buildings

MDPI

Review

Composite Materials Based on Waste Cooking Oil for Construction Applications

Anita Staroń

Department of Engineering and Chemical Technology, Cracow University of Technology, 24 Warszawska St., 31-155 Cracow, Poland; anita.staron@pk.edu.pl

Abstract: Used cooking oil after the thermal processing of food constitutes a difficult-to-degrade waste product, the quantities of which are increasing yearly due to the increasing pace of life and the establishment of new food service outlets. Frying allows for the preparation of a large amount of food for consumption in a short time but alters the physical and chemical properties of the oil used, which then becomes harmful to human health. Despite several possibilities for using waste cooking oil, environmentally safe ways to manage it are still being sought. In an effort to reduce the amount of waste, using cooking oil as a binder for the benefit of the construction industry seems plausible. This paper presents a literature review on the use of waste cooking oil to produce composite materials for construction purposes, addressing the process parameters of tipping solid materials comprising vegetable oil as a binder and examining their strength and absorbability. Methods of obtaining oil binders, either comprising vegetable oil alone or various mixtures, are described. In addition, the advantages of producing and using "green" materials are presented.

Keywords: waste cooking oil; green materials; oil binder; building block

Citation: Staroń, A. Composite Materials Based on Waste Cooking Oil for Construction Applications. *Buildings* **2023**, *13*, 994. https://doi.org/10.3390/buildings13040994

Academic Editors: Łukasz Sadowski and Antonio Caggiano

Received: 28 February 2023
Revised: 4 April 2023
Accepted: 8 April 2023
Published: 10 April 2023

1. Introduction

The frying process consumes edible vegetable oil and generates waste cooking oil (WCO), which is produced on a large scale in several areas, such as catering establishments, hotels, restaurants, and households. The thermal processing of food with vegetable oil allows for the rapid preparation of large quantities of food in a relatively short period of time. With the current fast pace of life, the popularity of fast food is growing [1]. During the frying process, high temperatures and rapid heat transfer between the cooking oil and the food product occur [2]. In addition, during frying, food preservation occurs due to the killing of microorganisms and the removal of water from the surface of the food [3]. The intensity of the changes occurring in the oil depends on a number of factors, including the type of food, the properties of the oil, temperature, frying, and even the material of the vessel in which the frying process is carried out [4].

The high temperatures during frying and the moisture in the cooking oil lead to chemical transformations that alter the physical and chemical properties of the oil. For example, hydrolysis results in an increase in the concentration of polar molecules, free fatty acids, and glycerol, while thermal degradation leads to the formation of alkanes, alkenes, ketones, and esters from triglycerides, among other compounds. Oxygen from the environment causes the oxidation of the oil components, and hydrogen peroxide formation and changes in the content of conjugated dienes and trienes are also observed [5,6]. The amount of undesirable reactions increases with increased oil use time [7].

Most WCO is produced in highly developed countries, with some of the main representatives being the United States (approximately 600,000 tons), Canada (approximately 135,000 tons), East Asian countries (100,000 tons), or countries of the European Union (approximately 850,000 tons). Such quantities pose a significant problem for society and a threat to the environment due to the difficulty of processing WCO and its improper disposal, which leads to sewage pollution [8,9]. Further, the liquid form of WCO makes it difficult to dispose of. This interferes with proper wastewater treatment, reduces the oxygen index, and disrupts the balance of ecosystem. Advances in the scientific world have, however, offered significant opportunities to modify WCO into raw materials for further use by society [10].

After the conversion process, WCO can be used in a variety of industries [11–16]. For example, WCO is used in biodiesel production, but its high free fatty acid (FFA) content results in the formation of soap or wax by products; thus, an esterification process with acid catalysts is carried out before transesterification. However, since this process is expensive, industries have started using bifunctional catalysts doped with calcium oxide and iron oxides, making a one-step esterification and transesterification process possible [10,17,18]. The cost of biodiesel production is affected by many factors, e.g., the glycerol content of WCO. The combustion characteristics of used cooking oil are very similar to those of diesel fuel in direct injection engines [19,20].

WCO is also used to produce biogas via its addition to the natural manure of pig slurries. Fermentation carried out in this manner is characterised by higher efficiency and leads to increased production of methane. The better performance of anaerobic digestion in reactors containing swine slurry and WCO is related to the peculiar decomposition of triglycerides. Methane production was negatively affected by the accumulation of palmitic acid, but this effect is reversible, which encourages co-digestion in agricultural biogas plants of pig slurry and waste cooking oil [21]. WCO can also serve as a raw material for the production of polyurethane foams after purification, where the polyols obtained via transesterification have been proven suitable for this purpose. Such foams constitute a higher-quality construction material compared to other products available on the market in terms of strength, water absorption, and sound [10]. The rigid polyurethane foam obtained from waste cooking oil has a density of 208.4 kg/m^3, a maximum compressive strength of 0.03 MPa, and the ability to take loads of 0.09 kN, proving that WCO-based polyurethane foam can be used to produce insulation boards [22]. Furthermore, WCO is used in the production of biosolids, where it undergoes chemical modifications that improve its oxidative stability, resulting in better lubrication performance. The products obtained via transesterification can also be subjected to hydrolysis, dehydrogenation, or Friedel-Crafts alkylation processes, which yield enhanced biogrease in terms of viscosity or oxidative stability. Further applications of WCO involve its use in common household products, such as dishwashing liquid, candles and in the production of graphene as a source of carbon from the pyrolysis of oil [23]. In addition, the pyrolysis products of WCO are noted for their collection capacity and high selectivity; thus, they can serve as a substitute for diesel fuel in terms of acting as collectors in the coal flotation process [24]. Sobrinho et al. used carbon from palm oil pyrolysis to adsorb cationic dyes because its adsorption capacity is comparable to that of activated carbon [25]. WCO has additionally been applied to plasticizers in the plastics industry (i.e., food packaging, toys, etc.). PVC samples with partial substitution with methyl esters showed more favorable thermal and mechanical properties. The conventional epoxy compound showed inferior low-temperature properties, greater oxidation stability, and higher glass transition temperatures for PVC compared to 2-ethylhexyl ester epoxy from waste cooking oil [26]. Thus, plasticizers based on dioctyl phthalate or petroleum, used in food packaging and in toys, have been highly hazardous, especially to the health of children and pregnant women. Therefore, the search for an alternative has led researchers to investigate WCO as a non-toxic and environmentally friendly product.

The present study focuses on the use of vegetable oils, including WCO, for the production of building materials. Materials containing oils as a binder are classified as green, and the technology for their production is relatively simple, eliminating the need for cement in building materials. Moreover, in the process of cement production, a substantial amount of carbon dioxide is released into the atmosphere, contributing to global warming. In addition, WCO in building materials is a useful approach to managing this difficult-to-degrade waste matter and obtaining a full-fledged product.

This paper presents a literature review on the production of composite materials for construction applications using waste vegetable oils. Literature data on the process parameters of WCO-based solid materials, their mechanical strength, and their physicochemical parameters were compared. The paper also presents the advantages and disadvantages of manufacturing building materials based on waste cooking oil and draws attention to the aspect of environmental safety, bearing in mind that this type of material can come into contact with soil and water and be exposed to changing weather conditions.

2. Composite Materials Based on WCO for Construction Applications

Currently, the construction sector is responsible for the use of approximately 50% of the world's natural resources and 40% of global energy consumption, which has led to the implementation of measures to protect the environment. In the paving industry, actions that contribute to a sustainable environment include the optimisation of bio-resources, taking into account their sustainability and renewability, and local production, as these have a significant impact on reducing costs and energy use itself [27]. The simple chemical composition of WCO allows for its use as a building material in, for example, asphalt mixtures. WCOs with different physical and chemical properties are used depending on the degree of WCO consumption. WCO with lower acidity and lower water content enhances the properties of asphalt binder to a higher degree. Asphalt binders are mainly modified with vegetable oils (including waste oils) because the consistency of these substances allows for their use as a viable substrate without incurring additional production costs [28]. WCO additives improve the low-temperature cracking resistance, fatigue cracking performance, and self-healing efficiency of asphalt [29]. The quality of the WCO used affects the performance of the modified asphalt based on the interaction bonds between the asphalt binder and the WCO [30]. Notably, the increase in bonding interactions between asphalt binder particles and processed edible oil waste affects the softening temperature, rutting resistance, and ageing of the asphalt [29]. However, asphalt modified with WCO additives is more desirable in colder regions due to its reduced softening point and increased penetration values [31]. The ageing performance of asphalt modified with precipitation cooking oil is greater than that of petroleum asphalt, though their thermal stability is comparable [32]. Considering the above discussion, large-scale research studies on the properties of asphalt mixtures infused with WCO are being conducted, and the WCO materials themselves are attracting interest [33–36]. Waste cooking oil can be used to produce thermoplastic composites that can be used to produce various types of building components, such as wall cladding, floorboards, roof panels, etc. [37–39]. Waste cooking oil may also be applied as an ingredient in the production of insulation materials such as polyurethane foams or recycled materials for roof insulation. These materials are extremely effective in preventing heat loss, which helps reduce energy consumption [40,41]. Waste cooking oil can also be used as a filler in the production of building panels. These panels are lighter and more durable than traditional building materials and are ideal for the construction of partition walls, suspended ceilings, etc. Waste cooking oil may also find an application as an ingredient in the production of boards with natural fibres, such as fibreboards or MDF boards. These boards are strong, durable, and easy to work with, which makes them popular in the construction industry [42,43].

Cavalcanti et al. [44] used epoxidized waste cooking oils in the production of lignocellulosic composites. Particle boards with a specific weight of 1130 to 1380 kg/m^3 were produced, in which the petroleum-derived epoxy resin was replaced by partially epoxidized vegetable oil. At a temperature higher than 300 °C, a significant weight loss was observed, resulting from the content of lignocellulose. A decrease in the mechanical strength of the composite was also observed due to the addition of wood chips to the polymer matrix, but satisfactory physical (material density) and mechanical (tensile strength) properties were observed.

Waste cooking oil was also used in the production of composite laminates consisting of bioresin reinforced with glass and flax fibres. WCO-based resins have improved impact properties in brittle matrices; therefore, they are a favourable alternative to composite laminates for structural applications [45].

In another study, Kevern [46] studied the effects of soybean oil on concrete, the addition of which led to moisture retention in fresh concrete, a positive effect on the curing process, and increased resistance to scaling. Previous studies have also confirmed these effects: the application of soybean oil to the surface of a concrete mix reduced the formation on the surface compared to unprotected concrete. Other researchers have investigated the use of WCO as an admixture in concrete, observing a reduction in air bubbles in concrete mixes containing refined cooking oil. The concrete-oil materials showed reduced compressive strength at 28 days, while the strength increased to a value comparable to that of concrete after 180 days. In addition, an increase in the emulsified cooking oil content resulted in an increase in chloride resistance and carbonation due to saponification processes occurring between the cooking oil and concrete components, which led to a reduction in pore distribution. However, the loss of air in the concrete block weakened its frost resistance [47]. Khidzir et al. [48] obtained similar results regarding the number of air voids in a concrete–oil mixture. However, when up to 2% food oil was used in the concrete mix, the researchers observed an improvement in the workability of the oil-enriched concrete mass, the structure of the concrete, and its strength properties.

Waste vegetable oil can act as a binding agent in construction materials, resulting in the so-called "WasteVege blocks", solid materials characterised by the absence of cement, as shown in [49]. Here, the materials in question consisted of sand and 10% liquid vegetable oil by weight. The mixture of ingredients was compacted in moulds and subsequently annealed in an oven at temperatures ranging from 160–200 °C for 10.5 days. WasteVege blocks obtained at 170 °C displayed the highest compressive strength (approximately 34 MPa) and stiffness (almost 20.16 MPa), while blocks obtained at 200 °C resulted in the lowest values for these parameters due to their high porosity.

Staroń et al. [50] optimized the process of producing oil blocks and produced construction materials based on WCO. The physicochemical properties, strength, and phytotoxicity of oil blocks were determined. A mixture of WCO, sulfuric acid, and sand was annealed at 180–220 °C for 12–20 h; the mass ratio of sulfuric (VI) acid to catalysed oil was 0.03–0.27, and the content of catalysed WCO relative to the mass of the whole mixture was constant at 15%. The environmental impact of green blocks was also investigated, revealing that small amounts of dibenzo[a,h] anthracene could leach out while no heavy metals were detected in the filtrates. In addition, the authors observed a higher than threefold increase in the above-ground portion of a *Sorghum saccharatum* plant grown in rainwater-soaked soil incubating the oil blocks compared to the control. The environmentally friendly binder consists of waste cooking oil and an acid catalyst, the use of which reduces the oil's curing time and the amount of energy used. In the process of obtaining composite materials based on WCO, Brønsted acids are used, most often sulfuric acid (VI) due to its high transesterification efficiency [44]. During the heating process, the compounds in WCO undergo polyesterification, forming a solid polyester.

Ping et al. used cooking oil, obtained after the heat treatment of food, and fly ash to produce tiles. Materials cured at 18 h were characterized by the highest strength parameters (a transverse strength of about 2300 N) and the lowest materials produced at 12 and 30 h of annealing (about 1500 N) [51]. Trials were conducted to obtain the masonry components from cooking oil, glycerol, and natural aggregates (sand and gravel). The ratio of cooking oil to glycerine was 1:3, and the binder content ranged from 14–20%. After compacting the samples, they were cured at 140–200 °C for 24–120 h. In the samples cured at 160 °C, the compressive strength improved with increasing annealing time (up to 96 h) to approximately 32 MPa. The lowest compressive strength was observed for the samples containing 20% binder annealed at 24 h. The most favourable curing temperature for the oil materials was determined to be in the 160–180 °C range. In another study, solid materials for structural applications were also obtained from glycerine pitch and its mixture with WCO. Glycerine pitch is a waste product of the glycerine purification process; it exists as a viscous, dark-coloured semisolid substance containing various organic and inorganic impurities. WCO was used to increase the binding strength of green materials and reduce their affinity for water. While obtaining the oil-based materials, an additional step of coating the samples was required. In the first step, oils were mixed with sand and fly ash, after which the samples were compacted and annealed to cure them. The materials contained 3–6% glycerine pitch or a 6–10% fat mixture; after annealing for 4 h at 190 °C, they were coated and annealed for a further 20 h. The tiles containing a mixture of glycerine pitch and WCO displayed higher water resistance and mechanical strength. In addition, the study showed that applying a coating of WCO to the materials resulted in a further increase in strength, regardless of how the coating was applied (e.g., spraying or dipping) [52].

Nadeem et al. used palm oil, sand, and fly ash to produce roof tiles [53], annealing the materials over 5–10 days. A palm oil content of 6–8% was sufficient to effectively combine the components of the mixture. The green materials obtained at 200 °C were characterised by reduced mechanical strength, so the thermal curing temperature was reduced to 190 °C. The tiles containing 35–50% filler were impermeable to water and exhibited low water absorption and high flexural strength (above 10 MPa for the materials annealed for more than 9 days). The amount of filler used in the green tiles is comparable to that used in traditional building materials. Further, a fly ash content of 30–60% imparts high mechanical strength and durability to concrete material [54].

In another study, Sam et al. used a binder consisting of waste engine oil and waste vegetable oil, which they mixed with fly ash and sand to produce vege-tiles [55]. These were characterised by high strength parameters (a bending strength up to 6.38 MPa), a low water absorption of 5.2%, and impermeability towards water molecules, allowing them to meet the ASTM standard for tiles. Sam et al. also presents the results of a study on the production of tiles containing binders obtained from fresh and waste vegetable oil, polysaccharides, fly ash, and sand. The oil-polysaccharide binders included rice flour, ethyl cellulose, potato, and corn starch. Vegetable oil (400 mL) was mixed with 10 g of polysaccharides with 20 min of sonication, followed by the addition of sand and powdered fly ash. The composition involved 10, 20, and 70% (w/w) of oil-polysaccharides, ash and sand, respectively. The prepared sample was annealed at 190 °C for 24 h and the most favourable effect on the properties of the generated tiles was achieved with the addition of ethyl cellulose, which increased their durability, mechanical properties, and permeability [56].

In summary, composite materials based on waste cooking oil (WCO) have been developed for a variety of construction applications. These materials are typically created by mixing waste cooking oil with other natural fibres or fillers, such as sawdust, rice husks, or corn cobs. One of the main advantages of using WCO-based composite materials is their high strength-to-weight ratio, making them ideal for construction applications such as building panels, roofing, and insulation. The materials are also highly resistant to fire, moisture, and insects, which can improve the durability of buildings.

3. Formation of Solid Composite Materials Based on WCO

Composites based on waste cooking oil can be used as roof tiles, paving stones, sidewalk edging, and paving slabs, among others. In the process of producing solid oil materials, the first step may involve exposing post-fried rapeseed oil to an acid catalyst, such as sulfuric acid. This serves to accelerate the polymerisation, esterification, and transesterification processes. An aggregate sand, for example, is then added to the system. The mixture is annealed at an appropriate temperature for a specific period to cure the oil blocks. Figure 1 depicts the stages in the process of obtaining the oil blocks.

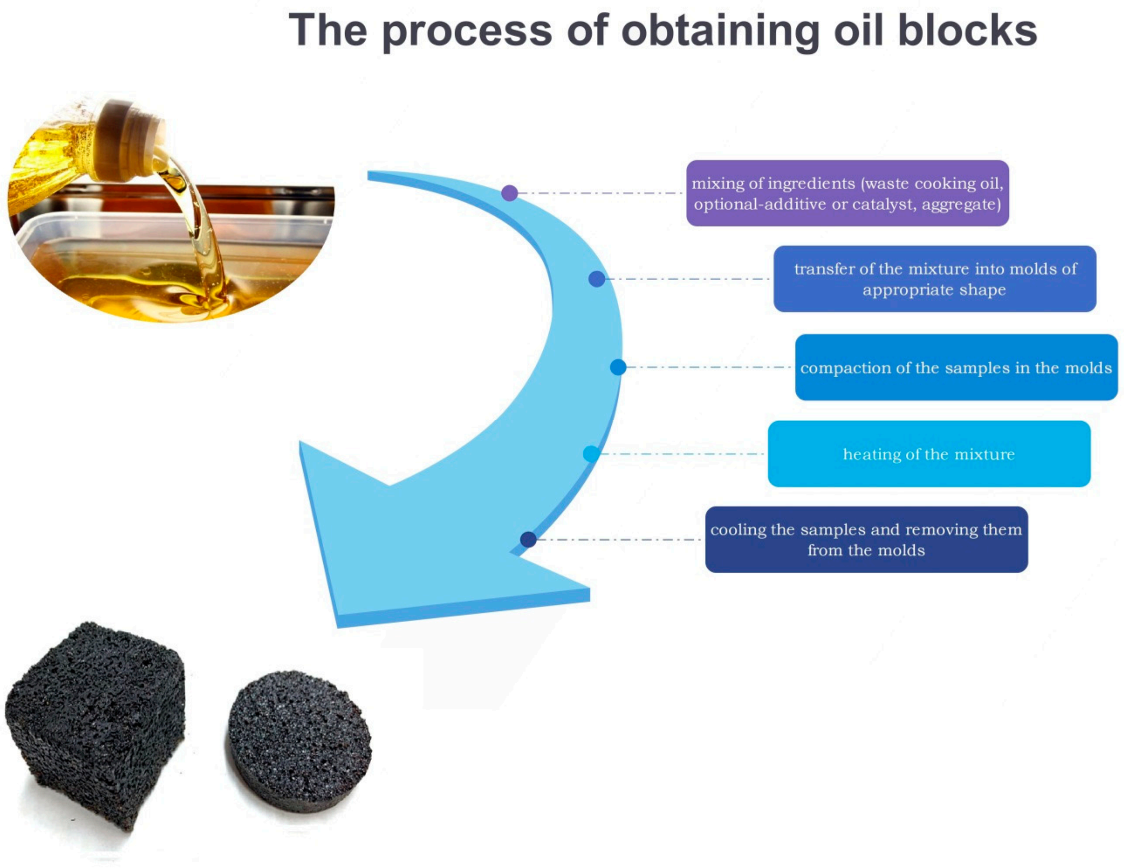

Figure 1. The stages in the process of oil blocks obtaining.

The hardening of the frying oil occurs in response to a number of reactions occurring during the process. The first of these is the polymerisation reaction, after which an esterification reaction takes place in the resultant products in an acidic environment provided by the added catalyst. During esterification, the diols and diquats present in the oil after frying undergo reactions, and the polyesters thus formed cause the matrix of the blocks to harden [57]. The transesterification process reduces the number of acidic compounds in the frying oil, where the fatty acids contained therein react with alkyl alcohols (e.g., methanol) in the presence of alkyl catalysts (i.e., sodium or potassium hydroxide). A by-product of glycerol is produced in addition to the ester mixture. This can be in the form of a mixture with a catalyst, non-transformable fatty acids, alcohol, or other impurities. In the first stage of transesterification, the base reacts with the alcohol to produce an alcoholate and a protonated catalyst. In the second step, the alcoholate begins a nucleophilic attack on the carbonyl group of the triglyceride to form an intermediate. The resulting diglyceride anions react with the protonated catalyst, resulting in a pure catalyst that can initiate subsequent cycles of transformation. The resulting diglycerides and monoglycerides are further converted to a mixture of esters and glycerol [58–60].

In the absence of an acid catalyst in the system, the thermal processes occurring within the vegetable oil initiates an oxygen polymerisation reaction, which increases the viscosity of the oil and causes it to harden [61,62]. Vegetable oils exhibit the ability to solidify as a result of transformations taking place within them; heating vegetable oil at 160–200 °C can lead to the generation of solid materials due to oxidation and polymersation reactions occurring in the oil [63]. Table 1 shows the advantages and disadvantages of using composites based on waste cooking oil in the construction sector.

Table 1. The advantages and disadvantages of using composites based on waste cooking oil in the construction sector.

Advantages of Using WCO-Based Composites in the Construction Sector	Disadvantages of Using WCO-Based Composites in the Construction Sector
Simple production technology	High energy intensity due to the need of materials annealing
Low cost raw materials	Limited scale of production (through furnace area)
Waste management	Variability in the composition of waste cooking oils
High strength parameters	Harmful contamination of WCO
Low water absorption of oil composites	Quantity and availability of raw materials depend on geopolitical situation
Short time to obtain the product	No assessment of the environmental impact of materials
Reduction in storage space (no need for maturation of cubes produced from waste oil in comparison with cement materials)	
Elimination of components that affect CO_2 emissions	

Undoubtedly, the factors determining the use of oil composite materials as building materials are the ability to source raw materials locally, the durability of the composites, their ability to be used according to their properties and their life cycle.

4. Discussion

Composites based on WCO constitute one of the applications of the latter and can serve as modern construction materials where the cement binder is replaced by WCO. The mechanical strength of oil blocks is comparable to that of traditional cement-based products; the blocks are formed by selecting appropriate values for process parameters, such as the temperature and annealing time of the material and the catalyst-to-waste oil mass ratio.

Composite materials with oil binders do not exhibit unsightly lime deposits, which is the case for materials obtained from cement. They are easily moulded into various shapes, which allows for their use in façades. Building materials employing vegetable oil or waste vegetable oil binders are environmentally friendly due to their relatively low carbon and embedded energy. The production of green materials reduces the consumption of conventional construction raw materials and is compatible with clean production and sustainable development. The technology for generating composite materials based on vegetable oil is relatively simple, requiring no specialised technical knowledge and complex apparatus facilities; it involves combining the ingredients (oil, aggregate, and an optional acid catalyst), compacting the mixture in a mould and annealing it.

Taking into account a number of advantageous features of composite materials based on WCO and the technology of obtaining them, it seems reasonable to try to introduce these materials to the construction market. In addition, the scale of the construction industry, the development of infrastructure, and the growing demand for new products provide great opportunities for the introduction of composite materials based on WCO in this sector. Building materials derived from waste cooking oil are often more sustainable and biodegradable than traditional materials. For example, some bioplastics made from waste cooking oil are biodegradable, meaning they can be broken down by natural processes and do not contribute to plastic pollution. Overall, using building materials derived from waste cooking oil can help reduce waste, lower carbon emissions, and promote sustainability in the construction industry.

5. Conclusions and Future Directions

Concerns for the environment and improving the quality of life necessitate proper waste management. This is especially important because nowadays, every human activity involves the creation of waste. For the sake of environmental protection, environmentally and economically beneficial measures should be introduced, preceded by optimization of resources, production in the construction industry, and sustainability. The introduction of new solutions in the construction sector is extremely important because the construction industry consumes more raw materials than other industrial sectors. In terms of total energy consumption, the built environment is also the largest contributor to greenhouse gas emissions. The use of waste oils in the production of building materials is in line with the principles of "green chemistry". However, despite extensive descriptions of the process of obtaining vege-blocks, comprehensive studies of their environmental safety remain of these products are lacking in the literature. WCO-based composite materials should have the following characteristics: required durability, harmless environmental impact, low economic factor in terms of raw materials and energy, and be safe in case of possible damage to human health and life. It is therefore necessary to conduct detailed studies of the environmental impact of oil blocks, the life cycle of the product, the degradability of the materials, the change in their physicochemical parameters under changing atmospheric conditions, and the leachability of the components of these materials under real-world conditions. It has become crucial to promote green building, which not only improves the quality of life but also does not degrade the planet. Environmentally friendly technologies and materials are part of sustainable construction. The introduction of new solutions and proper management of raw materials will optimize the economy and reduce the exploitation of the environment.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fuhrman, J. The Hidden Dangers of Fast and Processed Food. *Am. J. Lifestyle Med.* **2018**, *12*, 375. [CrossRef] [PubMed]
2. Wiege, B.; Fehling, E.; Matthäus, B.; Schmidt, M. Changes in Physical and Chemical Properties of Thermally and Oxidatively Degraded Sunflower Oil and Palm Fat. *Foods* **2020**, *9*, 1273. [CrossRef] [PubMed]
3. Zhang, X.; Zhang, M.; Adhikari, B. Recent developments in frying technologies applied to fresh foods. *Trends Food Sci. Technol.* **2020**, *98*, 68–81. [CrossRef]
4. Zaghi, A.N.; Barbalho, S.M.; Guiguer, E.L.; Otoboni, A.M. Frying Process: From Conventional to Air Frying Technology. *Food Rev. Int.* **2019**, *35*, 763–777. [CrossRef]
5. Panadare, D.C.; Rathod, V.K. Applications of Waste Cooking Oil Other Than Biodiesel: A Review. *Iran. J. Chem. Eng. (IJChE)* **2015**, *12*, 55–76.
6. Haq, I.U.; Akram, A.; Nawaz, A.; Zohu, X.; Abbas, S.Z.; Xu, Y.; Rafatullah, M. Comparative analysis of various waste cooking oils for esterification and transesterification processes to produce biodiesel. *Green Chem. Lett. Rev.* **2021**, *14*, 462–473. [CrossRef]
7. Mingming, H.; Quan, Z.; Sifen, W.; Guowen, Z.; Mingming, H.; Quan, Z.; Sifen, W.; Guowen, Z. Oxidative Stability of Frying Oil and Kinetics of Unsaturated Fatty Acids Oxidation under the Frying Condition of Western-style Fast Food Restaurants. *Sci. Technol. Food Ind.* **2022**, *43*, 15–22.
8. Awogbemi, O.; Onuh, E.I.; Inambao, F.L. Comparative study of properties and fatty acid composition of some neat vegetable oils and waste cooking oils. *Int. J. Low-Carbon Technol.* **2019**, *14*, 417–425. [CrossRef]
9. Yaqoob, H.; Teoh, Y.H.; Sher, F.; Farooq, M.U.; Jamil, M.A.; Kausar, Z.; Sabah, N.U.; Shah, M.F.; Rehman, H.Z.U.; Rehman, A.U. Potential of Waste Cooking Oil Biodiesel as Renewable Fuel in Combustion Engines: A Review. *Energies* **2021**, *14*, 2565. [CrossRef]
10. Awogbemi, O.; Kallon, D.V.V.; Aigbodion, V.S.; Panda, S. Advances in biotechnological applications of waste cooking oil. *Case Stud. Chem. Environ. Eng.* **2021**, *4*, 100158. [CrossRef]
11. Zaumanis, M.; Mallick, R.B.; Poulikakos, L.; Frank, R. Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100% recycled asphalt mixtures. *Comput. Chem. Eng.* **2014**, *71*, 538–550. [CrossRef]
12. Mannu, A.; Ferro, M.; Dugoni, G.C.; Panzeri, W.; Petretto, G.L.; Urgeghe, P.; Mele, A. Improving the recycling technology of waste cooking oils: Chemical fingerprint as tool for non-biodiesel application. *Waste Manag.* **2019**, *96*, 1–8. [CrossRef] [PubMed]

13. Sarno, M.; Iuliano, M.; Cirillo, C. Optimized procedure for the preparation of an enzymatic nanocatalyst to produce a bio-lubricant from waste cooking oil. *Chem. Eng. J.* **2019**, *377*, 120273. [CrossRef]
14. Salleh, W.N.F.W.; Tahir, S.M.; Mohamed, N.S. Synthesis of waste cooking oil-based polyurethane for solid polymer electrolyte. *Polym. Bull.* **2018**, *75*, 109–120. [CrossRef]
15. Pang, Y.; Zhao, Y.; Li, S.; Zhao, Y.; Li, J.; Hu, Z.; Zhang, C.; Xiao, D.; Yu, A. Engineering the oleaginous yeast *Yarrowia lipolytica* to produce limonene from waste cooking oil. *Biotechnol. Biofuels* **2019**, *12*, 241. [CrossRef]
16. Wu, B.; Sufi, A.; Ghosh Biswas, R.; Hisatsune, A.; Moxley-Paquette, V.; Ning, P.; Soong, R.; Dicks, A.P.; Simpson, A.J. Direct Conversion of McDonald's Waste Cooking Oil into a Biodegradable High-Resolution 3D-Printing Resin. *ACS Sustain. Chem. Eng.* **2020**, *8*, 1171–1177. [CrossRef]
17. Enguilo Gonzaga, V.; Romero, R.; Gómez-Espinosa, R.M.; Romero, A.; Martínez, S.L.; Natividad, R. Biodiesel Production from Waste Cooking Oil Catalyzed by a Bifunctional Catalyst. *ACS Omega* **2021**, *6*, 24092–24105. [CrossRef] [PubMed]
18. Degfie, T.A.; Mamo, T.T.; Mekonnen, Y.S. Optimized Biodiesel Production from Waste Cooking Oil (WCO) using Calcium Oxide (CaO) Nano-catalyst. *Sci. Rep.* **2019**, *9*, 1–8. [CrossRef]
19. Yu, C.W.; Bari, S.; Ameen, A. A comparison of combustion characteristics of waste cooking oil with diesel as fuel in a direct injection diesel engine. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2002**, *216*, 237–243. [CrossRef]
20. Mićić, R.; Tomić, M.; Martinović, F.; Kiss, F.; Simikić, M.; Aleksic, A. Reduction of free fatty acids in waste oil for biodiesel production by glycerolysis: Investigation and optimization of process parameters. *Green Process. Synth.* **2019**, *8*, 15–23. [CrossRef]
21. Marchetti, R.; Vasmara, C.; Fiume, F. Pig slurry improves the anaerobic digestion of waste cooking oil. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 8267–8279. [CrossRef]
22. Enderus, N.F.; Tahir, S.M. Green waste cooking oil-based rigid polyurethane foam. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *271*, 012062. [CrossRef]
23. Mamat, R.H.; Hamzah, F.; Hashim, A.; Abdullah, S.; Alrokayan, S.A.H.; Khan, H.A.; Safiay, M.; Jafar, S.M.; Asli, A.; Khusaimi, Z.; et al. Influence of volume variety of waste cooking palm oil as carbon source on graphene growth through double thermal chemical vapor deposition. In Proceedings of the 2018 IEEE International Conference on Semiconductor Electronics (ICSE), Kuala Lumpur, Malaysia, 15–17 August 2018; Institute of Electrical and Electronics Engineers Inc.: Piscatevi, NJ, USA, 2018; pp. 53–56.
24. Shen, L.; Min, F.; Liu, L.; Zhu, J.; Xue, C.; Cai, C.; Zhou, W.; Wang, C. Application of gaseous pyrolysis products of the waste cooking oil as coal flotation collector. *Fuel* **2019**, *239*, 446–451. [CrossRef]
25. Sobrinho, R.A.L.; Andrade, G.R.S.; Costa, L.P.; de Souza, M.J.B.; de Souza, A.M.G.P.; Gimenez, I.F. Ordered micro-mesoporous carbon from palm oil cooking waste via nanocasting in HZSM-5/SBA-15 composite: Preparation and adsorption studies. *J. Hazard. Mater.* **2019**, *362*, 53–61. [CrossRef] [PubMed]
26. Zheng, T.; Wu, Z.; Xie, Q.; Fang, J.; Hu, Y.; Lu, M.; Xia, F.; Nie, Y.; Ji, J. Structural modification of waste cooking oil methyl esters as cleaner plasticizer to substitute toxic dioctyl phthalate. *J. Clean. Prod.* **2018**, *186*, 1021–1030. [CrossRef]
27. Norouzi, M.; Chàfer, M.; Cabeza, L.F.; Jiménez, L.; Boer, D. Circular economy in the building and construction sector: A scientific evolution analysis. *J. Build. Eng.* **2021**, *44*, 102704. [CrossRef]
28. Al-Sabaeei, A.M.; Napiah, M.B.; Sutanto, M.H.; Alaloul, W.S.; Usman, A. A systematic review of bio-asphalt for flexible pavement applications: Coherent taxonomy, motivations, challenges and future directions. *J. Clean. Prod.* **2020**, *249*, 119357. [CrossRef]
29. Zhang, X.; Zhang, K.; Wu, C.; Liu, K.; Jiang, K. Preparation of bio-oil and its application in asphalt modification and rejuvenation: A review of the properties, practical application and life cycle assessment. *Constr. Build. Mater.* **2020**, *262*, 120528. [CrossRef]
30. Luo, Y.; Zhang, K. Review on Performance of Asphalt and Asphalt Mixture with Waste Cooking Oil. *Materials* **2023**, *16*, 1341. [CrossRef]
31. Azahar, W.N.A.W.; Jaya, R.P.; Hainin, M.R.; Bujang, M.; Ngadi, N. Chemical modification of waste cooking oil to improve the physical and rheological properties of asphalt binder. *Constr. Build. Mater.* **2016**, *126*, 218–226. [CrossRef]
32. Eriskin, E.; Karahancer, S.; Terzi, S.; Saltan, M. Waste frying oil modified bitumen usage for sustainable hot mix asphalt pavement. *Arch. Civ. Mech. Eng.* **2017**, *17*, 863–870. [CrossRef]
33. Wang, C.; Xie, T.; Cao, W. Performance of bio-oil modified paving asphalt: Chemical and rheological characterization. *Mater. Struct. Constr.* **2019**, *52*, 1–13. [CrossRef]
34. Elahi, Z.; Jakarni, F.M.; Muniandy, R.; Hassim, S.; Ab Razak, M.S.; Ansari, A.H.; Ben Zair, M.M. Waste cooking oil as a sustainable bio modifier for asphalt modification: A review. *Sustainability* **2021**, *13*, 11506. [CrossRef]
35. Peñaloza, D.; Vásquez, D.; Valdivieso, V.; Jaramillo, Y.; Plata, V.; Moreno, P. Theoretical analysis of waste cooking oil rejuvenator in reclaimed asphalt for sustainable hot asphalt mix preparation at the Área Metropolitana de Bucaramanga. *DYNA* **2022**, *89*, 79–87. [CrossRef]
36. Ramadhansyah, P.J.; Masri, K.A.; Wan Azahar, W.N.A.; Mashros, N.; Norhidayah, A.H.; Mohd Warid, M.N.; Satar, M.K.I.M.; Yaacob, H. Waste Cooking Oil as Bio Asphalt Binder: A Critical Review. In *IOP Conference Series: Materials Science and Engineering*; Institute of Physics Publishing: Bristol, UK, 2020; Volume 712, p. 012040.
37. Lligadas, G.; Ronda, J.C.; Galià, M.; Cádiz, V. Renewable polymeric materials from vegetable oils: A perspective. *Mater. Today* **2013**, *16*, 337–343. [CrossRef]
38. Cherubini, V.; Lamastra, F.R.; Bragaglia, M.; Nanni, F. Waste cooking oils as processing aids for eco-sustainable elastomeric compounding. *Prog. Rubber Plast. Recycl. Technol.* **2022**, *38*, 3–20. [CrossRef]

39. Rus, A.Z.M.; Salim, N.S.M.; Sapiee, N.H. Recycling of Cooking Oil Waste into Reactive Polyurethane for Blending with Thermoplastic Polyethylene. *Int. J. Polym. Sci.* **2015**, *2015*, 829795. [CrossRef]
40. González Peña, O.I.; López Zavala, M.Á.; Cabral Ruelas, H. Pharmaceuticals market, consumption trends and disease incidence are not driving the pharmaceutical research on water and wastewater. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2532. [CrossRef]
41. Sarmiento, A.M.; Guzmán, H.L.; Morales, G.; Romero, D.E.; Pataquiva-Mateus, A.Y. Expanded Polystyrene (EPS) and Waste Cooking Oil (WCO): From Urban Wastes to Potential Material of Construction. *Waste Biomass Valorization* **2016**, *7*, 1245–1254. [CrossRef]
42. Vitrone, F.; Ramos, D.; Ferrando, F.; Salvadó, J. Binderless fiberboards for sustainable construction. Materials, production methods and applications. *J. Build. Eng.* **2021**, *44*, 102625. [CrossRef]
43. Ibrahim, Z.; Aziz, A.A.; Ramli, R.; Mokhtar, A.; Omar, R.; Lee, S. Production of Medium Density Fibreboard (MDF) from Oil Palm Trunk (OPT). *J. Appl. Sci.* **2014**, *14*, 1174–1179. [CrossRef]
44. Bajraktarova-Valjakova, E.; Grozdanov, A.; Guguvcevski, L.; Korunoska-Stevkovska, V.; Kapusevska, B.; Gigovski, N.; Mijoska, A.; Bajraktarova-Misevska, C. Acid Etching as Surface Treatment Method for Luting of Glass-Ceramic Restorations, part 1: Acids, Application Protocol and Etching Effectiveness. *Open Access Maced. J. Med. Sci.* **2018**, *6*, 568–573. [CrossRef] [PubMed]
45. Fernandes, F.C.; Kirwan, K.; Wilson, P.R.; Coles, S.R. Sustainable Alternative Composites Using Waste Vegetable Oil Based Resins. *J. Polym. Environ.* **2019**, *27*, 2464–2477. [CrossRef]
46. Kevern, J. Using Soybean Oil to Improve the Durability of Concrete Pavements. *Int. J. Pavement Res. Technol.* **2010**, *3*, 280–285.
47. Han, M.-C.; Woo, D.-H. Effect of Waste Cooking Oil on Durability of High Volume Mineral Admixture Concrete. *J. Korean Recycl. Constr. Resour. Inst.* **2013**, *1*, 173–180.
48. Khidzir, A.B.M.; Zakaria, C.; Yap, K.W.; Kamal, N.; Beddu, S.; Talib, S.H.A. The Performance of Concrete Containing Used Cooking Oil. *Engineering* **2015**, 65–70. [CrossRef]
49. Adebayo, J.O.; Napiah, M.; Ibrahim, K.; Raduan Kabit, M. Evaluation of Waste Cooking Oil as Sustainable Binder for Building Blocks. *E3S Web Conf.* **2018**, *65*, 05003. [CrossRef]
50. Staroń, A.; Papla, A.; Midura, A.; Kijania-Kontak, M.; Świergosz, T.; Banach, M. Physicochemical properties, strength and phytotoxicity of building blocks with waste cooking oil as binder. *J. Clean. Prod.* **2022**, *335*, 130316. [CrossRef]
51. Wei Ping, T.; Swee Yong, C.; Zainab Habib, N.; Choon Auna, N. An Attempt to Maximize the Use of Used Cooking Oil and Fly Ash in the Production of Green Roofing Tile. *Int. J. Sustain. Constr. Eng. Technol.* **2022**, *13*, 273–281. [CrossRef]
52. Teoh, W.P.; Chee, S.Y.; Habib, N.Z.; Bashir, M.J.K.; Chok, V.S.; Ng, C.A. Chemical investigation and process optimization of glycerine pitch in the green production of roofing tiles. *J. Build. Eng.* **2021**, *43*, 102869. [CrossRef]
53. Nadeem, H.; Habib, N.Z.; Aun, N.C.; Zoorob, S.E.; Mustaffa, Z.; Nadeem, S. Production of environmentally friendly roofing tiles using palm oil as a binder. *Green Mater.* **2017**, *5*, 135–143. [CrossRef]
54. Zhang, D.; Zhang, T.; Yang, Q. Mechanical Properties and Damage Layer Thickness of Green Concrete under a Low-Temperature Environment. *Materials* **2022**, *15*, 7409. [CrossRef] [PubMed]
55. Sam, S.S.; Habib, N.Z.; Aun, N.C.; Yong, C.S.; Bashir, M.J.K.; Ping, T.W. Blended waste oil as alternative binder for the production of environmental friendly roofing tiles. *J. Clean. Prod.* **2020**, *258*, 120937. [CrossRef]
56. Sam, S.S.; Habib, N.Z.; Aun, N.C.; Yong, C.S.; Ching, F.Y. Encapsulation of the oil-starch binder for the production of decorative floor tiles. *Proc. Inst. Civ. Eng. Waste Resour. Manag.* **2019**, *172*, 102–106.
57. Staroń, A.; Kijania-Kontak, M.; Kozak, A.; Banach, M. Obtaining of oil blocks as a way to manage hazardous asbestos. *Waste Manag.* **2020**, *105*, 180–189. [CrossRef]
58. Schuchardt, U.; Sercheli, R.; Vargas, R.M. Transesterification of vegetable oils: A review. *J. Braz. Chem. Soc.* **1998**, *9*, 199–210. [CrossRef]
59. Boffito, D.C.; Pirola, C.; Galli, F.; Di Michele, A.; Bianchi, C.L. Free fatty acids esterification of waste cooking oil and its mixtures with rapeseed oil and diesel. *Fuel* **2013**, *108*, 612–619. [CrossRef]
60. Mazubert, A.; Aubin, J.; Elgue, S.; Poux, M. Intensification of waste cooking oil transformation by transesterification and esterification reactions in oscillatory baffled and microstructured reactors for biodiesel production. In *Green Processing and Synthesis*; Walter de Gruyter GmbH: Berlin, Germany, 2014; Volume 3, pp. 419–429.
61. Johnson, O.A.; Madzlan, N.; Kamaruddin, I. Encapsulation of petroleum sludge in building blocks. *Constr. Build. Mater.* **2015**, *78*, 281–288. [CrossRef]
62. Khor, Y.P.; Hew, K.S.; Abas, F.; Lai, O.M.; Cheong, L.Z.; Nehdi, I.A.; Sbihi, H.M.; Gewik, M.M.; Tan, C.P. Oxidation and Polymerization of Triacylglycerols: In-Depth Investigations towards the Impact of Heating Profiles. *Foods* **2019**, *8*, 475. [CrossRef] [PubMed]
63. Gomna, A.; N'Tsoukpoe, K.E.; Le Pierrès, N.; Coulibaly, Y. Review of vegetable oils behaviour at high temperature for solar plants: Stability, properties and current applications. *Sol. Energy Mater. Sol. Cells* **2019**, *200*, 109956. [CrossRef]