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# Advances in the Sustainable Development of Biobased Materials Using Plant and Animal Waste as Raw Materials: A Review

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**Abstract:** There is substantial concern about critical environmental problems related to waste in production sectors such as textile, construction, and packaging. The materials ascribed to the sector's unsustainability are primarily fabrics, plastic, and hazardous solvents, making developing new biobased materials imperative. As such, various strategies have been investigated to convert and recycle waste and give them commercial value via the manufacture of biobased materials. This review discusses the various types of raw materials as sources to develop new biobased materials that could promote the transition toward sustainability. According to the literature, the functional qualities of biobased materials are comparable to those of synthetic materials. Raw material sources such as biomass, derived from plant and animal-based waste, are attractive due to their low cost, abundance, and biodegradability. The manufacture of biomaterials, as well as their characterization and performance, are also discussed. Further, this review will offer a comprehensive view of the potential applicability and current commercial applications of the developed biobased materials in relevant areas such as packaging, construction, textile, and wastewater remediation. This could be a potential field of research to address the environmental challenges posed by the continuous growth of the global population.

**Keywords:** biobased materials; sustainable design; environmentally friendly materials; waste valorization; plant-based; animal-based; biomass

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**Citation:** Salazar Sandoval, S.; Amenábar, A.; Toledo, I.; Silva, N.; Contreras, P. Advances in the Sustainable Development of Biobased Materials Using Plant and Animal Waste as Raw Materials: A Review. *Sustainability* **2024**, *16*, 1073. https://doi.org/10.3390/su16031073

Academic Editors: Harshit Mahandra, Farzaneh Sadri and Monu Malik

Received: 28 November 2023
Revised: 22 January 2024
Accepted: 24 January 2024
Published: 26 January 2024

## 1. Introduction

A combination of factors between resource depletion, climate change, environmental pollution, health problems, and increased public awareness and regulation has compelled society to change its approach toward waste generation and adopt more sustainable practices, such as reuse, to address these challenges more effectively [1–3]. In this context, the textile, construction, and packaging industries face pressure to reduce the environmental impacts associated with their highly demanded production processes. For instance, the textile sector is known for using toxic chemicals in tanning, which not only presents a considerable burden on water sources but also involves animal cruelty [4,5]. Furthermore, concerns arise from wastewater released by the textile production sector, which also contains microplastics. The presence of microplastic fibers in the environment lacks sufficient regulation [6,7]. Similarly, the food packaging industry, reliant on petrochemicals, raises environmental concerns due to plastic packaging waste and the use of hazardous, non-biodegradable materials [8,9]. Moreover, the packaging sector contributes to almost 50% of global plastic waste, eventually disposed of in landfills or incinerated rather than being recycled [10,11]. The construction sector contributes to the depletion of raw materials and natural resources, thus having a prominent impact on the ecosystems and consuming high amounts of energy during the process [12,13]. Whereas concrete is a significant contributor to construction, its industry needs burning fuel or chemical processes, which account for greenhouse gas emissions (50% of the $CO_2$ produced worldwide comes from the construction sector). Furthermore, the construction sector promotes the propagation of respirable microparticles ($PM_{10}$, $PM_{2.5}$, and $PM_1$) [14]. Such microparticles can reach the respiratory tract and cause severe health issues and diseases that might appear years later [15,16]. The development of wastewater treatment methods is also an active area of research; however, the technologies used to eliminate pollutants have also proven to be limited in terms of their cost, complexity, efficiency, and environmental impact [17]. Conventional wastewater treatment methods such as adsorption, oxidation, and membrane separation have drawbacks: they are non-selective, expensive to regenerate, and consume an enormous amount of energy [18].

The transition toward more sustainable and less wasteful processes becomes critical in integrating the circular economy concept. The circular economy is a production and consumption model that emphasizes the design of systemic solutions to connect the value chains of productive ecosystems. The circular design approach involves reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended, reducing waste to a minimum and making the most of resources. Promoting circular economies not only benefits the environment and improves the quality of life for present and future generations but also presents economic opportunities [19–22]. In this context, research and development efforts in the field of waste-based biomaterials are key enablers for sustainable circular design by transforming undesired by-products into valuable materials for other industries, therefore closing the loop.

A widely recognized example is the production of Polylactic acid (PLA), a key material for many industries, generated from corn residues [23]. PLA-based polymers exhibit strong heat resistance and mechanical strength, making them a more environmentally friendly alternative to synthetic plastic in packaging applications. Furthermore, a variety of thermal insulator materials obtained from agricultural residues have been utilized. Materials constructed from chicken feathers and wood waste have been used to replace conventional ones like glass wool and polyurethane foams [24].

As eco-friendly technologies become increasingly favored due to consumer preferences, the term ‘biobased material’ has gained prominence in research. A material is considered biobased if it primarily consists of elements derived from plants or animals. The term refers to materials resulting from the manufacture of plant or animal biomass with potential uses in construction, fabric, or packaging [25–29]. When the primary component of the biobased material originates from biological waste, it significantly contributes to the sustainable economy by reducing dependence on non-renewable resources and promoting responsible waste management [30–33].

This review compiles data regarding diverse biobased materials, which are fabricated using plant and animal waste as their raw material. It provides a detailed overview of the entire generation route, encompassing waste pretreatment, the manufacture of biobased materials, their comprehensive characterization, property assessment, and their principal applications. In addition, an exploration of close-to-market and current commercial applications of waste-based raw materials is also covered in this review.

We focused on the last ten years of progress in the development and manufacture of products using plant or animal waste as raw materials, as well as their feasibility as potential tools for packaging, construction, textile, and wastewater remediation applications. The following scientific databases were searched for literature: PubMed, Web of Science, and Scopus. Furthermore, the keywords “biobased materials, raw materials, plant waste, animal waste, sustainability” were used. In addition, this review aims to analyze the research areas responsible for producing biobased materials to understand the impact on the progression of sustainable design.

## 2. Waste as Raw Materials to Develop a Biobased Material

As previously described, a biobased material refers to a product primarily composed of organic sources. Raw materials used to develop biobased materials originate from two sources: plant-based and animal-based. Utilizing waste from these sources offers the advantage of deriving materials from renewable resources. Co-products from industries like agriculture, wool, or food that might otherwise become waste can be valorized by using them as raw materials for manufacturing biobased materials. This approach could reduce the burden associated with residue management, presenting itself as an environmentally friendly alternative. Further, the benefits of incorporating plant or animal-based waste as components are well documented [34–36].

For instance, their biodegradability in diverse natural environments provides them with an advantage over petroleum-based substrates. Composites derived from waste such as sheep wool, peels, or seeds have evidenced biodegradability upon 90 days in soil [37–39]. Due to their mechanical strength and high elastic modulus due to their inherent crystallinity, plant and animal-based materials have promising potential as reinforcement fillers for diverse commercial applications [40–42]. These materials can also be formulated as gels or films for insulation or coating, as proven by the valorization of coconut, shrimp, pea, or quinoa waste [43–47].

### *2.1. Plant-Waste as Raw Materials for Biobased Materials*

Using plant-derived waste as raw materials is prevalent since many compounds, such as peels, fruits, leaves, seeds, or kernels, are not usually valorized and end up in landfills. As a result of their sustainability and low toxicity, plant-based substrates are extensively studied [48,49]. Further, valuable components in plant-based waste, such as polysaccharides, oils, proteins, and anti-oxidants, can be used as precursors or additives to obtain materials with improved mechanical and thermal properties [50]. A variety of plant sources have been explored or valorized as precursors for developing biobased materials. These include but are not limited to seeds (mango seed, rice husk, peas, citrus seed, hemp, flax, jute), cereals (rice, straw, cob, corn), peels (banana peel, orange peel, lemon peel, potato skin, garlic peel, jackfruit peel), and leaves (cactus leaves, orange leaves, pineapple leaves, green tea leaves) [50–52]. Studies have also examined the potential of flower waste from species such as *Hibiscus Sadbariffa*, *Thespesia Populnea*, *Juncus Acutus*, *Frucrarea*, *Sansevieria Trifasceata*, *Cereus*, *Curaurá* fiber, *Leucas Aspera*, and *Catharanthus Roseus* for producing sustainable biobased materials [53,54].

### *2.2. Animal-Waste as Raw Materials for Biobased Materials*

Although not as extensively explored as plant-derived substrates, which constitute the larger portion of global waste (63% being plant-based compared to animal-derived waste) [55,56], studies have also delved into the utilization of animal-based waste as renewable raw materials. Notably, materials sourced from natural aquatic resources such as crab shells, crude seashells, lobster shells, fish skin, or fish bones show significant potential. These marine animal-based raw materials have been reported to be unique in their chemical composition, biocompatibility, and durability [57,58]. As a result, these animal-based substrates have been used in packaging as pure or combined films [59,60] or in the production of adsorbents with high surface areas and porosity [61]. Conversely, agricultural animal waste, including wool, hair, or feathers, is also considered valuable in fibrillar proteins and oligopeptides [62,63]. Agricultural animal-waste has been asserted to produce raw materials exhibiting greater tensile strength and toughness than plant-based sources, making them suitable for building or reinforcement applications [64–66]. Despite the various disposal methods available for animal by-products, incineration and landfilling remain prevalent. However, these methods pose challenges such as pathogen spread and environmental pollution. Thus, recycling animal waste as a means of valorization for developing novel biobased materials becomes imperative.

## 3. Manufacture of Biobased Materials

Biobased materials can be used in various applications, including textile, packaging, building, or wastewater remediation. The chosen raw material and formulation of the biobased material will depend on such application. For example, a developed biomaterial with a potential application in construction should provide certain structural, thermal, and mechanical functions [67]. A viable biobased packaging or film requires biodegradability, in addition to elasticity, low permeability, and appropriate mechanical and anti-bacterial features [68]. Biobased textile design ought to produce structures comparable or superior to synthetic fibers in terms of durability, elasticity, softness, and end-of-life recyclability [69]. In contrast, a biomaterial aimed to remediate wastewater is preferred to feature high porosity and low solubility in water to envision the possibility of a reutilization cycle of said material [70]. In that regard, the pretreatment of the raw material and the manufacturing methods for biobased materials will impact its properties.

Figure 1 summarizes the generation route of a biobased material, starting with the pretreatment of the raw material (whether it is a plant or animal-based raw material), the manufacture of the biobased material, its characterization and performance, and finally, its potential application.

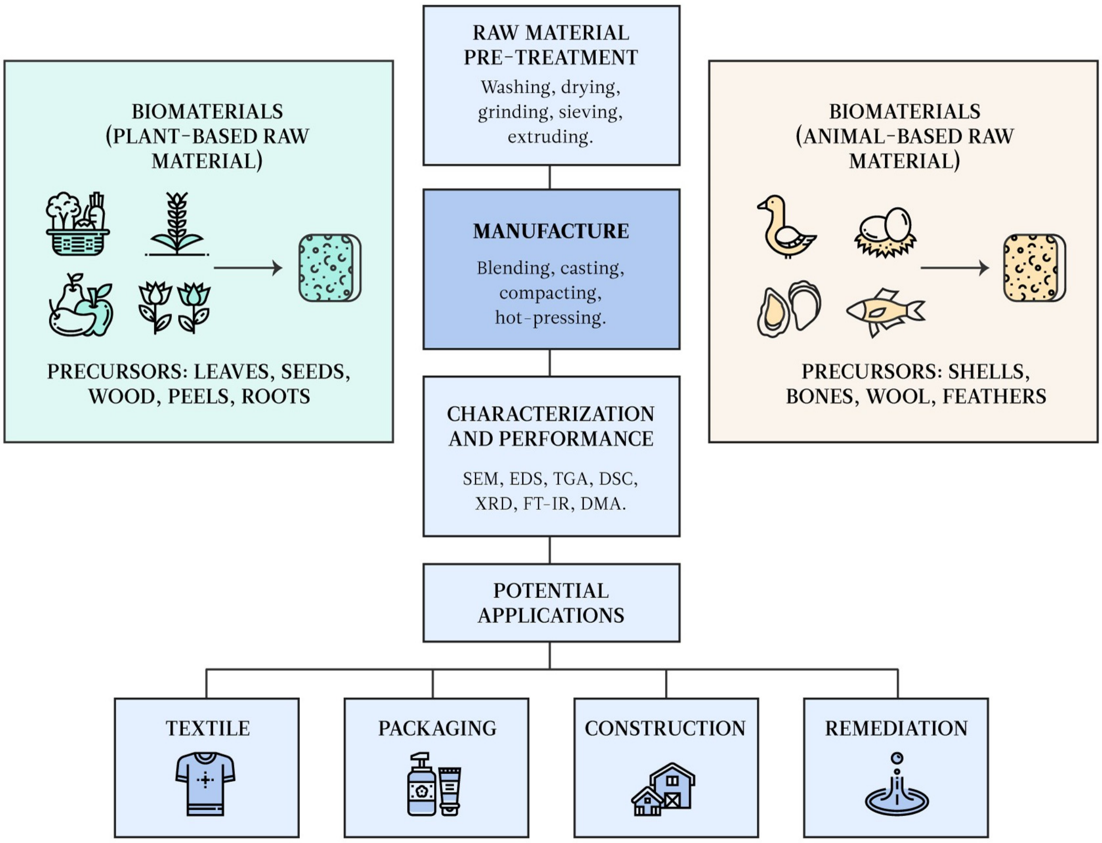

**Figure 1.** Generation route, characterization techniques, and potential applications of biobased materials using plant or animal waste as precursors.

### *3.1. Pretreatment of the Raw Materials*

The starting plant-based or animal-based raw material usually requires pretreatment before being subjected to the manufacturing process to obtain a biobased material. If the pretreatment of the raw material is not carried out properly, that could impact the final product's quality. Different pretreatment methods are based on physical, biological, or chemical principles, depending on the envisioned application for the biobased material.

Regardless of the characteristics and origin of the pristine raw material, the pretreatment can consist of washing, drying, grinding, sieving, extruding, extracting, or bleaching processes.

Raw materials are washed during the pretreatment to remove soil, dirt, stains, or other impurities. The washing procedure is usually performed in a deionized or distilled water bath. However, in the case of animal-based waste, the washing process is carried out thoroughly with NaOH, HCl, ethanol, or detergent solutions to deodorize or decolorize the raw material [71,72].

An essential pretreatment method involves drying the raw material to achieve the desired moisture content. Plant and animal-based raw materials often have humidity values exceeding 60%, which can complicate the manufacturing process, particularly if subsequent grinding or sieving processes are required. Further, residual moisture can promote microbial activity in the starting material. Depending on the raw material and its desired moisture content, the drying process can be carried out in a wide range of temperatures, varying from 40 to 200 °C. For example, among the tested temperatures for biobased materials preparation with wool as raw material, 150 °C seemed the most appropriate without compromising its physicochemical properties [64,73]. In contrast, coconut fibers displayed better results when dried at 100 °C. It is noteworthy that the drying temperatures can impact the properties of the biobased material, such as its durability or density [43,74].

Grinding is attained as a pretreatment method if a determined size distribution or homogeneity of the raw material is required. Further, the grinding parameters can be optimized to obtain a specific size range of the starting material. For instance, chipping is a grinding technique that provides final particle sizes in the cm range. In contrast, ultra-fine grinding is employed to achieve precursors with an average size of less than 30 μm. Additionally, grinding processes can be followed by sieving to separate the precursors from agglomerates or impurities and to verify the uniformity of particle sizes to the raw material [40,75,76].

Extrusion is a pretreatment procedure that involves breaking the structure of the precursors via a combination of heat and mass transfer within a container or reactor, followed by compression to remove impurities. The effectiveness of this pretreatment method has been evaluated in terms of different parameters, such as the temperature of the container (°C), the screw speed (rpm), the moisture content of the raw material (%), and its particle size (mm) [77,78].

If a specific component is of utmost relevance to developing the biobased material, separation techniques are performed as pretreatment (often referred to as extraction or mercerization). Mercerization has also been utilized to improve the mechanical properties of raw materials by alkaline-induced chemical changes. Extraction methods have proven to be effective in obtaining carbohydrates, oligomers, and fibers. The raw material is treated in an autoclave with controlled pressure and temperature, usually under sodium hydroxide (NaOH 3–5% $v/v$) or oxalic acid ($C_2H_2O_4$, 3–5% $v/v$) to provide alkaline or acidic conditions, respectively [79,80]. However, hot water extraction has also shown promising results as a more sustainable method [81]. If acid or alkaline treatment is conducted, the raw materials are cleaned thoroughly with distilled water to remove impurities and the residual acid or base.

Impurities might remain in the significant components after performing an extraction method. The raw material can be bleached in that scenario to obtain a higher-purity raw material. Bleaching sequences often occur in $Cl_2$, NaClO, $O_3$, or $H_2O_2$ [46,82]. However, due to its environmental impact, there is an increasing focus on developing green alternatives that do not involve bleaching.

The advantages and disadvantages of the different pretreatment methods are emphasized in Table 1.

**Table 1.** Related advantages and disadvantages of different pretreatment methods when manufacturing a biobased material.

| Pretreatment | Advantages | Disadvantages or Limitations | References |
|---|---|---|---|
| Washing | Removes impurities from the raw material. Reduces microbial load | Large amount of solvents are needed | [71,72] |
| Drying | Reduces moisture content. Improves mechanical performance | Can require extended heating periods | [73,74] |
| Grinding | Conversion of raw materials into fine powders (cm-µm size range) | High energy consumption | [75] |
| Sieving | Separates raw material from agglomerates. Provides uniform particle size distribution | Inefficient for separating wet materials or particles with similar sizes | [76] |
| Extruding | Increases mechanical and thermal resistance. Removes impurities. Solvent-free process. | Depending on the raw material, different process conditions must be tested | [77,78] |
| Extracting | Isolation of specific components. Improves wettability and mechanical properties. Provides a rough surface | Needs extensive washing with water afterward. Chemical residues might require neutralization | [79,80] |
| Bleaching | Removes impurities and pathogens. Improves appearance and mechanical performance | Requires high amounts of water, energy, and solvents | [82] |

### *3.2. Manufacturing the Biobased Materials*

After the pretreatment of the raw materials, the manufacturing process for biobased materials varies according to their intended application. Products derived from plant or animal waste-based raw materials are often enhanced by incorporating additional precursors to meet the stringent requirements for packaging, construction, textile, or wastewater remediation applications. As pristine raw materials may possess limitations in mechanical or physicochemical properties, the development of biobased materials often involves the inclusion of other precursors or additives, such as plasticizers or emulsifiers, resulting in a notable improvement in the final product's performance. Glycerol and sorbitol are two of the most utilized plasticizers since they can be recycled from the biodiesel sector. Furthermore, different glycerol or sorbitol concentrations have a significant impact on the water absorption, tensile strength, flexibility, and thickness of biobased products [43–45].

The fabrication of biobased packaging materials follows several principles, including the creation of layers or sheets via casting, layer-by-layer assembly, blending, or electrospinning methods [83,84]. Depending on the chosen procedure, layers with varying thicknesses and mechanical properties can be produced. Additives can be introduced during manufacture to enhance tensile strength and reduce brittleness.

Examples of biobased packaging are an edible coating made from orange tree leaves and the preparation of films made from crab and fish skins. Alparslan et al. used orange leaf waste and a blending method for the edible coating [47]. Pretreated orange leaves were blended with gelatin to hinder microbial growth. The composite was stirred to form a coating solution, further stabilized with glycerol/sorbitol, and homogenized using a blender. Polyvinyl alcohol (PVA)/crab waste films were also prepared using blending methods [60]. PVA was homogenized in distilled water. Then, different amounts of pretreated crab shell waste were mixed with the PVA solution while constantly stirring. The composites were sonicated before being put into Petri dishes and allowed to dry at room temperature. Arfat et al. reported the preparation of a film using fish skin waste using the casting method [85]. In summary, fish skin powder (generated during pretreatment) was mixed with glycerol as a plasticizer. The mixture was stirred, homogenized under high pressure, degassed, cast onto a silicon resin plate, and dried in an environmental chamber.

Biobased materials are extensively researched for construction applications, where the addition of binding materials has been noted to enhance their mechanical properties and durability [86]. Common manufacture methods of biobased materials for building applications are moistening the raw material, mixing it with a binder for mechanical performance (lime or gypsum), and finally, filling a mold with the desired dimensions. Compression techniques, such as hot-pressing or compaction, are applied during manufacturing when a thermoplastic matrix is necessary.

A composite film for building refurbishment was developed using rice husk as the raw material [87]. Gypsum acted as the primary stabilizer, while air lime was employed to slow the hardening process and prevent bacterial growth. Dry components were manually mixed and then homogenized with water, followed by mechanical blending without resting periods due to the rapid hardening of gypsum. Once a homogeneous consistency was attained, the composite was cast onto a metallic mold, left to dry at 25 °C, and demolded after two weeks before testing.

Building blocks derived from chicken feather waste were created by mixing dried feathers with gypsum plaster at different mass fractions, limited to 5% *wt.*, to maintain composite workability [88]. Water was added under manual agitation to prevent hardening. The mixture was poured into metal molds and dried in an oven for 1 h.

A Kevlar/coconut sheath matrix was fabricated via layer-by-layer assembly followed by hot pressing [89]. The composites were developed with different weight ratios and stacking sequences. Graphene nanoplatelets (GNPs) were added to the composite as an alternative to gypsum and lime to improve mechanical strength and interlaminar shear behavior. Increasing concentrations of GNPs (up to 0.75% *wt.*) were sonicated into the Kevlar/coconut sheath composite.

The manufacture of biobased materials for potential applications in the textile industry has been extensively documented [90]. This process is reported to ensure the quality of the developed fabric while optimizing the recovery of raw materials, thus minimizing energy consumption and preventing the use of hazardous chemicals. The production of biobased textiles consists of forming a sheet obtained from the raw material, which is mixed with a plasticizer (usually glycerol; water can also be used as a plasticizer, but it compromises the tensile strength of the fabric). These agents allow melt processing and enhance the flexibility of the biobased material. Laminated fabric derived from hemp, flax, and jute waste was processed by Chaudhary et al. [91]. First, the composite was fabricated, with a weight percentage of 25% from each biobased component, with an epoxy resin used as a matrix making up the final 25% of the weight. Then, a silica release gel was sprayed on a mold surface to prevent the resin from sticking. The composite was spread on the mold surface, and then a laminate was formed using a metallic roller. The laminate was cured and then removed from the mold.

The effects of chemical and mechanical manufacture methods on the properties of banana peel waste were studied [82]. The selected method would be determined by the intended application of the biobased material. In the chemical method, after mercerization with NaOH (0.5% *wt.*), the pretreated banana peels were deposited in a $Na_3PO_4$/EDTA mixture for 4 h. Two different conditions were tested: immersion at room temperature and immersion in a water bath. The morphological and mechanical characterization of the chemically treated banana peels revealed the formation of a rougher, fibrillated surface, which would be better suited for textile applications. On the other hand, mechanical manufacturing consisted of using a decorticator to remove the layers on the surface of the peels, washing the product with distilled water, and drying it for 2 h. The mechanically processed banana peels had a greater lignin concentration, which supports their potential use as composite reinforcement.

The reinforcement of textiles using sheep wool waste as raw material has also been reported [42]. Laminated composites were created by combining sheep wool with epoxy resins via melt consolidation at 180 °C. The pretreatment steps of wool waste are crucial, as they contain natural grease, dirt, and dust that must be removed for quality composite manufacturing. Different fabric types can be derived from wool waste, depending on the manufacturing technique used, such as weaving or knitting methods. Further, a water insulator, such as stearic acid, can be added to the fabric's surface during manufacturing to prevent undesired effects related to water contact [92].

Biobased materials for wastewater remediation can be readily used as the fine powder obtained from the pretreatment methods previously described. Nag et al. demonstrated the preparation of biosorbents based on jackfruit, mango, bamboo, garlic, onion, and coconut waste, which were washed, dried, and ground without further manipulation [93]. Shrimp shell waste was used to generate a mesoporous sorbent [94]. After acid (HCl 5% *wt.*) and alkaline (NaOH 0.5% *wt.*) pretreatment, the resultant product was washed with distilled water, dried, ground, and utilized in As (V) adsorption tests.

Other studies propose additional processing of cactus powder by dissolving salt solutions or organic solvents during manufacturing to produce a biobased sorbent material in a mucilage form [95]. The use of salt solutions over organic solvents is encouraged to reduce the environmental impacts. The activity of the mucilage as an adsorbent or flocculant agent depends on its preparation method. In the case of plant-based adsorbents, it has been reported that drying the biobased material over 120 °C negatively impacts its ability as a flocculant or adsorbent [96].

Moreover, incorporating precipitation or lyophilization into the raw material manufacturing process can yield a purer powder filtrate.

## 4. Characterization Techniques and Performance of the Biobased Materials

### 4.1. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)

SEM is used to observe the surface morphologies of synthesized biobased materials at different magnifications. SEM micrographs can reveal the nature of the surface, whether it is rough, porous, or smooth. Further, SEM analyses can be performed to ascertain changes in the surface of the raw material during manufacturing (for example, the effect of temperature), to differentiate the components of the biobased material, or as an indicator of the presence of impurities. The morphology of the biobased material would depend on its precursors and its envisioned application. Biobased materials developed for textile applications display fibrous structures. Samples fabricated for packaging and construction applications are expected to be intact, with no signs of cracking, brittleness, or fracture on their surface. In cementitious composites for construction applications, SEM can demonstrate biomaterial-cement adhesion using surface analysis, identifying grains and elements associated with mineralization fibers. The manufactured biomaterials feature porous or rough surfaces in wastewater remediation, which is attributed to increased removal efficiencies. SEM micrographs can also illustrate structural changes in the biomaterial after exposure to water, light, or deformation.

EDS is used as a semi-quantitative technique to determine the biomaterial's elemental composition. EDS and elemental mapping provide information on the elements present on the biobased material's surface. Due to the organic nature of the raw materials, C and O are predominant in the total elemental weight of the samples, encompassing over 80% of the elemental composition. However, minor peaks corresponding to Si, K, Mg, S, Ca, and Al have also been identified, primarily when the biobased material consists of a composite [60,97]. Moreover, EDS spectra prior to and after adsorption experiments can show peaks ascribed to a specific pollutant (Cr, Cd, Hg), further confirming its interaction with biobased materials used for wastewater remediation [96,98,99].

### 4.2. Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC)

The manufactured biobased material's decomposition, oxidation, volatility, and thermal stability can be ascertained using TGA and DSC analyses. Changes in the physicochemical properties of the products can be observed upon exposure to an increase in temperature related to weight loss. The thermograms usually display mass loss at 100 °C, which is related to the humidity and presence of water in the samples. Further mass changes indicate the biomaterial's degradation, which can determine if the biobased material is suitable for thermally sensitive applications. Understanding degradation profiles also aids in assessing thermal enhancements when incorporating specific components into composite development. Reported main composition temperatures fall within the range of 250–400 °C [46,100]. TGA thermograms can be supported by DSC analysis. The decomposition events observed in DSC thermograms are associated with phase transition temperatures of the biobased materials. Water evaporation at 100 °C is also perceptible in the DSC thermal profiles. Moreover, the endothermic peaks in the samples can be attributed to the degradation or denaturation of the components present in the biomaterial, observed at temperatures over 350 °C, consistent with the information provided by TGA [60,101].

### *4.3. Fourier Transform Infrared Spectroscopy (FT-IR)*

FT-IR spectra provide insight into the chemical changes present in the raw material upon manufacturing the biobased product, specifically in their functional groups. Further, differences in the intensity or position of some stretching or bending bands allow us to infer structural changes in the biobased material compared to the raw material. As carboxylic acids, alcohols, and amines are ubiquitous functional groups present in plant or animal-based raw materials, stretching vibrations associated with a C=O group (1700 $\text{cm}^{-1}$), N-H bond (1550 $\text{cm}^{-1}$) and O-H bond (3500 $\text{cm}^{-1}$) are usually identified in the FT-IR spectrum. Due to the organic nature of the materials, stretching peaks associated with C-H bonds (2850 $\text{cm}^{-1}$) are also prominent. The presence of a specific bond can contribute to the durability of the materials, such as disulfide bonds; therefore, identifying such stretching peaks (1000–1300 $\text{cm}^{-1}$) is relevant when characterizing the biobased product, especially in construction, textile, or packaging applications. The absence or appearance of specific peaks can also be observed upon manufacturing, ascribed to bond breakages and new bond formation during the process.

### *4.4. X-ray Photoelectron Spectroscopy (XPS)*

XPS is a surface-sensitive analytical characterization tool that can be used to examine structural changes in raw materials after they have been processed to produce the desired biobased product. The deconvolution of high-resolution spectra can reveal the chemical composition of the biobased material surface as well as the binding state of these elements. Due to the organic nature of the plant and animal-based starting materials, high-resolution C 1s spectra are prominent, displaying peaks in the range of 285–288 eV, which are consistent with C-C, C-H, C-N, C-O-C, and C=O binding energies. These distinct peaks can be attributed to ester, carboxylic acids, and amines that are inherent to the structure of biobased materials. The appearance of additional peaks after processing the raw materials can be assigned to new linkages due to the incorporation of binding agents or the formation of new structures in the biobased product.

As XPS spectra characterize the surface of the biobased material, information regarding adsorption behavior can also be obtained. Signals corresponding to Pb 4f (139 eV) and Cd 3d (405 eV) were observed after their adsorption [75]. Further, the deconvolution of O 1s (531–533 eV range) and N 1s (400–403 eV range) spectrum revealed the involvement of amine, hydroxyl, and ester groups in the removal of the heavy metals via the formation of coordination bonds [98].

### *4.5. X-ray Powder Diffraction (XRD)*

XRD is a non-destructive technique used to ascertain crystallographic information of the manufactured biobased materials. The diffraction patterns of the raw material can be compared with those of the biobased product to confirm the presence of a crystalline or semi-crystalline structure or if the manufacturing process promoted the formation of an amorphous profile. Usually, a higher crystal size arrangement is preferred for packaging, textile, construction, and wastewater remediation applications, as that would mitigate the biomaterial's chemical reactivity and water absorption. Further, a higher crystallinity is ascribed to enhanced mechanical properties, as amorphous biomaterials have been reported to be sensitive to fragmentation and deformation. The crystallinity index (CI) can be calculated from the diffractograms, reporting values over 60% for the manufactured biomaterials. XRD analysis can also elucidate the presence of impurities in the final product.

### *4.6. Transmission Electron Microscopy (TEM)*

Another microscope characterization approach that can provide information on the morphology, average diameter, and size distribution of biobased materials is TEM. It is possible to determine the constituent parts of the created product by comparing the obtained morphologies and structures with those from SEM. Furthermore, the effects of binding agents on their structural integrity can be determined. TEM micrographs, for example, showed that the addition of glycerol to the formulation caused coalescence between the biobased material's constituents, improving its stability and preventing agglomeration [45]. The surface of the biobased material can also be shown by TEM to have uneven surfaces as well as a distribution and arrangement of pore sizes. Notably, it was found that treating biobased materials with alkali or acid promoted the development of nanoscale pores required for wastewater remediation applications [61]. Finally, the size distribution obtained from TEM can complement the crystallite size information determined from XRD.

### *4.7. Mechanical Properties*

Mechanical properties must be evaluated for potential construction, textile, and packaging applications. Biobased materials can be used to modify or improve the mechanical features of a matrix. Moreover, the selected raw materials, the manufacturing process, and the mixture proportions will determine the ability of the biobased material to perform under different conditions, to withstand a specific load before breakage, and to prevent brittle failure. Many analyses can be carried out. Tensile and flexural strength, for example, are derived from stress–strain curves, which characterize the behavior of biobased materials when subjected to increasing loads. Delamination and deformation can be linked to changes in the slope. Notably, the inclusion of reinforcement or binding agents greatly enhanced the tensile strength of the biobased materials, which was dependent on the number of reinforcer layers and their interfacial adhesion [40,102,103].

Dynamic mechanical analysis (DMA) is another characterization technique that examines the properties of a biobased material exhibiting viscoelastic behavior. Variations in stiffness, load-transfer capabilities, and storage modulus are assessed using the biomaterial's response to cyclic loading. DMA evaluation of reinforced biobased materials revealed superior mechanical properties compared to pure matrices, indicating the importance of binding agents in improving biobased materials' performance, including resilience, tensile toughness, and stiffness [44,59,77].

To ascertain the dimensional changes of the material as a function of temperature, thermomechanical analysis (TMA) and thermal conductivity ($\lambda$) are employed. A thermal expansion/shrinkage (%) ratio, where 100% represents the materials' initial length, is used to visualize data as a function of temperature. Reduction in thermal expansion was noted in the reinforced biobased materials when compared to the pure samples [60]. Mechanical features can be comparable to synthetic materials depending on the raw material used and the developed biobased product.

### *4.8. Moisture Content and Water Absorption*

The manufactured biobased materials can be characterized in terms of their hygroscopicity. Typically, water absorption is evaluated using a climate-controlled chamber. The material's initial weight is recorded before submerging it in a water bath and compared to its weight after submersion to determine its moisture content. A lower moisture content is preferred as it indicates that the formulation resists water penetration. Studies have shown that water uptake in biobased materials decreased compared to their separate components [87,104]. When hydrophilic binders like glycerol are present, assessing or adjusting the hydrophilic/hydrophobic ratio in the biobased material becomes essential to control water vapor diffusity.

### *4.9. Biodegradability Tests*

The biodegradation of the manufactured materials is usually evaluated in soil and tested at different intervals, which range from a couple of days to months. Environmental conditions, such as rain, temperature, and humidity, are recorded during the experiments. The biobased material is then removed from the ground, cleaned with a brush, and weighed using an analytical balance to determine its weight loss and final mass after specific degradation periods. It has been reported that the percentage of biodegradation is proportional to the number of days of burial [37,38]. Biodegradation can also be assessed by visual observation, noting morphological changes related to cracks, erosion, or holes provided by SEM analysis.

### *4.10. Brunauer-Emmett-Teller Analysis (BET)*

BET analysis has also been reported for biobased materials. However, it is mainly performed for wastewater remediation applications when the adsorbent's specific surface area and pore size distribution are relevant parameters related to its adsorption performance. The obtained values can also be compared to conventional adsorbents, observing enhanced adsorption capacities when the surface area increases. Surface areas in the 1.23 and 200 $m^2/g$ ranges have been reported [48,86,95], where the raw material and the manufacturing process play a relevant role in the obtained value. Pore size distribution is also relevant to determine whether microporous or mesoporous regions are predominant. The desired pore size distribution would depend on the adsorbate to favor its interaction and adsorption on the material surface.

### *4.11. Pollutant Removal Efficiency*

The pollutant removal efficiencies (RE%) of biobased materials are measured using batch experiments to assess their effectiveness as a green technology for wastewater remediation. Briefly, a fixed volume of the pollutant (which can account for a heavy metal, a pesticide, or a dye) is placed in a container where a known mass of biobased material sorbent is added. Further, the system is subjected to constant stirring, and the pollutant concentration is measured at different intervals. The RE% regarding pH, biobased sorbent concentration, contact times, and temperature are also evaluated. Both plant and animal-based biomaterials have displayed great affinity towards organic and inorganic pollutants. For instance, RE% of over 90% have been reported for dye pollutants (Methylene blue, Congo red) [51], over 400 mg/g for heavy metals (Cu, Cr, Pb, Ni, Cd) [61,105], and even adsorption capacities of 99% have been reported for industrial wastewater effluents [106].

## 5. Potential Applications of Biobased Materials

The following section will discuss the feasibility of using biobased materials according to their properties and performance. Tables 2 and 3 summarize the biobased materials investigated and their potential applications.

### *5.1. Packaging*

Packaging materials biobased from plant or animal waste have received increasing attention as an alternative to traditional synthetic and petroleum-based plastic materials due to their low production cost and biodegradability. Some of the produced and tested biobased materials are presented in Figure 2.

Caro et al. proposed a novel active packaging based on quinoa protein films using inkjet printing for thymol loading [45]. The films were evaluated in terms of their mechanical and water absorption properties. Glycerol was added to improve the surface tension of the composites. The hybrid films exhibited increased elongation and tensile strength compared with the separate components. Further, the printable packaging was studied under simulated storage conditions for fresh fruit, successfully inhibiting bacterial activity against relevant microorganisms. The quinoa protein-thymol films exhibited higher antibacterial activity than the individual components used as control. The best results were obtained for Gram-negative bacteria.

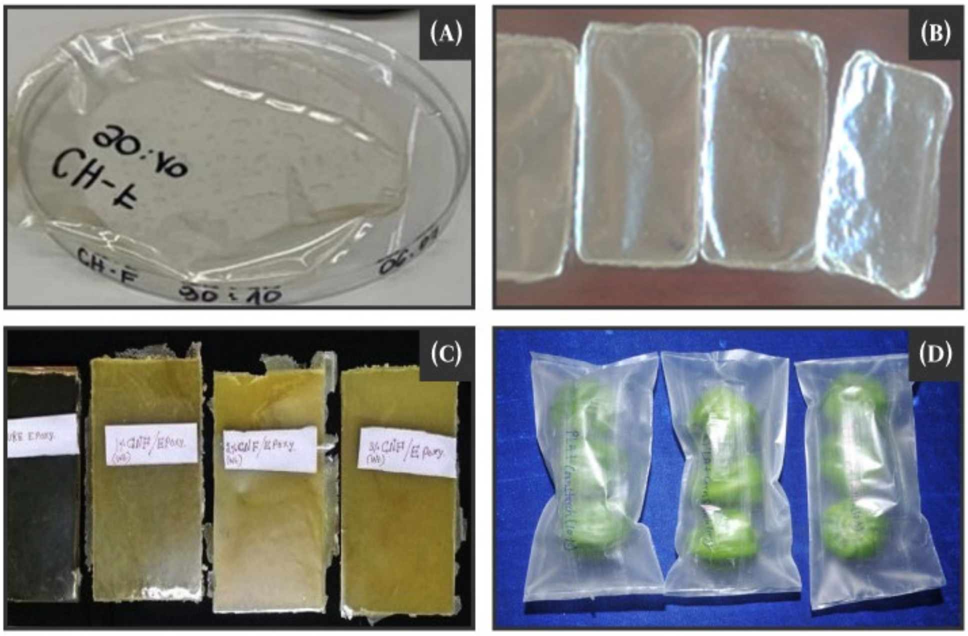

**Figure 2.** Biobased materials manufactured from plant or animal-based raw materials for packaging applications: films obtained from carp fish waste for storing blueberries (**A**). Adapted with permission from Ref. [59]; biodegradable packaging films prepared from shrimp and rice waste (**B**). Adapted with permission from Ref. [46]; packaging films fabricated with different weight percentages of pineapple leaf waste fiber (**C**). Adapted with permission from Ref. [104]; package derived from corn waste to preserve the shelf life of capsicum (**D**). Adapted with permission from Ref. [38].

A biobased and biodegradable packaging was developed by Mangaraj et al. as a film using corn waste as a raw material [38]. The biodegradable film was prepared using hot extrusion, obtaining a transparent film with a smooth, uniform surface (Figure 2D). The manufactured packaging was evaluated in terms of its mechanical strength and ability to maintain the quality of red chili peppers. The developed films were on par with petroleum-based materials in preserving the integrity of red chili peppers. Further, the biobased packaging increased the shelf life of capsicum three-fold in comparison to the unpackaged food, both at 8 and 25 °C.

Mehyar et al. described using pea waste as a raw material for a novel, biodegradable, and edible coating to prevent spoilage and hydrolytic rancidity of pine nuts and walnuts [44]. The pea-based film was combined with carnauba wax to prepare the biobased packaging. The combined precursors featured increased tensile strength when compared to the single components. Moreover, the developed material was adequate to prevent the oxidation of food at room temperature throughout 12 days.

Lemon peels were used to produce a biodegradable film for packaging [39], as described by Al-Salhany et al. The films were tested as a white cheese preservative, evidencing bacterial activity inhibition against Gram-positive and Gram-negative bacteria. A biodegradation of 97% for the packaging in soil was observed within 35 days.

Alparslan et al. studied the effects on the shelf life of pink shrimps using a packaging film derived from orange leaves [47]. The stored shrimps were evaluated throughout 14 days and compared with an uncoated group as a control. The antimicrobial and antioxidant results evidenced that the orange leaf-based packaging improved the quality and shelf life of the pink shrimps.

Pineapple leaf fibers (PALF) have been proposed as a low-cost raw material for manufacturing green packaging alternatives. The works described by Kengkhetkit et al. valorized pineapple leaf waste to produce biodegradable packaging. Their first work described an optimized method for manufacturing and extracting PALF using mechanical milling [41]. The procedure was simple compared to traditional methods without compromising the mechanical features of PALF. The developed material was evaluated as polypropylene reinforcement in their second work. The fabricated biobased material was tested with different concentrations of PALF (Figure 2C), finding that adding 2% *wt*. of PALF increased the composites' tensile strength and impact resistance [104].

The use of natural polysaccharides to develop modern packaging was studied by Janik et al. [59]. The authors produced a unique binary film by mixing furcellaran (a polysaccharide derived from red seaweed) with chitosan (extracted from crab exoskeletons). Furthermore, carp fish skin waste was used as an enriching agent in the chitosan/furcellaran matrix. The morphological and mechanical characterization of the biobased packaging was tested as a film, which revealed its smooth surface and the absence of cracks or brittleness. The films (Figure 2A) had a faint brownish tone that was translucent and naturally occurring in the skin of carp fish. Further, the material was tested in preserving blueberries, where an improvement in the antioxidant activity was observed compared to the controls: chitosan/furcellaran film, low-density polyethylene, and without films. Finally, blueberries stored in synthetic films showed higher weight loss than those in the biobased film.

An active food packaging material using crab shell waste was prepared by Liu et al. in the form of a powder [60]. Incorporating crab shell powder increased surface hydrophobicity, thermal stability, and antibacterial activity when compared to PVA with and without powder, with no significant differences in mechanical properties.

A biobased packaging was prepared using shrimp shells and rice fiber waste as raw materials and combined with a chitosan matrix for reinforcement [46]. The chitosan/shrimp and shell/rice fiber composites were prepared via casting, obtaining a transparent film in the process (Figure 2B). Experimental results proved that the material's mechanical properties were improved compared to the separate components, as well as its thermal stability and biodegradability. Further, the characterization of the green packaging demonstrated that it featured similar mechanical properties to those of synthetic or plastic films, serving as a potential sustainable alternative.

Chicken feather waste was valorized and proposed as a raw material substitute for synthesizing a biobased packaging material [72]. The mechanical and physicochemical properties of the films were analyzed. According to the tests, the packaging produced with 2% *wt.* glycerol featured the best mechanical and thermal properties. Further, the biobased material proved to be biodegradable.

Garrido et al. conducted similar research, using chicken feather waste to manufacture biodegradable packaging [66]. Further, an environmentally friendly extraction method was proposed, where the films were processed using hot extrusion and showed enhanced mechanical properties.

Egg white shells (EWS) were used to develop a biobased film for packaging. The raw material was processed using extrusion, and its thermal, mechanical, and physicochemical properties were measured to compare these results to those of commercial polylactic acid (PLA) [77]. The EWS biobased material displayed enhanced properties compared to PLA in terms of its sensitivity to water, thermal resistance, and flexibility.

Sheep wool (SW) has also been valorized as waste to manufacture biobased composites for packaging. Bhavsar et al. successfully prepared a biobased composite [107] via hydrolysis without using additional chemicals or binders for sustainable manufacturing. The green packaging also displayed complete biodegradability in soil within three months and provided nutrients for nourishment.

Using an alternative hot extrusion process, Szatkowski et al. aimed to produce packaging based on SW waste [37]. The mechanical and thermal properties of the biobased material were tested, demonstrating that the wool waste-based packaging had improved thermal insulation and surface roughness when compared to polystyrene packaging. The biodegradability of the biobased material upon soil burial and exposure to UV radiation was also confirmed.

Figure 2 illustrates a few examples of biobased materials developed from plant or animal-based raw materials for packaging applications.

## 5.2. Construction

Biobased materials have been studied thoroughly concerning their applications in construction and building, whether as a part of a structure or a refurbishment.

Nagarajan et al. proposed a biodegradable and low-cost construction material using coconut waste (Cocos Nucifera fibers; CNFs) [97]. The mechanical and thermal analysis of the developed material were investigated, concluding that adding CNFs increased the tensile strength and thermal stability of the loaded matrices. Similar research was conducted by Da Silva et al. [43], where coconut mesocarp (a fibrous mid-part of the fruit, comprising 85% of it), citrus pectin, and glycerol were manufactured using seventeen different formulations. The assays showed that higher amounts of coconut mesocarp fiber and glycerol increased the mechanical strength of the biobased material.

A biobased material derived from *Cocos nucifera* leaf sheath waste was hybridized with Kevlar as an alternative to laminate composites [89]. The effect of adding different concentrations of graphene nanoplatelets was also investigated. Statistical analysis and the evaluation of mechanical properties (Figure 3D) demonstrated that the shear strength of the biobased material increased significantly upon the addition of graphene nanoplatelets (0.25% *wt*.). Further, the coconut/Kevlar/graphene nanoplatelets exhibited superior interlaminar shear strength than pure Kevlar.

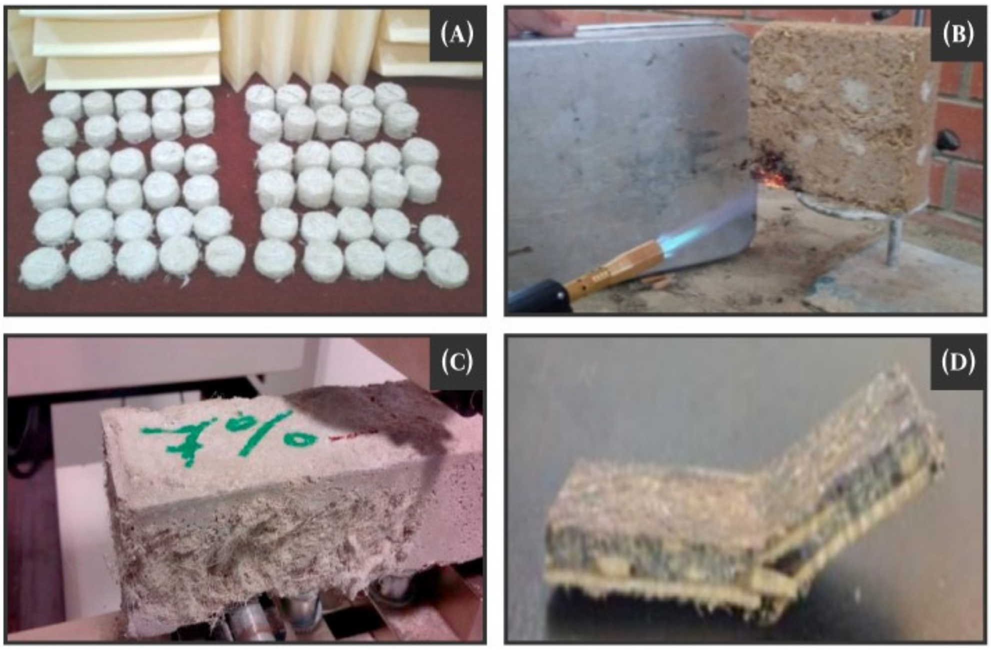

**Figure 3.** Biobased materials prepared from plant and animal-based waste for potential applications in the construction industries: utilization of chicken feather waste as a building insulator (**A**). Adapted with permission from Ref. [88]; fire resistance test of a biobased composite fabricated from rice husk waste (**B**). Adapted with permission from Ref. [55]; sheep wool waste as a reinforcement for concrete (**C**). Adapted with permission from Ref. [64]; mechanical strength test of a biobased Cocos nucifera composite for construction applications (**D**). Adapted with permission from Ref. [97].

Curaurá fiber has been studied as a raw material for developing a building block as an alternative for cementitious matrices [103]. Fibers of 10 mm showed the best mechanical properties and density results, envisioning their applications as coatings in walls or panels.

The properties of green aloe (*Frucrarea Foetida*; FF) as a raw material for reinforcement in coatings or construction were studied by Manimaran et al. [108]. The structural, mechanical, and thermal analysis of FF revealed the feasibility of using this plant-based fiber in the construction sector. A similar study was performed by Ramanaiha et al. but using Sansevieria (*S. Roxburghiana*; SR) as the raw material [40]. The developed biobased material's thermal stability and mechanical properties were evaluated, finding that such properties improved with the alkaline treatment of the plant-based product.

Zhou et al. evaluated the potential of oat plant roots for fabricating structures envisioned as building blocks in construction [109]. Plant roots were combined with dried agar membranes and explored as materials for fabricating self-supported 3D objects, with the design of the structures facilitated by computer tools.

Potato skin has been valorized as waste for developing diverse structures for construction applications [110]. Using glycerin as a plasticizer and altering one ingredient at a time, eight formulations were tested to see how they affected the biobased composite. A formulation consisting of water, potato skin flour, starch, and sorbitol proved to be the most promising for the application. This combination featured higher resistance to tension and torsion. Further, sage and rosemary were incorporated as ingredients to prevent mold formation.

Rice husk was manufactured as a raw material for potential applications in panels and refurbishment [87]. Different contents of rice husk (15–30% *wt.*) were added to a quarry fine/gypsum/air lime matrix to evaluate its effects in the formulation. The results showed that rice husk content improves the thermal conductivity and mechanical characteristics of building blocks and their ability to prevent humidity adsorption. Fire tests further revealed that the composites exhibited no fire propagation or considerable smoke production when the fire source was removed (Figure 3B).

Chicken feathers were valorized for manufacturing a product applicable as refurbishment and as an acoustic absorptive coating [88]. The raw materials were compacted in a 100-mm-diameter cylindrical mesh with varying thicknesses (25, 50, and 75 mm; Figure 3A). The results featured promising noise absorption coefficients, which increased with the biomaterial's thickness, reaching a maximum value of 0.99 at 1600 Hz.

The properties of sheep wool (SW) were evaluated in terms of their mechanical and thermal properties by Denes et al. [64]. While the results are promising, sheep wool featured an inferior performance as a concrete reinforcement or substitute compared to synthetic materials such as polypropylene. A 7% wool dosage (Figure 3C) was insufficient to significantly enhance the flexural and tensile strength of the composite. In contrast, mechanical strength was increased using the same amount of polypropylene.

Bosia et al. [73] also presented sheep wool as a novel raw material for sustainable construction applications, demonstrating its effectiveness as a building insulator via thermal conductivity and noise absorption experiments.

Figure 3 summarizes examples of biobased materials developed from plant or animal-based raw materials for construction applications.

### *5.3. Textile*

Biobased products have also presented advantages as textile or fabric materials compared to synthetic or traditional composites due to the higher mechanical properties ascribed to fiber reinforcement.

Balaji et al. proposed using Aloe Vera Cactus Leaves (SACL) fibers as an alternative to conventional fabric material and as reinforcement for composites [111]. The mechanical and physicochemical properties of the fibers, such as crystallinity and interfacial and tensile strength, were increased compared with those of other natural fibers, such as hemp, cotton, or flax, representing a feasible alternative to developing bio-based fabric.

Chee et al. studied the mechanical and thermal properties of composites composed of kenaf/epoxy, bamboo/epoxy, and bamboo/kenaf fibers for their potential application as a natural fabric [102]. Pure kenaf (Figure 4A), bamboo (Figure 4B), and epoxy mats were fabricated as control samples. Different mixing ratios were investigated, and positive hybridization effects, attributed to reduced coefficient of thermal expansion and improved mechanical properties, were observed on bamboo/kenaf 50:50 composites.

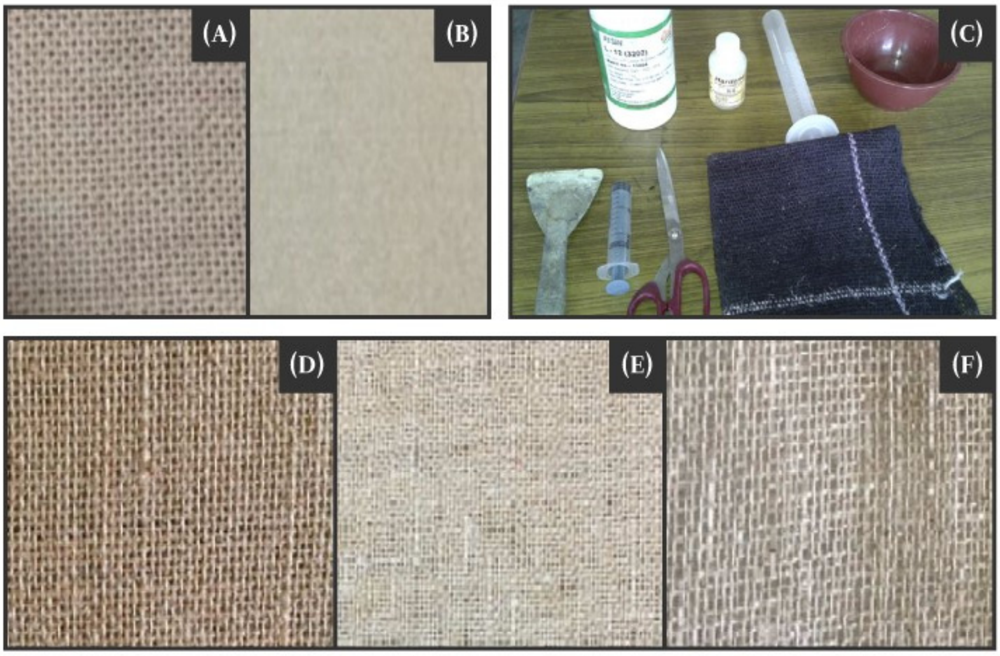

**Figure 4.** Biobased materials manufactured for potential applications in the textile industries: fabric obtained from kenaf (**A**) and bamboo (**B**) fibers [102]; preparation of a reinforced fabric composed of a sheep wool-epoxy composite (**C**). Adapted with permission from Ref. [42]; different biobased fabrics obtained from jute (**D**), hemp (**E**), and flax (**F**). Adapted with permission from Ref. [91].

Coconut fiber waste was used as a raw material to develop a sustainable fabric material [74]. The obtained composite was mixed with ammonium polyphosphate (APP) as a flame retardant, where a synergic effect occurred, resulting in a material with lower heat release and good flame retardance.

Fiber derived from banana peel waste was studied by Brindha et al., as well as their extraction methods [82]. For this purpose, chemical and mechanical extraction procedures were evaluated. Tensile, flexural, and SEM characterization revealed that chemically treated fibers had cleaner, rougher surfaces more suited for textile applications. In contrast, mechanically treated fibers may be better suited for construction or building industries due to their increased lignin concentration, as indicated by FTIR, SEM, and EDS analyses.

PALF was investigated as a potential biobased material for textile applications by Kakati et al. [71]. The fibers were extracted using NaOH treatment and grafted into a polyacrylate polymer. The composite exhibited improved thermal and mechanical properties compared to the separate components. An optimal PALF percentage (64.3%) was determined, promoting the degradation of the biomaterial in a soil environment.

Jute, hemp, and flax composites (Figure 4D, Figure 4E, and Figure 4F, respectively) were developed and characterized for their potential application as a biobased fabric [91]. Mechanical characterization was performed in different combinations of the precursors while testing their effects as reinforcers of an epoxy resin. Although all binary combinations had similar mechanical properties, the jute/hemp/epoxy formulation outperformed the other composites regarding hardness, flexural, and impact strength.

Karakoti et al. isolated Roselle fibers (*Hibiscus Sabdariffa* fibers; HSFs) to evaluate their potential application as a fabric [100]. The fibers were chemically treated using bleaching (2% oxalic acid), and their thermal and crystalline properties were compared to those of untreated fibers. Physicochemical characterization revealed that the bleaching process reduced the diameter of the fiber. As a result, a greater area would be accessible for attainable fiber-matrix adhesion while simultaneously having better thermal properties and crystallinity than raw fibers.

In a similar approach, Vinod et al. studied Madagascar Periwinkle fibers (*Catharanthus Roseus* fibers; CRFs) treated with alkali bleaching (5% NaOH) [112]. The obtained results agree with the behavior of HSFs, as the chemical treatment reduced the amorphous composition of the CRFs while also increasing their tensile strength, crystallinity, and wettability.

Thumbai fibers (Leucas Aspera fibers; LAFs) were also evaluated as raw materials for textile applications [113]. The fibers were treated with silane during manufacturing to improve their mechanical properties. The composites displayed enhanced tensile and shear strength, as well as thermal stability, in comparison to the untreated fibers.

Subramanian et al. aimed to develop a biobased fabric using Ceroid cacti fibers (*Cereus Hildamannianu*s fibers; CHFs) [114]. The fiber extraction was performed via cutting, drying, sieving, and washing with distilled water, obtaining promising mechanical properties and crystallinity without bleaching or chemical treatments.

Maache et al. developed a biobased textile using Soft rush fibers (*Juncus Effusus* fibers; JEFs), where the extracting process was also performed following a greener approach, using boiling water to extract the fiber bundles [115]. Physicochemical, mechanical, and thermal characterization of the plant-based fiber indicated the feasibility of its use as a biobased textile.

Kathirselvam et al. explored the isolation of Portia tree fibers (*Thespesia Populnea* fibers; TPFs), usually disposed of as waste [101]. The extraction process was performed via manual peeling, washing with distilled water, and drying for about 6 h. The structure and properties of the fiber were analyzed, with favorable results observed in terms of its tensile strength, crystallinity, and thermal stability. The developed material also featured a rough surface and bonded fiber cells, consistent with the attained mechanical properties.

Animal-based waste has also been valorized for its potential application as textiles. Ece et al. [65] examined the properties of horse hair fiber waste in terms of its durability, thermal stability, and mechanical strength. Results demonstrated the feasibility of using horse hair as a textile fiber due to its thermal, mechanical, and antibacterial properties.

Fibers derived from SW waste were studied by Bharath et al. [42]. Following alkali treatment, the wool fiber was employed as reinforcement for an epoxy matrix. Formulations (Figure 4C) were produced considering different criteria, such as hole diameter and thickness. Experimental results evidenced that the tensile strength of the fabrics increased with thickness but decreased with the hole diameter. However, the thickness of the material contributed to fracture toughness.

Figure 4 illustrates some of the manufactured biobased materials for textile applications discussed in this section.

### 5.4. Wastewater Remediation

Plant and animal-based biomaterials have been explored as a cost-efficient and environmentally friendly alternative to granulated activated carbon (GAC) for wastewater remediation. Despite being a better overall adsorbent, the use of GAC is limited due to cost-consuming manufacturing processes. Hence, plant and animal-based waste have been explored to remove inorganic and organic pollutants via adsorption or as coagulant/flocculant agents.

Madre cacao leaves (Gliricidia Sepium leaves; GSL) powder (Figure 5A) was investigated for wastewater remediation by Suganya et al. [116] Cr (VI) was chosen as adsorbate, and the parameters for the heavy metal elimination were tested. The biobased sorbent was also evaluated regarding its reusability, evidencing performances of maximal removal of 99% at equilibrium.

Green tea leaf waste derived from Camellia Sinensis was used as a biosorbent for removing Cr, Zn, Ni, Cu, and Fe from synthetic wastewater [117]. Maximum adsorption was 99% at pH 2.0, with a contact time of 3 h. and an adsorbent dosage of 0.8 g/L.

Thermodynamic parameters were also determined, which showed that the adsorption process was spontaneous and exothermic.

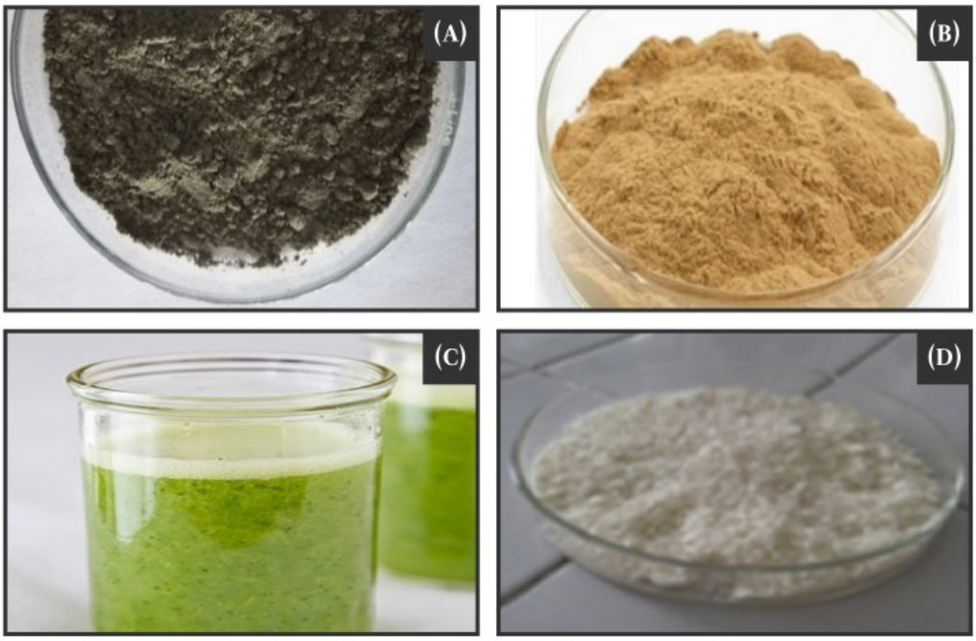

**Figure 5.** Biobased products for potential applications in wastewater remediation obtained from plant or animal-based raw materials: Gliricidia Sepium leaf powder to eliminate Cr (VI) (**A**). Adapted with permission from Ref. [117]; mango seed waste biosorbent for the removal of Pb (II) and Cd (II) (**B**). Adapted with permission from Ref. [75]; cactus mucilage for potential flocculation of pollutants (**C**) Adapted with permission from Ref. [51]; shell fish waste biosorbent for removal of As (V) from aqueous solution (**D**). Adapted with permission from Ref. [94].

Nag et al. developed seven different biobased materials as an alternative for wastewater treatment and Cr (VI) removal [93]. The plant-based sorbents were developed using seven different raw materials. The adsorption capacities of all biobased materials were compared, decreasing in the following order: mango leaf > jackfruit leaf > rubber leaf > onion peel > bamboo leaf > garlic peel > coconut shell. The results were consistent with the estimated surface areas of each biosorbent. Further, the mango leaf biosorbent outperformed the rest in the reusability studies.

Mango seed waste was utilized as raw material to obtain a sustainable biosorbent [75]. The plant-based material (Figure 5B) evidenced a maximum adsorption capacity of 263 mg/L for $Pb^{2+}$ (removal of 93%, pH 5.0, 10 min.) and 93 mg/L for $Cd^{2+}$ (removal of 78%, pH 7.5, 10 min.). Moreover, the regeneration cycles demonstrated that the biobased sorbent maintained 98% of its adsorption capacities.

Sellami et al. [118] investigated the use of cactus juice (Figure 5C) as a flocculant agent alternative for polyacrylamide. The tests were carried out using wastewater samples acquired from the manufacturers of confectionery and glue. The RE% efficiency of the biobased flocculant was promising (88% for suspended solids and 67% for chemical oxygen demand).

Eggshell waste (ESW) was recycled and valorized to obtain a biobased sorbent for $Ni^{2+}$ removal from wastewater [105]. The maximum adsorption capacity of the material was 109 mg/g within 80 min. Further, the maximum removal efficiency of the eggshell-based biosorbent was compared with that of other biobased sorbents, outperforming inorganic ones such as vermiculite (25 mg/g) or phosphate rock (7 mg/g) under similar experimental conditions. However, it exhibited lower adsorption capacities compared to Moringa oleifera and rice bran-based biosorbents, which performed better at 163 mg/g and 153 mg/g, respectively. Notably, it demonstrated higher adsorption capacities than plant-based adsorbents such as grapefruit peel waste (46 mg/g) and cassava peel waste (57 mg/g).

Ibrahim et al. [119] valorized ESW to obtain a biobased powder for $Pb^{2+}$ removal from wastewater. The adsorbent characterized by a high surface area and pore volume, facilitated rapid adsorption rates (within 10 min) and achieved a maximum adsorption capacity of 1005 mg/g.

Fishbone waste powder, chicken femur, and chicken beak waste were used to develop green biosorbents for removing $Cd^{2+}$ from wastewater [120]. The chicken femur powder, exhibiting higher surface areas compared to chicken beak and fishbone materials, demonstrated the highest adsorption capacity (22.9 mg/g). Maximum removal capacities were achieved by all adsorbents at pH 6.0 within 80 min of using an adsorbent mass of 2 g/L.

A shellfish waste material (Figure 5D) to adsorb arsenic from wastewater was designed by Billah et al. [94]. The efficiency of the biosorbent was evaluated in the presence of competing ions such as $Cl^-$, $NO_3{}^-$, and $PO_4{}^{3-}$. Arsenic uptake was pH dependent; the optimized parameters were pH 5.0 with a RE% of 99%. Further, RE% of 90% was attained after four adsorption–desorption cycles.

Prawn shell waste was used to develop a composite with activated carbon to enhance the adsorption performance of the separate components [61]. The porous composite was tested in heavy metal solutions at different pH and contact times, obtaining adsorption capacities of 318 mg/g ($Cr^{6+}$), 280 mg/g ($Cu^{2+}$), and 256 mg/g ($Cd^{2+}$).

Figure 5 compiles examples of some of the investigated biobased materials for potential applications in wastewater remediation.

Tables 2 and 3 present various biobased materials developed from plant and animal waste used as raw materials. The tables summarize the precursor raw material, pretreatment methods applied before manufacturing the biobased material, characterization methods used to evaluate their properties, and potential applications.

**Table 2.** Summary of the biobased materials manufactured from plant-based raw materials discussed in this review.

| Raw Material | Pretreatment | Characterization | Potential Application | Reference |
|---|---|---|---|---|
| Bamboo and kenaf | Washing, drying | DMA, thermal expansion | Textile | [94] |
| Banana peel | Washing, drying, extracting | Mechanical properties, SEM, FT-IR | Textile | [70] |
| Cactus juice | Washing, grinding, drying | FT-IR | Wastewater remediation | [115] |
| Catharanthus Roseus fiber | Washing, drying, extracting, bleaching | Mechanical properties, FT-IR, XRD, TGA, SEM, moisture content | Textile | [108] |
| Cereus Hildamanniaus fiber | Washing, drying, extracting | Mechanical properties, FT-IR, XRD, SEM | Textile | [110] |
| Cocos Nucifera fiber | Washing, drying, extracting, grinding | Mechanical properties, XRD, SEM, EDS, FT-IR | Construction | [81] |
| Cocos Nucifera fiber | Washing, drying | Mechanical properties, XRD | Construction | [90] |
| Corn fiber | Washing, drying | Mechanical properties, SEM, TGA, DSC, FT-IR, XRD | Packaging | [98] |
| Curaurá fiber | Drying, grinding, sieving | Mechanical properties, BET, SEM, moisture content | Construction | [95] |
| Frucracea Foetida fiber | Washing, drying, extracting | Mechanical properties, XRD, FT-IR, TGA, SEM, TEM, EDS | Construction | [104] |

**Table 2.** *Cont.*

| Raw Material | Pretreatment | Characterization | Potential Application | Reference |
|---|---|---|---|---|
| Gliricidia Sepium fiber | Washing, drying grinding, sieving | BET, SEM, XRD, FT-IR | Wastewater remediation | [113] |
| Green tea leaves | Drying, bleaching, grinding | Mechanical properties, moisture content | Wastewater remediation | [114] |
| Hibiscus Sabdariffa fiber | Washing, drying, extracting, bleaching | XRD, FT-IR, TGA | Textile | [93] |
| Jute, hemp, and flax | Washing, drying | Mechanical properties, SEM | Textile | [83] |
| Leucas Aspera fiber | Washing, drying, bleaching | Mechanical properties, XRD, SEM, FT-IR, TGA | Textile | [109] |
| Mango leaf, garlic peel, onion peel, bamboo leaf | Washing, drying, extracting, sieving | SEM, BET, FT-IR | Wastewater remediation | [86] |
| Mango seeds | Washing, grinding, drying | SEM, EDS, FT-IR, XPS | Wastewater remediation | [62] |
| Oat plant roots | Washing, drying | Mechanical properties | Construction, packaging | [109] |
| Orange leaf | Washing, drying, extracting | Mechanical properties, SEM, FT-IR, TGA, XRD | Packaging | [76] |
| Pea seed | Washing, drying, extruding | Mechanical properties | Packaging | [44] |
| Pineapple leaf | Washing, drying, grinding, extruding | Mechanical properties, SEM, TGA | Packaging | [102] |
| Pineapple leaf | Washing, drying, extruding, grinding | Mechanical properties, moisture content, SEM, TGA | Construction | [96] |
| Potato skin | Washing, drying, extracting | Mechanical properties | Construction, packaging | [106] |
| Rice husk | Washing, drying, grinding, sieving | Thermal conductivity, abrasion, moisture content | Construction | [79] |
| Sanseviera fiber | Washing, drying, extracting | Mechanical properties, TGA | Construction | [64] |
| Thespesia Populnea fiber | Washing, drying, extracting | Mechanical properties, XRD, FT-IR, TGA, DSC | Packaging | [112] |

**Table 3.** Summary of the biobased materials manufactured from animal-based raw material discussed in this review.

| Raw Material | Pretreatment | Characterization | Potential Application | Reference |
|---|---|---|---|---|
| Carp fish skin | Washing, drying, extruding | Mechanical properties, moisture content | Packaging | [46] |
| Chicken feathers | Washing, drying, grinding | Mechanical properties, SEM, FT-IR, XRD, TGA, DSC, XPS | Packaging | [58] |
| Chicken feathers | Washing, drying, grinding | DMA, FT-IR, DSC, SEM | Construction | [80] |
| Chicken feathers | Washing, drying, extracting | Mechanical properties, FT-IR | Packaging | [52] |
| Crab shell | Washing, drying, grinding, extracting | DMA, SEM, FT-IR, DSC, XRD | Packaging | [47] |

**Table 3.** *Cont.*

| Raw Material | Pretreatment | Characterization | Potential Application | Reference |
|---|---|---|---|---|
| Eggshell waste | Washing, drying, extracting | SEM, EDS, FT-IR, XRD | Wastewater remediation | [99] |
| Fish bones | Washing, drying, grinding | FT-IR, XRD, BET, SEM, EDS | Wastewater remediation | [44] |
| Horse hair | Washing, drying, bleaching | Mechanical properties | Textile | [51] |
| Prawn shell | Washing, drying, grinding | SEM, FT-IR, XRD, BET, TEM | Wastewater remediation | [48] |
| Sheep wool | Washing, drying, extruding | Mechanical properties | Textile | [84] |
| Sheep wool | Washing, drying, bleaching | Mechanical and thermal properties, FT-IR | Packaging | [103] |
| Sheep wool | Washing, drying, grinding | Mechanical properties, moisture content | Construction | [50] |
| Shrimp shell | Washing, drying, extruding | Mechanical properties, FT-IR, NMR, TGA, SEM | Packaging | [87] |

## 6. Research Areas Responsible for Producing Biobased Materials

As illustrated in the many examples in the previous section, the sustainable transformation of plant and animal-based raw materials, along with the valorization of organic waste, has driven research toward developing value-added biobased materials. These materials hold potential applications in packaging, construction, textile, and wastewater remediation, drawing attention from various research domains. Figure 6 provides an overview of the research areas for developing biobased materials discussed in this review. The graphic was produced using data from all the references in Tables 2 and 3. Eight groups were identified for classification based on the affiliations of the first and corresponding authors in the publications under discussion. For each research topic, the percentages reflect the number of studies cited in this review.

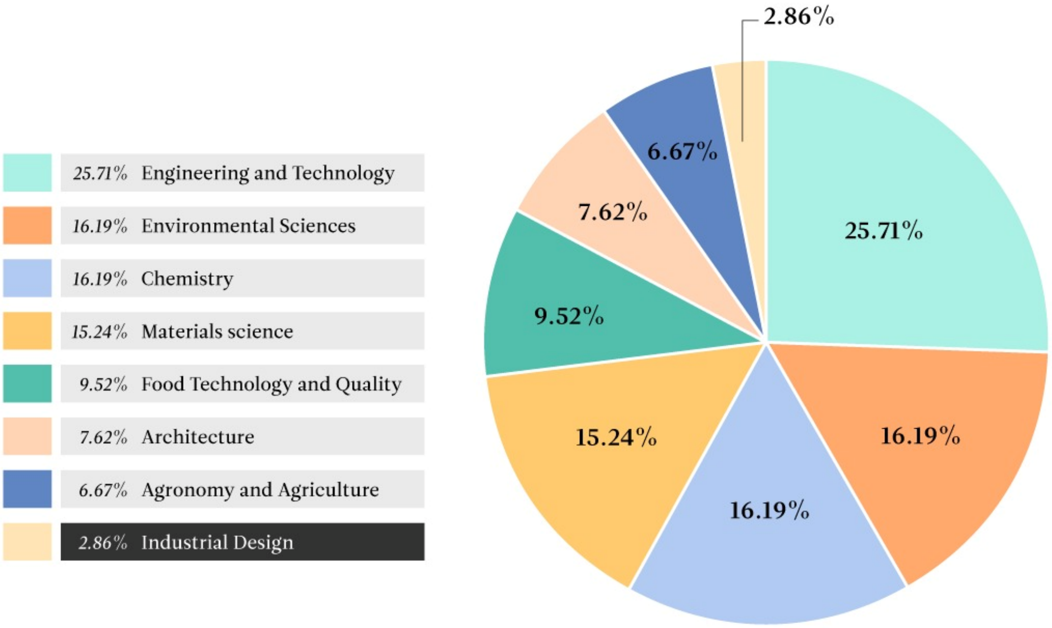

**Figure 6.** Summary of research areas developing biobased materials from plant and animal-waste.

Engineering and technology have substantially contributed to the publications analyzed in this review, accounting for 25.7% of the total. Additionally, chemistry and materials science collectively represent 31.3% of the discussed articles, with 16.1 and 15.2% individual contributions, respectively. Notably, metrics pertaining to biobased materials development in industrial design require improvement, representing only 2.8% of the total articles. This suggests a need for increased visibility of research efforts or the integration of sustainable practices within product manufacturing by valorizing plant and animal-based waste.

## 7. Commercial Applications of Biobased Materials

As the demand for more sustainable materials increases, a growing number of researchers, startups, and companies have seized market opportunities by introducing biobased materials as supplies for other industries and developing their products using biobased materials. To inform this interest with concrete data, a targeted study was conducted. This study serves to outline the current presence of biobased applications that are close to market or already available commercially, focusing on the use of plant-based and animal-based raw materials.

Data was collected from Google search using systematic keyword-based querying. Based on the raw materials discussed in this review in Tables 2 and 3, as well as on their potential applications, the queries were structured using four types of terms: raw material, material category (plant-based, animal-based), application category (packaging, textile, construction, and water remediation), and business category (startup, company, among others). For example, "banana peel plant-based textile startup". The search included all possible crossings between raw materials and the four application categories. The search results included different types of websites, including scientific articles, newspapers, magazines, blogs, and companies' landing pages, among others. Scientific articles and early-stage research projects were excluded from the results to focus on close-to-market and commercially available applications. The remaining results were classified into R&D projects, startups, and companies.

In assessing commercial applications of bio-based materials, a total of 194 current cases were identified, split into 135 plant-based and 59 animal-based projects, as summarized in Table 4. Within plant-based applications, the packaging category leads with 61 cases (45%), followed by construction with 38 cases (28%), textiles with 30 cases (22%), and wastewater remediation with 6 cases (4%). On the other hand, animal-based applications are distributed with 24 cases (41%) in packaging, 12 cases (20%) in construction, 19 cases (32%) in textiles, and 4 cases (7%) in wastewater remediation.

**Table 4.** Summary of the online search results on commercial applications of plant-based and animal-based raw materials and their distribution over applications categories and business categories.

| Categories | | Plant-Based | | Animal-Based | |
|---|---|---|---|---|---|
| Application category | Packaging | 61 | 45% | 24 | 41% |
| | Construction | 38 | 28% | 13 | 22% |
| | Textile | 30 | 22% | 18 | 30% |
| | Wastewater remediation | 6 | 4% | 4 | 7% |
| | Total | 135 | 100% | 59 | 100% |
| Business Category | R&D | 22 | 16% | 23 | 39% |
| | Startup | 14 | 10% | 17 | 29% |
| | Company | 99 | 73% | 19 | 32% |
| | Total | 135 | 100% | 59 | 100% |

Table 4 further categorizes the projects by their stage of development. There are 22 R&D cases for plant-based applications, accounting for 16% of the total. Startups represent 14 cases, which is 10%, and established companies contribute the most with 99 cases, or 73%. In contrast, animal-based applications show a higher engagement in the earlier stages of development, with 23 R&D cases (39%) and 16 startups (27%). Established companies are involved in 20 cases, representing 34% of animal-based applications. This distribution indicates that plant-based applications are more frequently developed within established companies, suggesting a mature market presence. Conversely, the animal-based sector is characterized by a stronger focus on research and development, pointing to a field still in a growth phase with considerable involvement from newer enterprises.

Among the surveyed plant-based raw materials, jute, hemp, and flax collectively account for the majority, with 49 application projects identified, evidencing their broad utility and acceptance in commercial ventures. Bamboo and kenaf together rank second with 18 applications, primarily in construction and packaging sectors, and rice husk follows with 14 applications, showcasing a diverse range of uses from construction to wastewater remediation. Notably absent from the list of commercial applications are raw materials derived from several plant species, including *Catharanthus Roseus*, *Cereus Hildamannianus*, *Curaurá*, *Frucrarea Foetida*, *Gliricidia Sepium*, *Hibiscus Sabdariffa, Leucas Aspera*, and *Thespesia Populnea*, suggesting potential gaps in market utilization or areas ripe for innovation.

Table 5 reveals a varied distribution in using bio-based materials according to application category. For packaging, 61 applications are distributed across 12 different materials, indicating a wide range of options in this category. In comparison, the textile category, with 30 applications, also shows significant diversity, with applications spread across 11 different materials. In contrast, applications in construction, totaling 38 cases, are predominantly concentrated in five materials: bamboo and kenaf (7), jute, hemp, and flax (19), rice husk (8), coco nucifera fiber, and potato skin. This concentration suggests a preference for certain materials in structural applications, unlike the packaging and textile categories, where a greater variety of materials is observed. Table 5 also indicates that most plant-based material applications are available via established companies, with fewer contributions from R&D projects and startups. These commercial applications concentrate on three main raw materials, suggesting that the market for applications of plant-based materials is led by specific industries or ecosystems.

R&D projects, although less frequent, are present across various materials, indicating ongoing research in this field. Startups, while also fewer in number than companies, contribute to a range of applications, demonstrating their role in introducing innovative approaches in the bio-based material sector. This pattern suggests that while foundational research and initial innovations often stem from R&D projects and startups, established companies in certain industries may play a significant role in bringing these applications to market.

Within the scope of animal-based materials, Table 6 underscores that sheep wool, crab shell, and chicken feathers are the materials with the most numerous market applications, featuring 14, 13, and 10 projects, respectively.

Table 6 also reveals certain patterns or clusters in the use of animal-based raw materials. Shells from aquatic crustaceans, including those from shrimps, crabs, and prawns, are primarily involved in packaging applications like bioplastic films. These materials also show applications in textiles as biobased fibers and wastewater remediation as flocculants. Yet, no applications in construction have been identified for these materials. On the other hand, materials used in construction are diverse, with a focus on agricultural animal waste, including sheep wool, horse hair, and chicken feathers, primarily used for in-wall thermal and acoustic insulation and textiles.

Regarding market penetration, Table 6 indicates a general trend towards R&D and startups, reflecting the nascent stage of the associated technologies. A notable exception is the application of sheep wool, which is predominantly found in established companies. This could indicate sheep wool's significant role and longstanding tradition in the textile industry.

**Table 5.** Summary of the application projects of plant-based raw materials.

| Raw Material | Applications | R&D | Startups | Companies | References |
|---|---|---|---|---|---|
| Bamboo and kenaf | Packaging (7), Construction (7), Textile (4). | - | 3 | 15 | [121–138] |
| Banana peel | Packaging (1), Textile (3), Wastewater remediation (1). | 1 | - | 4 | [139–143] |
| Catharanthus Roseus fiber | - | - | - | - | - |
| *Cereus Hildamannianus* fiber | - | - | - | - | - |
| Cocos Nucifera fiber | Packaging (3), Construction (2), Textile (2). | 2 | 1 | 4 | [144–150] |
| Corn fiber | Packaging (4), Textile (5). | - | - | 9 | [151–159] |
| Curaurá fiber | - | - | - | - | - |
| *Frucrarea Foetida* fiber | - | - | - | - | - |
| *Gliricidia Sepium* fiber | - | - | - | - | - |
| Green tea leaves | Packaging (2), Textile (1). | 2 | - | 1 | [160–162] |
| *Hibiscus Sabdariffa* fiber | - | - | - | - | - |
| Jute, hemp, and flax | Packaging (21), Construction (19), Textile (9). | 6 | 4 | 39 | [163–211] |
| *Leucas Aspera* fiber | - | - | - | - | - |
| Mango leaf, garlic peel, onion peel, bamboo leaf | Packaging (1). | 1 | - | - | [212] |
| Mango seeds | Packaging (3), Textile (1). | 2 | 1 | 1 | [213–216] |
| Orange leaf | Textile (1). | - | - | 1 | [217] |
| Pea starch | Packaging (7). | 2 | - | 5 | [218–224] |
| Pineapple leaf | Packaging (5), Textile (1), Wastewater remediation (1). | 3 | - | 4 | [225–231] |
| Oat plant roots | - | - | - | - | - |
| Potato skin | Packaging (3), Construction (2), Wastewater remediation (1). | 1 | 3 | 2 | [232–237] |
| Rice husk | Packaging (4), Construction (8), Textile (1), Wastewater remediation (3). | 2 | 2 | 12 | [238–253] |
| *Sansevieria* fiber | Textile (2). | - | - | 2 | [254,255] |
| *Thespesia Populnea* fiber | - | - | - | - | - |
| Total | Packaging (61), Construction (38), Textile (30), Wastewater remediation (6). | 22 | 14 | 99 | - |

The review presented in Tables 4–6 provides an updated overview of the commercial applications of biobased materials, both plant-based and animal-based. This analysis reveals a variety of uses and distribution. The review presented in Tables 4–6 provides an updated overview of the commercial applications of biobased materials, both plant-based and animal-based. This analysis reveals a variety of uses and distribution across different market sectors. There is a trend towards a more significant presence of established companies in the development of plant-based material applications, while in the realm of animal-based materials, there is a notable focus on research and development, as well as startup involvement. These findings offer an understanding of how these materials are currently positioned in the market and may indicate potential areas for future research and development. The inclusion of this section in the paper aims to provide useful context for subsequent discussions on sustainability and innovation in the field of biobased materials across different market sectors.

**Table 6.** Summary of the application projects of animal-based raw materials.

| Raw Material | Applications | R&D | Startups | Companies | References |
|---|---|---|---|---|---|
| Carp fish skin | Construction (1). | - | 1 | - | [256] |
| Chicken feathers | Packaging (3), Construction (4), Textile (3). | 5 | 4 | 1 | [257–266] |
| Crab shell | Packaging (4), Textile (6), Wastewater remediation (3). | 7 | 4 | 2 | [267–279] |
| Eggshell waste | Packaging (3), Construction (2), Textile (2). | 2 | 2 | 3 | [280–286] |
| Fish bones | Packaging (1), Construction (1). | - | 1 | 1 | [287,288] |
| Horse hair | Construction (2), Textile (1). | 3 | - | - | [289–291] |
| Prawn shell | Packaging (4), Wastewater remediation (1). | 4 | - | 1 | [292–296] |
| Sheep wool | Packaging (6), Construction (3), Textile (5). | 1 | 4 | 9 | [297–310] |
| Shrimp shell | Packaging (3), Textile (1). | 1 | 1 | 2 | [311–314] |
| Total | Packaging (24), Construction (13), Textile (18), Wastewater remediation (4). | 23 | 16 | 20 | - |

## 8. Conclusions and Final Remarks

The valorization of plant and animal-based raw materials, especially as waste, holds significant relevance, considering the critical global issue of disposal. Utilizing these resources for the development of biobased materials facilitates recycling. As such, incorporating these materials into a value chain to foster a circular economy becomes imperative. This review has comprehensively examined the advancements in the sustainable development of biobased materials using plant and animal waste. Our findings underscore the significant potential of these materials in various industries, including packaging, construction, textile, and wastewater remediation. We observed that biobased materials derived from plant and animal waste are not limited to a single use but have diverse applications. Moreover, the extraction and manufacturing methods of biobased materials have proved to be greener, more energy efficient, and more cost-effective compared to synthetic materials.

Since most waste valorization procedures are accomplished on a laboratory scale, further emphasis should be placed on technological and economic studies to assess the potential of industrializing biobased products. Drawbacks concerning processing cost, efficiency, and safety must also be addressed. Despite this, the commercialization of biobased materials is likely to increase because of a greater understanding of environmental issues, the development of efficient production processes, and the identification of new prospects and possible uses. Commercial applications are more mature in the plant-based sector with established companies, while animal-based applications are still burgeoning with substantial involvement from startups and R&D. The versatility of these materials suggests a rich field for further exploration and innovation. However, introducing biobased products confronts various hurdles, including an absence of research activities in developing nations with abundant plant and animal-based raw resources. Furthermore, before entering the market, the qualities of biobased materials must meet norms, product requirements, and strict regulations.

**Author Contributions:** Conceptualization, S.S.S., A.A., N.S. and P.C.; validation, S.S.S., A.A., I.T., N.S. and P.C.; formal analysis, S.S.S., A.A., I.T., N.S. and P.C.; investigation, S.S.S., A.A., I.T., N.S. and P.C.; resources, A.A. and P.C.; writing—original draft preparation, S.S.S. and N.S.; writing—review and editing, S.S.S., A.A., I.T., N.S. and P.C.; visualization, S.S.S., A.A., I.T., N.S. and P.C.; supervision, S.S.S., A.A., N.S. and P.C.; funding acquisition, A.A. and P.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This review was supported by Facultad de Diseño, Universidad del Desarrollo, Santiago, Chile.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data is contained within the article.

**Acknowledgments:** The authors would like to acknowledge María de Los Angeles Moreno for her assistance with all Figures.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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