Hindawi
Journal of Chemistry
Volume 2022, Article ID 3656932, 13 pages
https://doi.org/10.1155/2022/3656932

Review Article

Processing Agroindustry By-Products for Obtaining Value-Added Products and Reducing Environmental Impact

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Received 13 August 2021; Revised 22 September 2021; Accepted 14 March 2022; Published 1 April 2022

Academic Editor: Alberto Figoli

Over four billion tons of foods are produced annually on the planet, and about a third is wasted. A minimal part of this waste is incinerated or sent to landfills for treatment, avoiding contamination and diseases; the rest is disposed of elsewhere. The current review was aimed at broadening the panorama on the potential of agroindustrial by-products in applications such as biofuels, biomaterials, biocompounds, pharmaceuticals, and food ingredients. It also exposes the main chemical, physical, and biochemical treatments for converting by-products into raw materials with added value through low environmental impact processes. The value of agroindustrial waste is limited due to the scarce information available. There is a need for further research in unexplored areas to find ways of adding value to these by-products and minimizing their contamination. Instead of throwing away or burning by-products, they can be transformed into useful materials such as polymers, fuels, antioxidants, phenols, and lipids, which will effectively reduce food waste and environmental impact.

1. Introduction

The residues or by-products are waste materials that have lost their usefulness or economic value generated in human activities, such as industry, commerce, forest exploitation, livestock, and agriculture [1]. The principal types of by-products are construction materials, mining constituents, and health, radioactive, domestic, commercial, and industrial wastes resulting from the processes of manufacture and industrial activities [2].

In general, wastes comprise exorbitant amounts of garbage transported from domestic or industrial areas to a landfill or a processing plant to prevent environmental impact due to their high degree of contamination. The principal resources affected by these residues are the soil, air, and aquifers. Besides, their disposal has a high cost and does not solve the problem.

The Food and Agriculture Organization of the United Nations reported that a third (approximately 1.3 billion tons annually) of the total food produced for humans is wasted worldwide [3, 4]. Agroindustrial by-products are primarily produced through the food chain in harvest operations, storage, transportation, industrial processing, packaging, wholesale and retail, domestic consumption, and other activities [5]. Nevertheless, many agroindustrial by-products are not reused or treated for proper disposal, negatively impacting human or animal health [6].

The traditional way of disposing of agroindustrial by-products is by landfill storage and incineration outdoor, which cause more contamination and do not generate valuable products.

The conversion of by-products to useful products or biorefinery must be strategic to obtain a high recovery and low environmental impact [7].

In recent years, scientists and business people worldwide have worked together to identify physical, chemical, or biochemical treatments that give utility to agroindustrial by-products [8], converting them into value-added products, such as fuels, food ingredients, chemicals, biomaterials, pharmaceuticals, and fertilizers [9–11].

This review was aimed at showing the transformation treatments of agroindustrial by-products and the diversity of unconventional sources for gathering raw materials and broadening the panorama on the usefulness and valorization of the by-products.

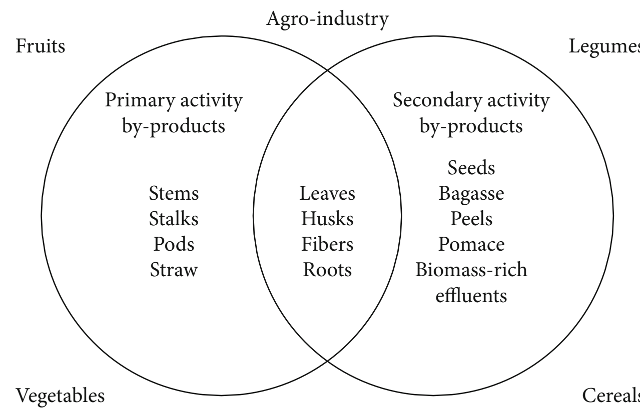

Figure 1: Agroindustry by-products.

2. Methodology and Criteria Used for the Search and Selection of References

The methodology used for this review was following the guidelines proposed by Snyder [12]. We used both the systematic literature review and the integrative review approaches. Accordingly, four steps were utilized: (1) the design of the review, (2) the conduction of the review, (3) the analysis of the information, and (4) the review's writing. The databases used for this work were ScienceDirect, Elsevier, Springer, and Google Scholar. The emphasis in the literature search was given to scientific evidence supporting the use of agroindustrial by-products as raw materials to obtain products with characteristics of interest for other industries, the treatments used in their transformation, and their environmental impacts. Furthermore, to reduce the sample size and avoid the articles unrelated to the review, the search was restricted to the last ten years, followed by the debauched checking of abstract and conclusions to choose the appropriate articles.

3. Agroindustrial By-Products

The agricultural products most used in the industry are fruits, vegetables, legumes, and cereals, and their processing generates waste or by-products that have no apparent value. The by-products are derived from primary activities such as agricultural activity (harvesting and pruning) and secondary activities such as the industrial processing of the primary products (Figure 1) [11].

The by-products of primary sources are the residues resulting from harvesting, pruning activities, and collecting products in the field crops. These can be logs, straws, leaves, husks, roots, and seeded pods from crops [11].

These by-products can be considered green or dry according to their moisture content. Greens are high in moisture content and generally decompose in the field. Dry waste has low water content, such as straw, stems, stubble, or leaves, that can be incorporated into the soil, burned, or collected; the collected regularly are used as livestock feed [2, 13].

On the other hand, by-products resulting from secondary activities are the remnants of the industrial transformation of crops into products. These are mixtures of shells, seeds, roots, bagasse, skins, pulps, and effluents rich in biomass resulting from the industrial process to obtain juices, sauces, jams, and flours, among others [1, 14]. Some by-products can be green or dry, such as leaves, husks, or roots, in which the classification depends on the use of the main product. For example, corn destined to make flour produces primary by-products, such as the leaves and stems of the harvest; however, the corn used to preserve grains maintains the leaves at harvest, but these are discarded in the processing.

The agroindustry produces a large number of by-products each year, and a few of them are traditionally reused in animal feed, crop fertilization, and fuel production, but most are disposed of in landfills or incinerated for disposal [15–17]. However, by-products have a complex and valuable content of chemical and nutritional components, implying that more high-value by-products can be processed for other uses, such as raw materials used in industries as pharmaceutics, food, construction, or medicine [18–20]. The recovery of raw materials of those interesting compounds from by-products depends on the quantities of value-added molecules they have and the treatment that has to be applied to obtain them.

4. Treatments Applied to By-Products

The growing interest in valuing the by-products from agroindustries has led the search for treatments capable of transformation with economic and environmental benefits. From 2006 to date, research related to the use of by-products has increased worldwide, being first-world countries at the top of the list [3].

The pretreatments and treatment processes (processing) applied to by-products use a series of physical, chemical, or biochemical methods to transform organic matter into new products or extract the compounds of interest [9]. Figure 2 shows the principal treatments applied to agroindustrial by-products and the potential biomolecules recovered from them.

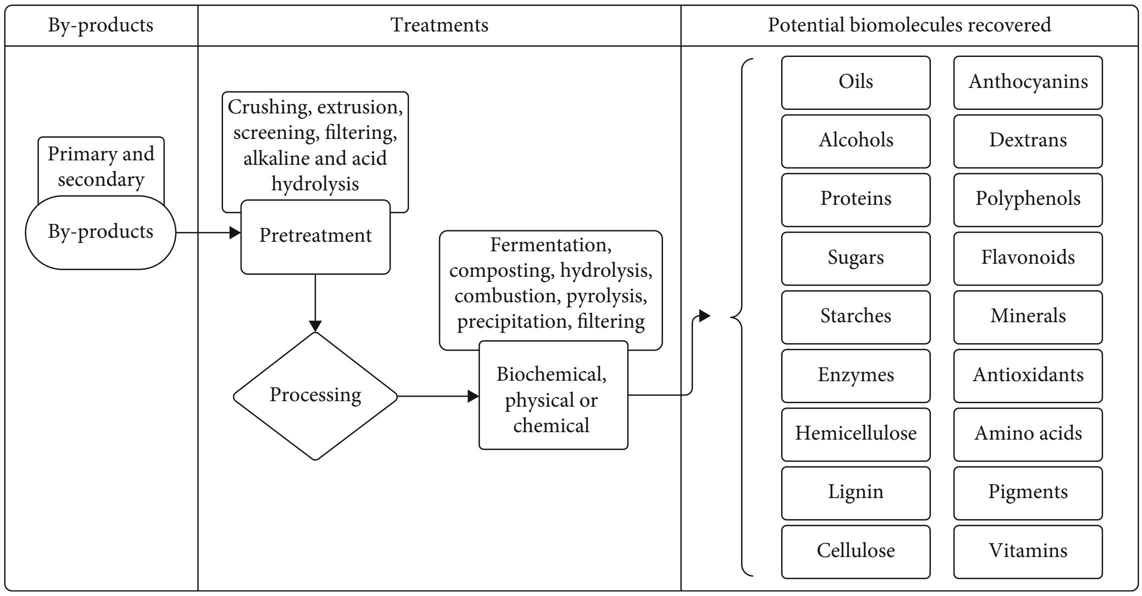

Figure 2: Potential biomolecules recovered from by-products using emerging techniques.

By-product pretreatments are those physical methods such as crushing, screening, and filtering and chemical methods such as alkaline hydrolysis, which facilitate access to reactive molecules, followed by processes to obtain the raw material of interest [21]. Treatment processes such as fermentation, pyrolysis, precipitation, hydrolysis, combustion, composting, and filtration generate the segregation of toxic and lower value compounds from raw materials and transform biomass into new products [22]. The objective of the pretreatment and processing of agroindustrial by-products is to generate value-added compounds useful in food ingredients, pharmaceuticals, fuels, and biological materials [23]. The main processes to which the by-products are subjected to obtain new commercial valued products are described below.

4.1. Biochemical Treatments. Biochemical treatments use the metabolisms of microorganisms such as fungi and bacteria to replace one or more synthetic compounds in chemical reactions. These treatments are also widely used to generate compounds mostly compatible with animals and humans and produce waste with lower contamination than synthetic chemical compounds [7, 24]. Fermentation and composting are the most common of those treatments.

4.1.1. Fermentation. Fermentation is an incomplete oxidation process carried out by fungi or bacteria, which converts the organic matter of complex molecules such as sugars into simple compounds, e.g., alcohols, propionic acid, acetic acid, lactic acid, butyric acid, and galacturonic acid.

Fermentation can be conducted with solid or semisolid materials and water or oxygen limitations [9, 25]. It has been reported that the fermented sweet corn husk and cob and bagasse are utilized to generate animal feed; an experiment that lasted 90 days included 48 fattening steers (264 ± 37.4 kg body weight) randomly allocated to three diets. The average BW gain was significant in steers with a diet containing a mixture of bagasse–vinasse, including pineapple peel silage [26].

Also, grape pomace, a by-product recalcitrant to degradation, when fermented by fungi, reduces phytotoxicity of water-soluble fractions by eliminating monoaromatic compounds. The transformation of grape pomace was evaluated using a steam pretreatment followed by incubation for 90 days with six different fungi. Several of the fungi tested reduced the phytotoxicity of water-soluble fraction from steam-pretreated grape pomace after 90-day incubation; a fraction was applied to lettuce and tomato seeds under germination (83.1 and 90.1 of percent germination). *Ulocladium botrytis* G. gave the most considerable effective phytotoxicity reduction. The resulting product has been used as organic amendment in agriculture [27].

Torres-León et al. [28] reported that solid state from the fermentation of mango seed using the fungus *Aspergillus niger* could mobilize the polyphenolic compounds improving their antioxidants properties. The total phenol content in ethanol extract increased ($p < 0.05$) from 984 mg gallic acid equivalents/100 g to 3288 mg gallic acid equivalents/100 g at 20 h of fermentation. This ethanol extract is particularly promising as a natural antioxidant.

Furthermore, Carpinelli Macedo et al. [29] generated lactic acid (31.6 g/L) from the fermentation of cassava bagasse and corn liquor using *Bacillus amylovorus* and *Lactobacillus acidophilus*.

The review of Mu et al. [30] reported that hydrogen production based on the consumption of lactate has the potential to be the predominant fermentation mechanism when using a variety of potential feedstocks. The latent beneficial effects of lactate-based hydrogen-producing processes are hydrogen production, biomass retention, pH regulation, oxygen depletion, microbial contamination, substrate hydrolysis, and detoxification. They mention that to have advantageous lactate-driven hydrogen fermentation systems, it is necessary to consider multiple aspects, including the characteristics of the substrate/feed material, the culture conditions, and the biological factors. The application could prevent the frequently reported operational problems in hydrogen-producing bioreactors, such as overgrowth of lactate-producing bacteria and, in the worst case, a process failure.

4.1.2. Composting. Composting is an oxidative biological decomposition process of organic materials generated by the metabolism of existing microorganisms such as psychrotrophic, Saccharomycetales fungal strains, and the bacteria actinobacteria and proteobacteria [31, 32]. Composting is carried out under aerobic conditions and part of the process under thermophilic conditions (>50°C). Vermicompost is a variant of this process that uses the metabolism of worms to transform complex molecules into simple ones.

Various cellulose-rich by-products and phenolic compounds can produce urea, ammonia, and other simple compounds by vermicomposting. The compounds obtained are easily assimilated by crops [33].

The use of grape pomace compost added with hen droppings proved to increase the dry matter in corn more than chemical fertilizer. 0.71 g compost/pot, used as an organic fertilizer in corn grown during twenty days, increased dry matter more than 10% when compared to chemical fertilizer [34]. Besides, the vermicomposting of sugarcane bagasse has been used to obtain lignocellulosic products faster than traditional composting. The waste by-products of the sugarcane industry, bagasse, press-mud, and trash have been subjected to fermentation followed by vermicomposting to shorten stabilization time and improve the quality of the products. Press-mud alone and in combination with other by-products from the sugar processing industries was predecomposed for 30 days by fermenting with a combination of *Pleurotus sajorcaju*, *Trichoderma viride*, *Aspergillus niger*, and *Pseudomonas striatum*. This treatment was followed by vermicomposting for 40 days with the native earthworm, *Drawida willsi*. The effect of adding microbial consortium in the sugarcane by-products reduced the time required for vermicomposting from 40 days to 20 days and produced a nutrient-enriched compost product [35].

Significantly, various by-products rich in cellulose and phenolic compounds can break down to produce urea, ammonia, and other simple compounds that are easier to integrate into the crops [33]. Composting reduces phytotoxicity, eliminates pathogens, weeds, and seeds, and stabilizes the material concerning the demand of nitrogen and oxygen to avoid microbial competition for these elements with plant roots [36].

4.2. Chemical Treatments

4.2.1. Hydrolysis. Hydrolysis is a chemical process in which a molecule is divided into two parts by adding water or other compounds. It usually involves adding of diluted acids or alkaline solutions to dissociate complex molecules or compounds to simple elements.

The acid hydrolysis process is applied to some lignocellulosic by-product fragments of cellulose and hemicellulose, which can be used as a raw material in other products [37]. For example, Martín-Sampedro et al. [38] obtained a stable thermal lignin from *Populus alba* L. using 180°C, 60 min with a liquid/solid ratio of 20 : 1, and 3% *w*/*w* of H_2SO_4.

Abaide et al. [39] reported the production of cellobiose (18.0 g/L), xylose (17.7 g/L), arabinose (3.6 g/L), glucose (1.5 g/L), and levulinic acid (0.7 g/L) sugars. The procedure consisted of the acid application of subcritical water hydrolysis on rice husks at 25 MPa in a semicontinuous mode. The highest reducing sugar yield (18.0 ± 2.9 g/100 g husks) and efficiency (39.5 ± 1.7 g sugars/100 g carbohydrates) were obtained at 220°C and 7.5 g water/g husks.

Tibolla et al. [40] utilized alkaline and acidic hydrolysis on a banana peel, obtaining nanocellulosic materials (average diameter of 3.72 nm). A cellulose compound was isolated from banana peel by applying alkaline treatment and bleaching followed by acid hydrolysis with 0.1, 1.0, or 10% *v*/*v* H_2SO_4.

4.2.2. Precipitation. The precipitation process is utilized to separate products from a solution; a solid and liquid phase is usually obtained due to the chemical reaction between them. Alcohols are precipitating agents, which cause the separation of related products. He et al. [41] recovered insoluble dietary fiber (IDF) from blackcurrant pomace (68.73 ± 0.35 g IDF/100 g), banana peels (54.06 ± 0.30 g IDF/100 g), clementine peel (42.55 ± 0.55 g IDF/100 g), oat hull (74.53 ± 1.14 g IDF/100 g), potato peel (59.38 ± 1.02 g IDF/100 g), and wheat bran (45.6 ± 0.18 g IDF/100 g) by-products utilizing the ethanol washing method. Their results showed that the dietary fiber obtained by the alcoholic extraction contained bound phenolic compounds and had water and oil holding properties, protein absorption, and radical scavenging capacities. These authors also demonstrated the carrier properties and protective effects against heat shock of the six IDFs on three Lactobacillus strains (*Lactobacillus acidophilus* LMG9433T, *Lactobacillus casei* LMG6904T, and *Lactobacillus rhamnosus* LMG25859), observing a better response with the IDF of clementine peel.

Zhang et al. [42] utilized ethanol precipitation to obtain polysaccharides from bamboo. The process was carried out using the bamboo shoot waste that was defatted and decolored with petroleum. The pretreated residues were filtrated, air-dried, and extracted twice with distilled water in an ultrasonic processor. The extract was concentrated using a rotary evaporator under reduced pressure, and ethanol was added to precipitate polysaccharides. Then, the mixture was centrifuged to obtain the precipitated polysaccharides. They concluded that the polysaccharides' physicochemical properties and antioxidant activities were enhanced by the ethanol concentration used to precipitate, 75%.

Campos et al. [43] also applied the precipitation process with a low carrageenan concentration (<0.3% *w*/*v*) to industrial pineapple residues (stems and peels), obtaining a high recovery yield of active bromelain enzyme.

4.2.3. Pyrolysis. Pyrolysis is a process by which organic materials suffer thermal degradation into smaller volatile particles, without oxygen or any other oxidants [11].

By-products are converted into oils, a mixture of gases (methane, hydrogen, carbon dioxide, and carbon monoxide), ash, mainly enriched with carbon, and heat energy [3, 35, 44]. Gurevich Messina et al. [45] applied copyrolysis on peanut shells and cassava starch mixtures obtaining biochar with low water and mineral content and maximizing the bio-oil yield. A mixture composed of 75 w % of starch and 25 w % of peanut shells led to a maximum bio-oil yield (58.2 w %), while its water content was reduced by 3.4% compared with the value expected from the weighted average of the individual results of each component in the mixture. Furthermore, the addition of the starch to the peanut shells led to biochar with less ash content.

Marculescu and Ciuta [46] reported that the pyrolysis applied to grape marc, in a tubular batch reactor with inert conditions (nitrogen 100 cm^3/min) and the heating rate (40-50°C/min) to 500°C, produced three fractions: a liquid (light hydrocarbons), a solid (char and ash), and a volatile (CO_2, CO, H_2, CH_4, C_2H_4, and C_2H_6). Their results demonstrated that the energy provided by the grape marc was 19,729 kJ/kg, energy potential even higher than wood biomass.

Additionally, Kwon et al. [47] applied the pyrolysis process to banana peel, as an alternative transformation treatment of wastes with low environmental impact; they obtained a rich biochar material. To synergistically increase the sustainability of banana peel pyrolysis, in their study, they adopted carbon dioxide as raw material and examined the production of syngas as compared to the process with N_2 in the environment. CO_2-Cofeed pyrolysis expedited the thermal cracking of volatile pyrolysates from the banana peel, resulting in the gas phase homogeneous reaction between CO_2 and the pyrolysates at ≥420°C; this promoted the formation of CO in the temperature region, and more than twenty times of CO was formed in comparison with pyrolysis in the N_2 environment. The researchers demonstrated the environmental benefits of the process due to the use of CO_2 as a reactant.

4.2.4. Direct Combustion. The combustion of agroindustrial wastes consists of the rapid chemical oxidation of biomass, use of oxygen, energy release, and the simultaneous formation of the latest oxidation products of organic matter, CO_2, and water. This process aims to obtain heat energy by direct combustion of dry by-products such as stems, logs, cobs, or straws mainly produced at the harvest stage [48]. Agroindustrial by-products are generally burned for various purposes, including cooking, charcoal production, steam generation, mechanical applications, and electrical energy applications. Due to its lower cost, direct combustion is still considered a dominant technology [9]. Park et al. [48] found that a useful high calorific resource can be obtained by mixing the pepper, rice chaff, and spent coffee ground, molded into pellets.

Also, Ríos-Badrán et al. [49] evaluated the calorific power of sustainable biofuels by manufacturing pellets obtained from rice husks and wheat straws. They found that the pellets made from mixtures of both by-products improved the combustion characteristics having the highest calorific power (4301.10–4573.50 kcal/g) and the most reduced value of ashes compared to those pellets made only of rice husks (3090.64–4049.05 kcal/g). Accordingly, Miranda et al. [50] show that the mixtures of by-products could enhance both the manufacture of the pellet and the thermal properties of the combustion power of olive pomace and forest waste pellets, depending on the proportions of the components and their physicochemical characteristics.

4.3. Physicist Treatments

4.3.1. Filtration. The use of standard and new technology membranes carries out filtration based on selective porous barriers, through which fluids and solutes are selectively transported with the application of transmembrane pressure. Nowadays, micro-, ultra-, and nanofiltration have been proposed not only for the treatment but also for the valorization of agroindustrial by-products. These technologies present advantages such as mild operation conditions and specificity and they are noncontaminant.

The membrane processes are based mainly on some key factors that influence the performance of the process such as the physicochemical composition of the feed stream, the operating parameters, and the membrane features. Accordingly, membrane fouling is the result of specific interactions between the membrane and the properties of the feed components such as molecular size, shape, ionic charge, chemical interactions, and zeta potential, among others, so they must be considered in the process. Furthermore, engineering factors have a prominent influence on membrane fouling, so the temperature, the transmembrane pressure, and the cross-flow velocity have to be considered. Finally, the membrane structure properties of hydrophilicity, hydrophobicity, pore size, and charge influence the process too [51].

These separation processes focus on liquid by-products rich in biomass and phenolic compounds, such as anthocyanins, phenolic acids, and flavonoids. There is currently a trend to apply membrane technology in industrial processes known as the circular economy, in which the reuse of waste plays a crucial role. Therefore, membrane technology (micro-, ultra-, and nanofiltration) applies to processes involving by-products of agribusiness [52].

Cicci et al. [53] applied ultra- and nanofiltration membranes to olive mill wastewater to obtain organic products used as growing media for microalgae. The results of the membrane process demonstrated that the use of membranes seems to be a practical technology to purify organic materials from olive mill wastewater, as long as short-term fouling is under control.

Cassano et al. [54] combined ultra- and nanofiltration membranes, recovering nutraceutical compounds from agrofood wastewater. The authors conclude that the separation capability of the combination offers new opportunities for the formulation of nutraceutical products while reducing the environmental pollution. Their efficiency depends on factors such as membrane material, the molecular weight of the organic components, and engineering conditions such as pressure, feed flow rate, temperature, and volume, among others.

Also, Castro-Muñoz et al. [55] show in their review detailed analysis on the use of emerging technologies such as pressure-driven membrane filtration processes. They argue that filtration is not only used exclusively to separate by-products and subsequent disposal but can also be used to recover and fractionate high value-added compounds, such as phenolic compounds, from agroindustrial by-products. Also, membrane filtration processes have several benefits: easy scaling, high productivity in permeate flows, low energy requirements, high separation efficiency, simple operation, and the absence of phase transition.

The "nejayote" is a by-product from the alkaline cooking of maize grain in the nixtamalization process and unfortunately contributes to environmental contamination. Castro-Muñoz et al. [56] proposed ultra- and nanofiltration membranes to recover phenolic compounds and fermentable carbohydrates, from the nixtamalization process. The research of these authors demonstrated the potential the nejayote can have in recovering high added value compounds, such as carbohydrates, polyphenols, gums, and calcium components, of interest in the food, pharmaceutical, and biotechnological areas.

4.3.2. Other Physical Processes. Physical processes do not generate chemical changes in by-products; however, they are considered pretreatments. Examples of these are extrusion, grinding, maceration, washing, mixing, heat treatment, and reverse osmosis, among the main ones. Also, before processing, waste should be stored under favorable conditions that do not cause its deterioration [11, 52]. Furthermore, the biochemical, physical, and chemical processes involved in using agroindustrial by-products must ensure the rapid use of waste and be cost-effective in maintaining the added value of the products obtained with such treatments.

Xie et al. [57] utilized a high-pressure process to study the physicochemical properties of pectins obtained from potato peel waste. They found that the high-pressure treatments led to an increase in the galacturonic acid content, as well as in the degree of esterification (Gal+Ara)/Rha ratio, and molecular weight decreases. These results suggest that high-pressure treatments could be an efficient technique to modify pectin from potato peel waste to get thickener or stabilizer agents.

Gouw et al. [58] utilized a heat treatment for increasing the amount and bioaccessibility of phenolics and dietary fiber in four pomace fruits (PF). The process was carried out using the frozen pomace (wet) thawed at room temperature dried in an impingement oven set at 110°C for 3 h and tested in vitro digestion as primary treatment. The results showed all PF have interesting phenolic and dietary fiber content. Authors suggest that their study demonstrated the potential of using FP as fiber-rich and antioxidant functional ingredient.

Also, Arcila et al. [59] utilized the extrusion pretreatment with high or low moisture (15% and 30% w) and high or low screw speed (120 and 250 rpm) to increase the non-starch polysaccharides from wheat bran enabling greater in vitro fermentability by human fecal microbiota.

5. Application of By-Products

As mentioned, by-products contain compounds of excellent chemical and nutritional interest, such as proteins, sugars, enzymes, pigments, flavorings, alcohols, fatty acids, antioxidants, vitamins, minerals, gelling agents, biofuels, antiseptics, and fungicides, among others (Figure 3) [60, 61]. The different treatments mentioned above are applied to by-products for recovering raw materials for its transformation into biofuels, chemicals, biomaterials, pharmaceutical ingredients, and foodstuffs [17]. Below, we will detail the application of the various by-products that have been documented in recent years.

5.1. Biofuels. Biofuel production represents a new economic opportunity to reduce greenhouse gas emissions and improve sustainable energy production. Besides, the possibility of recycling wastes for bioenergy production can reduce oil dependence and have positive impacts on the economy, environment, and society. Biofuels are generated by fermentation and thermochemical processes of biomass [62, 63].

Biofuel production can use substrates such as seeds, grains, or sugars from crops of maize, wheat, rice, and first-generation sugar. However, these conflict with food production; thus, alternative sources rich in lignocellulosic biomass such as by-products are sought [44]. The use of by-products does not enter conflict with staple foods, in addition to be low-cost substrates.

For instance, Maragkaki et al. [64] utilized sewage sludge mixtures with five different residues (95/5 *w*/*w*) to obtain biogas by digestion. Their study shows that the higher methane production was in the following order: crude glycerol > food waste > cheese whey > grape residues > sheep manure. Also, in the research by Scaldaferri and Pasa [65], cashew nutshell liquid was used as a feedstock to produce green diesel (mixed hydrocarbons with 98% efficiency) by cracking it in a batch tank reactor.

Alvarez-Guzmán et al. [66] reported significant efficiency in producing hydrogen and alcohols (ethanol and 2,3-butanediol) using sugarcane molasses instead of wheat straw hydrolysate by dark fermentation with an *Antarctic psychrophilic* GA0F bacterium.

Regarding the use of different substrates, Molinuevo-Salces et al. [67] analyzed the potential of swine manure as substrate and apple pomace as a cosubstrate for biofuel production into biogas based on manure. Different bacterial and yeast strains (strains of *Kluyveromyces marxianus*, *K. lactis*, *Lachancea thermotolerans*, and *Saccharomyces cerevisiae*) were compared to produce bioethanol, obtaining yields of 0.371–0.444 g/g substrate. Also, specific methane yields from bioethanol and biobutanol fermentation residues were 463 and 290 mL CH_4/g substrate, respectively. Methane yield for the codigestion of apple pomace and swine manure was 596 mL CH_4 g/substrate, with an apple pomace percentage of 14.6% and a substrate concentration of 9.38 g/L. The

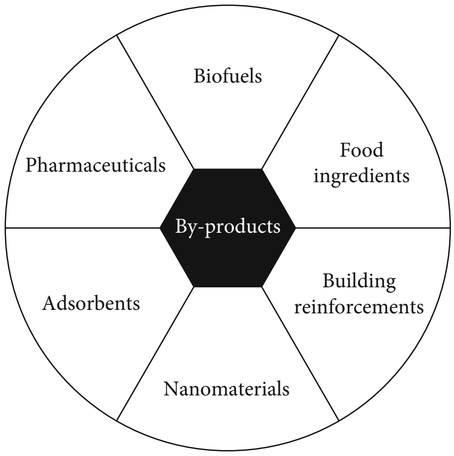

Figure 3: Potential application of by-products.

researchers concluded that apple pomace significantly impacted biofuel production (bioethanol, biomethane, and biobutanol) as cosubstrate.

5.2. Food Ingredients and Pharmaceuticals. The valorization of by-products as pharmaceutical and food ingredients is widely recognized [58–60]. By-products can be used as primary substrates or raw materials to produce multiple medium or high value-added compounds.

He et al. [41] efficiently recovered dietary fiber from blackcurrant pomace, banana peels, clementine peel, oat hull, potato peel, and wheat bran through an ethanol-washing process directed to dried by-products to be applied as probiotics.

On the other hand, cassava bagasse (18% *w*/*v*) and corn liquors (12% *v*/*v*) were pretreated by enzymatic hydrolysis (*Rhizopus oligosporus* amylase) and then fermented with *Lactobacillus amylovorus* and *Lactobacillus acidophilus* to produce lactic acid [29]. Furthermore, natural deep eutectic solvents extracted phenolic compounds from onion seed, olive cake, tomato waste, and pear waste [68]. Wheat bran acid hydrolysate is being used to produce triacylglycerols of oleic acid by fermentation with the yeast *Rhodotorula mucilaginosa* Y-MG1 [69]. Also, sugarcane bagasse, corn stalks, and rice bran irradiated with UV and gamma were used to produce the immunosuppressant mycophenolic acid under solid-state fermentation by the *Penicillium roqueforti* fungus [24].

Nejayote, produced by nixtamalization, is a source of food, nutraceutical, and cosmeceutical ingredients. Ramírez-Jiménez and Castro-Muñoz [70] reported that feruloylated arabinoxylans extracted from nejayote have viscoelastic and nutraceutical properties that can be used as texture enhancer and also as probiotic and insulin regulator. They also identified hydroxycinnamic acids in nejayote (p-coumaric and ferulic acid) that can be utilized as antioxidants in the food and cosmetic industry.

Waste and by-products are currently used as raw materials in fermentation broths to produce valuable compounds. In addition, some pretreatments applied to by-products provide them the chemical properties for their products to be considered efficient ingredients in biotechnological applications. García-Depraect et al. [71] evaluated the effect of long-time refrigeration to effectively preserve the hydrogenogenic biomass for months, supplying readily available inoculants after reactivation. Hydrogen-producing bacteria and lactic acid bacteria had a notable presence all over the whole period of preservation and during reactivation.

Table 1 shows several products with food and pharmaceutical value obtained from agroindustrial by-products.

5.3. Materials: Adsorbents, Nanomaterials, and Building Reinforcements. An emerging field of exploitation of agroindustrial by-products is their use as adsorbents for heavy metals, nanomaterials, and building reinforcements.

Adsorbents for heavy metals are expensive, and the origin of the elements is synthetic. Recently, attention has been given to biobased materials, mainly agroindustrial by-products such as fruits, cereals, legumes, and vegetables, easily accessible in large quantities.

By-products from citrus are rich in lignin, cellulose, and pectin containing many functional groups such as hydroxyl and carboxylic groups that could bind to divalent cations. Meseldzija et al. [72] used lemon peels as a low-cost adsorbent to remove 89% of the copper ions from mining wastewater at natural pH (pH 3). Also, Cunha et al. [73] utilized coconut mesocarp and magnetic cobalt ferrite in xerogel to remove 86% and 49% of cadmium (pH 3) and lead (pH 4) ions, respectively. The coconut mesocarp showed high reuse capacities in three successive reduction cycles. Likewise, Muniz et al. [74] utilized ripe okra and passion fruit seeds as natural coagulants to dairy wastewater for solid-liquid separation in coagulation/flocculation. Both materials could reduce up to 90% of the turbidity. These results suggest that the seeds of both materials could be good sources of coagulant agents that can replace the metallic coagulants and reduce the production of agroindustrial wastes.

On the other hand, cellulose has been widely used to prepare thermosetting and thermoplastic polymers as to replace glass fiber. Cellulose is the best alternative to fiberglass because it offers minor abrasion to the fiber during processing and it can be recycled; besides, it is cheap and available [75].

It has also been possible to extract cellulose up to the nanoscale, showing outstanding characteristics by using chemical methods that reduce its diameter and length [76]. The term "nanocellulose" generally refers to cellulose materials with at least one dimension in the nanometric range [75]. Accordingly, by-products have proven to be a reliable source for the extraction of nanocellulose. It has been reported that applying a chemical (hydrolysis acid) and physical pretreatments (washed, dried, milled, and filtering) to grape pomace resulted in bleached cellulose pulp, and then, through acidic hydrolysis and ultrasound treatments, cellulose nanocrystals were obtained [77]. Also, cellulose nanofibers have been obtained from banana peel bran using chemical (alkaline treatment, bleaching, and acid hydrolysis) and enzymatic treatment (alkaline treatment and hydrolysis with xylanase) [40].

Table 1: By-products with food and pharmaceutical value.

By-products		Value-added products	Source
Cassava	Bagasse	Gluten-free noodle	Fiorda et al. [86]
Sugarcane	Bagasse	Ethanol, lactic acid	de Moraes Rocha et al. [87]; Laopaiboon et al. [88]
Palm	Empty fruit bunch	Xylose	Tan et al. [89]
Pineapple	Peels	Citric acid	Kuforiji et al. [90]
Pineapple	Husk	Dietary fiber	Martins et al. [91]
Tomato	Pomace	Dietary fiber	Martins et al. [91]
Rice	Bran	Dietary fiber	Martins et al. [91]
Pea	Pod	Dietary fiber	Martins et al. [91]
Coffee	Bean	Chlorogenic acids, monosaccharides, disaccharides, oligosaccharides, proteins, minerals, and carboxylic acids	Pérez-Sariñana et al. [92]
Coffee	Husk	Chlorogenic acids, gallic acid, and phenolics	Das Neves et al. [93]; Gemechu [15]
Melon	Peels	Proteins	Silva et al. [94]
Melon	Seeds	Soluble sugars	Silva et al. [94]
Soybean	Seeds	Linoleic acid, linolenic acid	Silva et al. [94]
Grape	Seeds	Linoleic acid, linolenic acid	Silva et al. [94]
Olive	Pomace	Antioxidant	Bermúdez-Oria et al. [95]
Banana	Stalk	Phenolic acids	Arun et al. [96]
Mango	Pulp	Dietary fiber	Martins et al. [91]
Mango	Seeds	Linoleic acid, linolenic acid	Silva et al. [94]

Franco et al. [78] obtained nanocellulose from peach palm residues by ultrafine grinding and chemical delignification. Further, materials dispersed in polymer matrices such as nanocellulose can result in nanocomposites showing enhanced mechanical properties. The use of nanocellulose-based composites as adsorbents for metals is of great interest. For example, Tshikovhi et al. [79] analyzed nanocellulose-based hydrogel by incorporating graphene oxide into the cellulose matrix using NaOH/urea to remove copper(II) ions from an aqueous solution, finding a direct correlation between an increase in the adsorption of copper ions with an increase in graphene oxide/nanocellulose ratio.

Another exciting use of by-products is the obtention of prolamins using chemical solvents. The process generates nanofibers and nanoparticles from grains of corn, sorghum, and wheat [80]. The nanomaterials obtained are conformed principally of prolamins with different vital roles in the food industry and medicine to shield bioactive compounds, emulsion stabilizing, drug delivery systems, and control release of fertilizer.

Besides, cellulose acetate was obtained from corncob through hydrothermal treatment followed by dilute sodium hydroxide (cellulose) and acetylation reactions [22]. Also, lipase, laccase, and amylase have been immobilized into salinized green coconut fiber oxidized by periodate [81].

The replacement of ground-granulated blast furnace slag up to 40% with dehydroxylated corncob produces a geopolymer concrete at ambient curing conditions [82], exhibiting higher strengths than Portland cement concrete [83]. Likewise, Vega-Castro et al. [84] produced polyhydroxyalkanoates from the pineapple peel fermentation process.

Table 2 shows some applications of agroindustrial by-products as nanomaterials, adsorbents, and building reinforcements.

As shown, the raw materials obtained from different agroindustrial by-products have essential applications as carriers of drugs, biofuels, food ingredients, compounds of high nutraceutical value, antioxidants, biopolymers, adsorbent compounds, and concrete reinforcements, among others.

6. Importance of the Use of Agroindustrial By-Products as Raw Materials

The growing demand for products, energy, and environmental policy has considerably increased the interest in recycling, reuse, and recovery of by-products, residues, wastes, and sewage [16]. The use of agroindustrial by-products solves different environmental problems, originated by the generation and disposal of these wastes; it reduces the demand for renewable and nonrenewable natural resources as raw materials. According to the international agenda for 2030, the Sustainable Development Goals aim to halve per capita food waste globally at the retail and consumer level and reduce food losses in production and supply chains, including postharvest losses [4].

One of the aspects that can define the sustainability of development is its environmental impact. The use of

Table 2: By-product applications as nanomaterials, adsorbents, and building reinforcements.

By-products		Use	Source
Açaí	Fibers	Concrete binder	Azevedo et al. [97]
Cauliflower	Cores	Heavy metal adsorbent (Cd^{2+}, Cu^{2+}, Ni^{2+}, and Zn^{2+})	Landin-Sandoval et al. [98]
Coconut	Shell	Heavy metal adsorbent (Cd^{2+}, Cu^{2+}, Ni^{2+}, and Zn^{2+})	Landin-Sandoval et al. [98]
Grape	Pomace	Nanofibers as green agent for dendritic silver synthesis	Carbone et al. [99]
Palm	Oil fuel ash	Concrete binder	Nagaratnam et al. [100]
Palm	Shell	CO_2 adsorbent	Ochedi et al. [101]
Rice	Husk	CO_2 adsorbent	Ochedi et al. [101]
Soybean	Pods	Nanofibers as reinforcement of films proteins	González et al. [102]
Soybean	Hulls	Copper ions adsorbent	Wartelle and Marshall [103]
Walnut	Shell	CO_2 adsorbent	Ochedi et al. [101]

agroindustrial by-products reduces this environmental impact and the cost of waste treatment. At the same time, it benefits the corporations economically by adding value to by-products and wastes. Accordingly, "the circular economy" is presented as a system of resource utilization, where reduction (minimum use of raw materials), reuse (maximum reuse of products and components), and recycle (high-quality reuse of raw materials) are the elements based on the production systems [85].

Accordingly, the processing of by-products must adjust to a sustainable system; thus, in the extraction of value-added raw materials, the environmental impact that this process could generate must be considered. As well as the evaluation of the economic viability of the proposed processes is also essential; for this reason, it is necessary to estimate the retail price of the potential product, range of applications, storage costs, transportation, volume and size, flexibility, and location of the by-products [36].

Zihare et al. [6] suggest considering engineering, environmental, and economic criteria to evaluate the impact of the transformation of by-products, helping scientists and investors make sound decisions. Other essential aspects to consider in the transformation of by-products are toxicity (pesticides and mycotoxins), hygiene, safety issues, effects of processing and storage on the functional components of by-products, and interactions with other compounds [15].

7. Discussion

Agroindustrial by-products represent a critical problem for their traditional disposal, but they can function as high-value feedstock in other industries. With the above mentioned, the agroindustrial by-products offer various applications as raw materials in the food, pharmaceutical, and fuel industries, among others. However, the appropriate pretreatments and treatments must be chosen strategically to obtain materials with high nutritional value, later translating into rising economic value.

There is a need to explore the most significant number of physical, chemical, or biochemical treatments in the by-products to standardize the methods for obtaining the products of interest and discern the performance of each product and be able to transfer it to an industrial scale. The combination of treatments is a promising opportunity. In turn, they enhance the reduction of the quantitative environmental impact by using raw materials derived from by-products instead of synthesized raw materials.

The development of extraction and purification systems for raw materials could facilitate access to chemical components with greater sensitivity and specificity. The methods for obtaining biomaterials related to nanomaterials require a more exhaustive analysis to detect by-products with these properties, which could considerably increase the economical and chemical value. The study of the treatments of alternative sources of raw materials for the pharmaceutical, food, fuel, construction, and biomaterials industries is limited in these aspects. It is essential to consider that the recovery of biocompounds from by-products must be a sustainable process that contributes to economic, environmental, and social development.

8. Conclusions

Throughout this in-depth review, pretreatments and treatments such as fermentation, composting, hydrolysis, precipitation, pyrolysis, combustion, and filtration can be used to recover, separate, and fractionate specific compounds; in agreement to their properties, they have potential applications in the biofuels, biomaterials, biocompounds, pharmaceuticals, and food industries from new sources, known as agroindustrial by-products. By-products are on the rise in both producing and transforming countries.

Agricultural production and consumption continue increasing, putting high pressure on natural resources. Food losses in the value chain must be addressed or considered for soil amendments and for the production of environment-friendly by-products.

The circular economy is a production and consumption model that involves sharing, renting, reusing, repairing, renovating, and recycling existing materials and products as many times as possible to create added value. In this way, the life cycle of the products increases. The knowledge of the various applications of agroindustrial by-products as new raw materials with added value in other industries opens the picture to focus the efforts to apply emerging technologies in the recovery of these materials. In practice, it means reducing waste to a minimum. When a product reaches the end of its useful life, its materials are kept within the economy whenever possible. These can be used productively repeatedly, thus creating additional value. This type of economic model must be implemented by all industries, not just agribusiness, to have less impact on the environment and natural resources.

Furthermore, the high costs of waste disposal make it necessary for industries that use large-scale production processes to focus on by-product recycling. The main concern is the disposal of large amounts discarded and the major environmental problems they can generate. The population worldwide must adopt modern methods and technologies to obtain value-added products such as polymers, fuels, antioxidants, phenols, and lipids, among the main ones from by-products instead of throwing away or burning food waste. In the future, governments may legislate to ensure the use of approaches such as those described herein to reduce water and environmental pollution.

Therefore, researchers must explore suitable treatments to improve the recovery of valuable materials and apply technologies, according to the characteristics of the by-products, to retain functionalities in all processing and storage conditions. Due to the diversity of by-products, specific protocols and statistical methods optimizing the procurement, transformation, and recovery of the products of interest should be proposed. This review should open the picture to encourage using by-products to generate raw materials with high added value through processes that do not affect the environment.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflict of interests, including financial, personal, or otherwise.

Acknowledgments

We thank CONACYT for both the postgraduate scholarship given to Almaraz-Sánchez Iván (CVU: 1033956) and for the SNI support to Mendoza-Sánchez Magdalena (CVU: 228845).

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