material selection is informed by both performance outcomes and processing behavior. By testing multiple food-waste streams under identical manufacturing conditions, the research demonstrates that food-waste fillers are not interchangeable and that their suitability for façade applications varies substantially.

First, the results show pronounced differences in mechanical performance among the investigated fillers. Hazelnut shell composites achieved the highest overall performance, with mean flexural strength of 62.6 MPa, flexural modulus of 5.62 GPa, and Charpy impact resistance of 3.42 kJ/m^2, followed by pistachio shells (53.9 MPa, 5.24 GPa, and 1.39 kJ/m^2, respectively). In contrast, composites containing date seeds, beer brewing waste, avocado pits, and mango kernels exhibited substantially lower flexural strengths (12.8–35.7 MPa) and impact resistance, indicating up to a five-fold difference in mechanical performance depending solely on filler type.

Second, durability-related testing revealed significant variation in moisture sensitivity and resistance to freeze–thaw cycling. Water absorption after 28 days ranged from 3.57–4.18 wt% for date and hazelnut composites to 30.07 wt% for avocado-based com-

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posites, with mango-based composites reaching 17.45 wt%. Freeze–thaw cycling further differentiated material behavior: hazelnut and date seed composites maintained structural integrity, while avocado, pistachio, and beer brewing waste specimens exhibited morphological degradation such as blistering, cracking, or shape distortion. These results indicate that hygroscopicity and microstructural stability are critical performance parameters for façade suitability.

Third, optical microscopy and processing observations demonstrate a strong correlation between filler homogeneity, processability, and composite performance. Fillers with relatively uniform particle morphology and lower moisture affinity produced denser composites with fewer voids and more stable filler–matrix bonding. Conversely, heterogeneous particle size distributions, residual impurities, and moisture-related processing issues led to localized defects that directly translated into reduced mechanical strength and durability. These findings confirm that microstructural characteristics and filler–matrix compatibility govern composite behavior more strongly than density alone.

Fourth, the study highlights that processing requirements are decisive for material selection alongside mechanical performance. Several fillers required extensive drying, repeated milling, or manual sieving, and avocado and mango fillers necessitated adjustments to the filler–resin ratio due to low mix viscosity. These constraints limit process stability and scalability, indicating that technical performance alone is insufficient for façade applications where repeatability and manufacturing robustness are essential.

Finally, from a scalability perspective, the analysis suggests that hazelnut and pistachio shells offer the most promising balance between availability, cost, and processability within the Dutch context. Under conservative assumptions, the estimated annual availability of hazelnut shells alone could theoretically support the production of more than 8 million m^2 of façade cladding tiles, based on a 45 vol% filler content and standard tile dimensions of 400 mm $\times$ 400 mm $\times$ 4.2 mm. While indicative, this estimate highlights the potential of selected food-waste streams to contribute meaningfully to low-carbon façade material systems, provided that supply-chain coordination and processing automation are addressed.

Overall, this research demonstrates that food-waste-based bio-composites can meet key performance requirements for façade cladding, but only when material science considerations, processing behavior, and systemic supply constraints are evaluated in parallel. Successful implementation therefore depends not only on material feasibility, but also on integrated technical, logistical, and organizational strategies that enable consistent quality and scalable production.

6. Limitations and Future Research

This study represents an exploratory assessment of food-waste-derived bulk fillers for bio-composite façade cladding and is subject to several limitations that define its scope.

First, the selection of food-waste streams was constrained by accessibility, regulatory conditions, and the availability of consistent quantities during the project timeframe. As a result, the investigated fillers represent a strategic but non-exhaustive subset of potential food-waste resources. Future research should expand the range of investigated streams and systematically assess variability related to source heterogeneity, seasonal effects, and pre-processing conditions.

Second, the experimental investigation focused on a single resin system (furan-based thermoset) and a limited range of filler–resin volume fractions. While this enabled controlled comparison between filler types, it limits the generalizability of the findings. Future work should explore alternative bio-based and hybrid matrices, surface treatments, and coupling strategies to enhance filler–matrix compatibility and moisture resistance.

Third, performance evaluation was limited to short-term mechanical behavior, water absorption, and freeze–thaw resistance. Key façade-relevant properties, including fire performance, UV stability, resistance to atmospheric pollutants, fatigue under cyclic loading, and long-term ageing, were beyond the scope of this study and must be addressed before regulatory compliance can be assessed.

Moreover, scalability and system-level impacts were not quantitatively evaluated. Material preparation involved energy-intensive and partially manual processes, such as drying, milling, and sieving, which may significantly affect environmental and economic performance on an industrial scale. Future research should therefore integrate life-cycle assessment, energy analysis, and techno-economic evaluation, alongside investigations into automated processing and supply-chain integration.

Finally, successful development of food-waste-based bio-composites requires knowledge extending beyond structural engineering alone, drawing on material science and chemistry to understand filler composition, particle interactions, and matrix compatibility. A more systemic, interdisciplinary research approach may therefore enable more targeted selection and optimization of food-waste resources in future studies.

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References

1. Baptista, J.F.; Kokare, S.; Francisco, A.V.; Godina, R.; Aelenei, D. A comparative life cycle assessment of ETICS and ventilated façade systems with timber cladding. *Energy Build.* **2024**, *304*, 113842.
2. European Union. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law). *OJL* **2021**, *243*, 1–17.
3. Intergovernmental Panel on Climate Change. Climate change: Implications for buildings. *Ecos* **2014**, *15*, 29–34.
4. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a global carbon sink. *Nat. Sustain.* **2020**, *3*, 269–276. [CrossRef]
5. Dutil, Y.; Rousse, D.; Quesada, G. Sustainable buildings: An ever evolving target. *Sustainability* **2011**, *3*, 443–464. [CrossRef]
6. Göswein, V.; Reichmann, J.; Habert, G.; Pittau, F. Land availability in Europe for a radical shift toward bio-based construction. *Sustain. Cities Soc.* **2021**, *70*, 102929. [CrossRef]
7. Tomei, J.; Richard Helliwell, R. Food versus fuel? Going beyond biofuels. *Land Use Policy* **2016**, *56*, 320–326. [CrossRef]
8. Rathmann, R.; Szklo, A.; Schaeffer, R. Land use competition for production of food and liquid biofuels: An analysis of the arguments in the current debate. *Renew. Energy* **2010**, *35*, 14–22. [CrossRef]
9. Graham-Rowe, D. Agriculture: Beyond food versus fuel. *Nature* **2011**, *474*, S6–S8. [CrossRef]
10. Motamedi, S.; Rousse, D.R.; Promis, G. The evolution of crop-based materials in the built environment: A review of the applications, performance, and challenges. *Energies* **2023**, *16*, 5252. [CrossRef]
11. Singh, R.; Das, R.; Sangwan, S.; Rohatgi, B.; Khanam, R.; Peera, S.K.P.G.; Das, S.; Lyngdoh, Y.A.; Langyan, S.; Shukla, A.; et al. Utilisation of agro-industrial waste for sustainable green production: A review. *Environ. Sustain.* **2021**, *4*, 619–636. [CrossRef]

12. United Nations Environment Programme. *Food Waste Index Report 2024. Think Eat Save: Tracking Progress to Halve Global Food Waste*; UNEP: Nairobi, Kenya, 2024.
13. De Jong, B.; Boysen-Urban, K.; De Laurentiis, V.; Philippidis, G.; Bartelings, H.; Mancini, L.; Biganzoli, F.; Sanye Mengual, E.; Sala, S.; Lasarte Lopez, J.; et al. *Assessing the Economic, Social and Environmental Impacts of Food Waste Reduction Targets—A Model-Based Analysis*; Publications Office of the European Union: Luxembourg, 2023.
14. Graham-Rowe, E.; Jessop, D.C.; Sparks, P. Identifying motivations and barriers to minimising household food waste. *Resour. Conserv. Recycl.* **2014**, *84*, 15–23. [CrossRef]
15. Prasertsan, P.; Prasertsan, S.; H-Kittikun, A. Recycling of agro-industrial wastes through cleaner technology. *Biotechnology* **2010**, *10*, 1–11.
16. Vilaboa Díaz, A.; Francisco López, A.; Bello Bugallo, P.M. Analysis of biowaste-based materials in the construction sector: Evaluation of thermal behaviour and life cycle assessment (LCA). *Waste Biomass Valorization* **2022**, *13*, 4983–5004. [CrossRef]
17. Kurnik, K.; Krzyżyński, M.; Treder, K.; Tretyn, A.; Tyburski, J. Study on utilizing solid food industry waste with brewers' spent grain and potato pulp as possible peroxidase sources. *J. Food Biochem.* **2018**, *42*, e12446. [CrossRef]
18. Soares, M.; Faria, L.; Miranda, T.; Pereira, E.; Vilarinho, C.; Carvalho, J. The potential of agri-food waste to solve construction's environmental problems: A review. *Clean. Circ. Bioecon.* **2025**, *10*, 100138. [CrossRef]
19. *LETI Embodied Carbon Primer. Supplementary Guidance to the Climate Emergency Design Guide*; LETI: London, UK, 2020.
20. Ortega-Exposito, F.; van der Burgh, F.; Böttger, W. Biobased façade materials in Europe. In *Bio-Based Building Materials—Proceedings of ICBBM 2023*; Amziane, S., Merta, I., Page, J., Eds.; RILEM Bookseries; Springer: Cham, Switzerland, 2023; pp. 123–143.
21. Raja, P.; Murugan, V.; Ravichandran, S.; Behera, L.; Mensah, R.A.; Mani, S.; Kasi, A.; Balasubramanian, K.B.N.; Sas, G.; Vahabi, H.; et al. A Review of Sustainable Bio-Based Insulation Materials for Energy-Efficient Buildings. *Macromol. Mater. Eng.* **2023**, *308*, 2300086. [CrossRef]
22. Sandak, A.; Sandak, J.; Brzezicki, M.; Kutnar, A. *Bio-Based Building Skin*; Springer: Singapore, 2019.
23. Klein, T. Integral Façade Construction: Towards a New Product Architecture for Curtain Walls. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2013.
24. Roig, I. Biocomposites for interior façades and partitions to improve air quality in new buildings and restorations. *Reinf. Plast.* **2018**, *62*, 270–274. [CrossRef]
25. Morganti, L.; Vandi, L.; Astudillo Larraz, J.; García-Jaca, J.; Navarro Muedra, A.; Pracucci, A. A1–A5 embodied carbon assessment to evaluate bio-based components in façade system modules. *Sustainability* **2024**, *16*, 1190. [CrossRef]
26. Lau, K.; Hung, P.; Zhu, M.-H.; Hui, D. Properties of natural fibre composites for structural engineering applications. *Compos. Part B Eng.* **2018**, *136*, 222–233. [CrossRef]
27. Shanmugam, V.; Mensah, R.A.; Försth, M.; Sas, G.; Restás, A.; Addy, C.; Xu, Q.; Jiang, L.; Neisiany, R.E.; Singha, S.; et al. Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Compos. Part C Open Access* **2021**, *5*, 100138. [CrossRef]
28. Salasinska, K.; Barczewski, M.; Górny, R.; Kloziński, A. Evaluation of highly filled epoxy composites modified with walnut shell waste filler. *Polym. Bull.* **2018**, *75*, 2511–2528. [CrossRef]
29. Karaagac, B. Use of ground pistachio shell as alternative filler in natural rubber/styrene–butadiene rubber-based rubber compounds. *Polym. Compos.* **2014**, *35*, 245–252. [CrossRef]
30. Barczewski, M.; Matykiewicz, D.; Krygier, A.; Andrzejewski, J.; Skórczewska, K. Characterization of poly(lactic acid) biocomposites filled with chestnut shell waste. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 914–924. [CrossRef]
31. Neuhaus, L. Bio-Composites from Food-Waste. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2024.
32. Ghosh, S.; Merhi, N.; Neuhaus, L.; Sathyamurthy, P.; Sel, E.; Bilow, M.; Ioannou, O.; Overend, M. Towards Environmentally Sustainable Bio-Based Load-Bearing Components in Buildings: The Feasibility, Early-Stage Development and Testing of Five Possible Building Components to Meet Specific Performance requirements. In *Bio-Based Building Materials—Proceedings of ICBBM 2025*; Amziane, S., Toledo Filho, R.D., da Gloria, M.Y.R., Page, J., Eds.; RILEM Bookseries, 60; Springer: Cham, Switzerland, 2025; pp. 751–763.
33. Neuhaus, L.; Overend, M.; Ioannou, O. Bulk fillers from food waste for polymeric bio-composites: The influence of filler type, particle size and volume ratio on furan-matrix composites. *Constr. Build. Mater.* **2025**, *502*, 144303. [CrossRef]
34. CBS. Netherlands Is the EU's Second-Largest Exporter and Importer of Goods. Available online: https://www.cbs.nl/en-gb/news/2024/17/netherlands-is-second-largest-exporter-and-importer-of-goods-in-eu#:~:text=Netherlands%20is%20the%20EUâĂŹs%20second,Source:%20CBS%2C%20Eurostat (accessed on 20 August 2025).
35. CBI. The Netherlands: Market Potential for Fresh Fruit and Vegetables. Available online: https://www.cbi.eu/market-information/fresh-fruit-vegetables/netherlands/market-potential (accessed on 20 August 2025).
36. Eurostat. The Fruit and Vegetable Sector in the EU—A Statistical Overview. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=The_fruit_and_vegetable_sector_in_the_EU_-_a_statistical_overview#Output_values (accessed on 20 August 2025).

37. Bos-Brouwers, H.E.J.; Kok, M.G.; Viquez-Zamora, A.M. *Climate Footprint of Food Waste in The Netherlands*; Wageningen Food & Biobased Research: Wageningen, The Netherlands, 2024.
38. CBS. Industrial Waste. In *Trends in The Netherlands 2019*; Statistics Netherlands: The Hague, The Netherlands, 2019. Available online: https://longreads.cbs.nl/trends19-eng/society/figures/environment/#industrieelafval-en (accessed on 20 August 2025).
39. StatLine. Agricultural Data. CBS Open Data Portal. Available online: https://opendata.cbs.nl/#/CBS/en/dataset/80783eng/table (accessed on 20 August 2025).
40. Welink, J.H. Meer Waarde uit de Reststromen: Toekomstverkenning van Mogelijkheden Recycling Reststromen uit Voeding-en Genotsmiddelen Industrie. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2014.
41. CBS. More Restaurants and Catering, Fewer Bars and Cafés. Available online: https://www.cbs.nl/en-gb/news/2024/43/more-restaurants-and-catering-fewer-bars-and-cafes#:~:text=Nearly%20half%20of%20all%20food,per%20capita%20in%20Noord%2DHolland (accessed on 20 August 2025).
42. Milieu Centraal. Hoeveel Voedsel Verspillen We? Available online: https://www.milieucentraal.nl/eten-en-drinken/voedselverspilling/hoeveel-voedsel-verspillen-we/ (accessed on 20 August 2025).
43. Rabobank. Horeca Verspilt 5–6 Miljoen Kilogram Minder Voedsel, Maar Nog Altijd voor Bijna 650 Miljoen Euro. Available online: https://www.rabobank.nl/kennis/d011381929-horeca-verspilt-5-6-miljoen-kilogram-minder-voedsel-maar-nog-altijd-voor-bijna-650-miljoen-euro (accessed on 20 August 2025).
44. Rijkswaterstaat, Ministry of Infrastructure and Water Management. Afvalverwerking in Nederland: Cijfers 2020. Available online: https://www.afvalcirculair.nl/actueel/nieuws/afvalnieuws/2022/afvalverwerking-nederland-cijfers-2020/ (accessed on 20 August 2025).
45. European Environmental Agency. Netherlands: Waste Prevention Country Profile 2021. Available online: https://www.eea.europa.eu/themes/waste/waste-prevention/countries/2021-waste-prevention-country-profiles/netherlands-waste-prevention-country-profile-2021.pdf (accessed on 7 August 2025).
46. VANG: Huishoudelijk Afval. Afvalpreventieprogramma Nederland. Available online: https://vang-hha.nl/kennisbibliotheek/afvalpreventieprogramma-nederland/ (accessed on 7 August 2025).
47. European Parliament and Council. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Off. J. Eur. Union* **2008**, *312*, 3–30.
48. Rood, T.; Muilwijk, H.; Westhoek, H. *Food for the Circular Economy*; PBL Netherlands Environmental Assessment Agency: The Hague, The Netherlands, 2017.
49. Sezer, A.A.; Fredriksson, A. Environmental impact of construction transport and the effects of building certification schemes. *Resour. Conserv. Recycl.* **2021**, *172*, 105688. [CrossRef]
50. Ajila, C.M.; Aalami, M.; Leelavathi, K.; Prasada Rao, U.J.S. Mango peel powder: A potential source of antioxidant and dietary fiber in macaroni preparations. *Innov. Food Sci. Emerg. Technol.* **2010**, *11*, 219–224. [CrossRef]
51. Thoden van Velzen, E.U.; Molenveld, K.; Brouwer, M.T.; van der Zee, M.; Smeding, I. *Issue Paper: Recycling of Different Waste Streams*; Wageningen Food & Biobased Research: Wageningen, The Netherlands, 2021. [CrossRef]
52. FAO. FAOSTAT Database. Available online: www.fao.org/faostat (accessed on 8 August 2025).
53. García-Mahecha, M.; Soto-Valdez, H.; Peralta, E.; Carvajal-Millan, E.; Madera-Santana, T.J.; Lomelí-Ramírez, M.G.; Colín-Chávez, C. Production and Characterization of Cellulosic Pulp from Mango Agro-Industrial Waste and Potential Applications. *Polymers* **2023**, *15*, 3163. [CrossRef]
54. Bangar, S.P.; Dunno, K.; Dhull, S.B.; Kumar Siroha, A.; Changan, S.; Maqsood, S.; Rusu, A.V. Avocado seed discoveries: Chemical composition, biological properties, and industrial food applications. *Food Chem. X* **2022**, *16*, 100507. [CrossRef]
55. CBS. Avocado Imports Up by 19 Percent in 2020. Available online: https://www.cbs.nl/en-gb/news/2021/07/avocado-imports-up-by-19-percent-in-2020 (accessed on 8 August 2025).
56. Zhu, J. Reducing the Waste of Fresh Avocados from Kenya into The Netherlands by Using the Iceberg Model. Master's Thesis, Inholland University of Applied Sciences, Delft, The Netherlands, 24 June 2023.
57. Schepers, H.T.A.M.; Kwanten, E.F.J. Selection and breeding of hazelnut cultivars suitable for organic cultivation in The Netherlands. *Acta Hortic.* **2005**, *686*, 87–90. [CrossRef]
58. OEC. Shelled Hazelnuts/Filberts—Bilateral Trade Netherlands. Available online: https://oec.world/en/profile/bilateral-product/shelled-hazelnutsfilberts/reporter/nld (accessed on 7 August 2025).
59. Ollani, S.; Peano, C.; Sottile, F. Recent innovations on the reuse of almond and hazelnut by-products: A review. *Sustainability* **2024**, *16*, 2577. [CrossRef]
60. Tareq Noaman, A.; Abed, M.S.; Al-Gebory, L.; Al-Zubaidi, A.B.; Al-Tabbakh, A.A. Production of Agro-Waste Cement Composites: Influence of Nutshells on Mechanical and Hardened Properties. *Constr. Build. Mater.* **2023**, *394*, 132137. [CrossRef]
61. Ferguson, L.; Polito, V.; Kallsen, C. The pistachio tree. Botany and physiology and factors that affect yield. In *Pistachio Production Manual*, 4th ed.; University of California, Fruit & Nut Research Information Center: Davis, CA, USA, 2005.

62. CBI. Pistachios: Market Potential. Available online: https://www.cbi.eu/market-information/processed-fruit-vegetables-edible-nuts/pistachios/market-potential (accessed on 8 August 2025).
63. Fereidooni, L.; Morais, A.-R.C.; Shiflett, M.B. Application of pistachio shell waste in composites, nanocomposites, and carbon electrode fabrication: A review. *Resour. Conserv. Recycl.* **2024**, *203*, 107403. [CrossRef]
64. CBS. First Fall in Number of Breweries Since 2010. Available online: https://www.cbs.nl/en-gb/news/2025/09/first-fall-in-number-of-breweries-since-2010 (accessed on 8 August 2025).
65. Rachwał, K.; Waśko, A.; Gustaw, K.; Polak-Berecka, M. Utilization of brewery wastes in food industry. *PeerJ* **2020**, *8*, e9427. [CrossRef]
66. Soceanu, A.; Dobrinas, S.; Popescu, V.; Buzatu, A.; Sirbu, A. Sustainable Strategies for the Recovery and Valorization of Brewery By-Products—A Multidisciplinary Approach. *Sustainability* **2024**, *16*, 220. [CrossRef]
67. Chattaraj, S.; Mitra, D.; Ganguly, A.; Thatoi, H.; Das Mohapatra, P.K. A critical review on the biotechnological potential of Brewers' waste: Challenges and future alternatives. *Curr. Res. Microb. Sci.* **2024**, *6*, 100228. [CrossRef]
68. CBI. Tea in The Netherlands: Product Factsheet. Available online: https://www.cbi.eu/sites/default/files/market-information/cbi_2016_-_tea_-_pfs_nl_-_final_draft_redacted.pdf (accessed on 8 August 2025).
69. Duan, J.; Obi Reddy, K.; Ashok, B.; Cai, J.; Zhang, L.; Varada Rajulu, A. Effects of spent tea leaf powder on the properties and functions of cellulose green composite films. *J. Environ. Chem. Eng.* **2016**, *4*, 440–448. [CrossRef]
70. Rahman, A.; Chowdhury, M.A.; Hossain, N.; Shuvho, M.B.A.; Kowser, M.A.; Rahman, M.R.; Chani, M.T.S.; Kuok, K.K.; Rahman, M.M. Improvement of Mechanical, Thermal, and Physical Behaviors of Jute/Cotton Biocomposites Reinforced by Spent Tea Leaf Particles. *J. Compos. Sci.* **2022**, *6*, 145. [CrossRef]
71. CBI. Dates: Market Potential. Available online: https://www.cbi.eu/market-information/processed-fruit-vegetables-edible-nuts/dates-0/market-potential (accessed on 8 August 2025).
72. Abdillah, L.; Andriani, M. Friendly alternative healthy drinks through the use of date seeds as coffee powder. In Proceedings of the ICEBM 2012 International Conference on Entrepreneurship and Business Management, Jakarta, Indonesia, 22–23 December 2012.
73. Ghnimi, S.; Umer, S.; Karim, A.; Kamal-Eldin, A. Date fruit (*Phoenix dactylifera* L.): An underutilized food seeking industrial valorization. *NFS J.* **2017**, *6*, 1–10. [CrossRef]
74. Daffee. Date Seed Coffee. Available online: https://daffee.nl/pages/daffee (accessed on 8 August 2025).
75. Fragassa, C.; Vannucchi de Camargo, F.; Santulli, C. Sustainable biocomposites: Harnessing the potential of waste seed-based fillers in eco-friendly materials. *Sustainability* **2024**, *16*, 1526. [CrossRef]
76. Fabris, H.J.; Knauss, W.G. Synthetic polymer adhesives. In *Comprehensive Polymer Science and Supplements*; Allen, G., Bevington, J.C., Eds.; Pergamon: Oxford, UK, 1989; Volume 7, pp. 131–177.
77. Pascault, J.-P.; Höfer, R.; Fuertes, P. Mono-, Di-, and oligosaccharides as precursors for polymer synthesis. In *Polymer Science: A Comprehensive Reference*; Matyjaszewski, K., Möller, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2012; pp. 59–82.
78. Fink, J.K. Furan resins. In *Reactive Polymers Fundamentals and Applications*; Fink, J.K., Ed.; William Andrew Publishing: Norwich, NY, USA, 2005; pp. 307–320.
79. Wiersma, J. Recycling of Bio-Composite Façades Panels: Exploring the Possibilities of Recycling bio Composites into Filler for a New Bio Composite Façade Product. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2025.
80. *ISO 14125:1998*; Fibre-Reinforced Plastic Composites—Determination of flexural properties. International Organization for Standardization: Geneva, Switzerland, 1998.
81. *ISO 179 1:2023*; Plastics—Determination of Charpy Impact Properties. International Organization for Standardization: Geneva, Switzerland, 2023.
82. Garnett, T.; Roos, E.; Little, D.C. *Lean, Green, Mean, Obscene…? What Is Efficiency? And Is It Sustainable? Animal Production and Consumption Reconsidered*; Food Climate Research Network (FCRN): Oxford, UK, 2015.
83. NWO. Food Waste-Based Bio-Composites (FoWaBa-Bio). Available online: https://www.nwo.nl/en/projects/dkiuk90955 (accessed on 7 August 2025).