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Derivation of hazardous wastes: Pharmaceutical and food applications

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Abstract:
Around the globe, solid waste generation rates are reaching 2.01 billion tons, resulting in a footprint of 0.78 kg per person per day as of 2020. It is expected to escalate by 70% and reach approximately 3.42 billion tons by the end of 2050, indicating that waste generating and its disposal are a relevant issue worldwide. Waste can be a source of various useful pharmaceutical and food raw materials, which partially solves the global waste problem.

This comprehensive review paper focuses on different types of wastes that can yield carbohydrate polymers for pharmaceutical or food purposes. It covers systemic documentation and summarizes numerous scientific articles published in 2004–2022.

The review demonstrates a great perspective for waste re-utilization as an alternative source of pharmaceutical and food materials. It provides a complete insight into the responsible approach to hazardous waste recycling, thus promoting research in bio-waste remediation, novel raw materials, and natural sustainability.

Keywords: Agricultural waste, macromolecules, carbohydrate polymers, excipients, raw material, environment, waste generating

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INTRODUCTION

The European Union Waste Framework Directive 2008/98/EC, Art. 3, defines waste as “an object that the holder discards, intends to discard, or is required to discard” [1]. Waste generation is divided into the urban areas in developed or developing countries, with metropolitan regions of developing countries generating less garbage compared to the urban areas of developed or industrialized countries (Table 1) [2].

Waste can be classified based on its origin and type. The Union Ministry of Environment, Forests, and Climate Change of India issued a new set of Solid Waste Management Rules in 2016. The document highlights such major issues as waste segregation at place, disposal of hygienic waste, waste-to-energy methods, waste management in mountain regions, etc. [3].

Misclassification of waste leads to inappropriate handling and thus to hazards for environment or human health. This review examines the current research and methodologies that look into the source of harmful waste materials and assess their potential for repurposing as raw materials for new waste derivatives that promote sustainable practices and reduce waste burden.

STUDY OBJECTS AND METHODS

This review focuses on unsafe agricultural, municipal, industrial, farming, and biological wastes that could be used again in the food industry and healthcare. It covers influential publications registered in PubMed, Scopus, WoS, and eLIBRARY.RU within the past three decades. The information obtained was categorized based on key metrics and then subjected to a detailed comparative analysis.

Table 1 Classification of waste by its origin

Type of waste	Description
Domestic/municipal/commercial	Generated by such routine household activities as cooking, cleaning, repairing, painting, etc.
Construction/industrial	Generated by construction sites as a result of demolition, repair, construction processes, e.g., bricks, stones, cement, sand, plumbing material, electric materials, etc.
E-waste	Electronic appliances approaching the end of their useful life; hazardous to health due to presence of harmful components, e.g., heavy metals.
Biodegradable	Organic waste, e.g., fruits, vegetables, food, paper, cardboard, etc., generated by offices, schools, commercial buildings, etc. Includes such agricultural and industrial wastes as cotton, wool, leaves, timber, etc.
Non-biodegradable	Metal, plastic, steel, glass, etc.
Derelict vehicles/hazardous waste	Trucks, cars, or any other automobiles with metal scrape value that are abandoned on the roads or elsewhere
Farm/agricultural	Generated by agricultural activities, e.g., planting, harvesting, cutting, weeding, dairy production, animal slaughter, etc.

RESUITS AND DISCUSSION

Pharmaceutically valuable excipients from agricultural waste. Materials obtained by processing various agricultural waste include cellulose polymer, microcrystalline cellulose, starch, silica, chitosan, enzymes, etc.

Cellulose from agricultural waste. The unique fiber shape of cellulose is responsible for its biological function and diverse applications. Fibrils and microfibrillar bands make up its morphological hierarchy [4].

Cellulose from cotton stalk. Science knows numerous biochemical ways to extract cellulose and its derived nano-materials by breaching the hydrogen bonds between fibrils. The traditional methods include hydrolysis by chemicals or enzymes, defibrillation by mortar and pestle, and oxidation by 2,2,6,6-tetramethylpyperidine-1-oxyl (TEMPO). The TEMPO-facilitated oxidation trailed by mechanical breakdown yields cellulose nanofibrils of a uniform size. Cellulose nanofibrils are used in modified coatings in medicines, food packing or containers, nano-paper, absorbents, and nano-composites. Degumming of cotton bark is a pre-treatment for cellulose nanofibril extraction. The dried films of cellulose nanofibrils are usually examined for their yields, morphologies, crystalline structures, thermal characteristics, natural charge, and various properties. Miao *et al.* [5] reported that the resulting yield, which was as high as 20%, had a better crystallinity than the original material. The starting materials included sulfuric acid (98%), hydrogen peroxide (30%), DMSO, TEMPO (98%), sodium hydroxide (97%), sodium bromide (99.6%), sodium hypochlorite (12%), and sodium carbonate [5].

Cellulose from corn husk. Sodium carboxymethyl cellulose is a chemically altered polymer synthesized from cellulose by treating it with a water-soluble base and an organochlorine compound, e.g., monochloroacetic acid, using an organic reaction medium under heterogeneous condition. The chemicals employed are sodium hydroxide, chloroacetic acid, silver nitrate, ethanol, methanol, glacial acetic acid, benzene, ammonium oxalate, sodium chlorite, sulfuric acid, etc. [6].

Cellulose from orange peel. Cellulose can be obtained from orange peel by pulping sulfite with sodium sulfite and sodium metabisulphite. Orange peel is heated in liquid with sodium sulfate (Na_2O_3S). The final cellulose has good yield, luster, whiteness, and water retention, as well as stable molecular weight, high purity, and low crystallinity [7]. Cellulose and carboxy methyl cellulose can also be obtained from orange peel by alkali treatment [8].

Cellulose from oil palm empty fruit bunch fiber. Containing 42% of α-cellulose, empty fruit bunch fiber is a potential origin of cellulose. It is extracted by a multistep process based on a combination of alkaline treatment and bleaching. Two foremost factors affect the isolation and lightening of palm tree cellulose. First, empty fruits have 17.2% of lignin, 70% holocellulose, 42% α-cellulose, 17.2% sodium-hydroxide-soluble materials, 2.8% hot water-soluble materials, and 0.7% ash content. Second, empty fruit bunch fiber is more subtle to alkaline. After the alkaline treatment, the fibers are oxidatively bleached with a peracid/hydrogen peroxide mix to remove non-cellulosic components and increase thread hydrophilicity and approachability. Al-Hoqbani *et al.* [9] reported 30 mmol of potassium bromate, 30 mmol thiourea dioxide, and 150 g simplest unsaturated carboxylic acid as the best conditions for additional grafting (per 100 g cellulose).

Cellulose from balloon bellflower peel. In China and Korea, balloon bellflower (*Platycodon grandiflorum* A. DC) is used to cure cough, rhinitis, sore throat, hyperlipidemia, high blood pressure, and hyperglycemia. Cellulose could be recovered from this source material by chlorination and alkaline extraction [10].

Cellulose from wheat straw and soy hull. Other probable sources of cellulose nanofibrils include wheat straw and soy hull. The current application of soy hull is feeding cattle as a source of fibers while wheat straw is usually discarded as waste. In this case, cellulose extraction relies on the chemical-mechanical technique. Cellulose nanofibrils possess good thermal characteristics, with thermal breakdown temperatures up to 45%, which makes them good candidates for thermoplastic composites. Wheat straw cellulose nanofibers have prospective utility in aerospace, automotive, and medical bio-composites. Due to their shorter length, soy hull nanofibers were reported to have a better utility in low-to-medium-grade composite applications, such as commodities and building items [11].

Cellulose from soyabean straw. Soybean straw technical fibers have a high cellulose content (85%) but poor crystallinity (47%). Although they have low crystallinity, the cellulose crystals are well aligned along the fiber axis. The breaking tenacity and elongation of technical fibers are higher than those of ordinary bast fibers, e.g., linen or kenaf, but lower than those of cotton. The breaking tenacity (2.7 g/den) and breaking elongation (4%) are higher in technical fibers than in wheat straw and sorghum stalk and leaf fibers, but lower than in cotton fibers. The nature and qualities of technical fibers of soybean straw indicate that they could be used in textiles, composites, and other industrial applications. Soybean straw reduces reliance on non-renewable petroleum resources for fibers like nylon or polyester [12].

Cellulose from sorghum leaves and stems. Sorghum leaves and stems are mainly discarded as by-products. However, their chemical profile includes cellulose, hemicellulose, and such polymeric substance as lignin, which are of no economic value. The process of cellulose extraction involves alkali treatment followed by acid treatment. The resulting breaking toughness and elongation were reported as comparable to those demonstrated by natural fibers [13].

Cellulose from banana waste. To isolate cellulose fibers, banana fibers have to be separated from lignin, hemicellulose, and pectin by applying an alkaline solution and bleaching. Elanthikkal *et al.* solubilized pectin and hemicelluloses using an alkaline solution procedure [14]. The washing with deionized water removed solubilized components. The bleaching technique was used to whiten the pulp by breaking down phenolic compounds or molecules with chromophoric groups found in lignin. The by-products of that breakdown also had to be removed by treating banana fibers with 5% sodium hypochlorite at 30°C for 3 h.

Cellulose from grape skin. Grape beverage production leaves 50 million tons of pomace per year. Grape pomace is known to impede germination by immobilizing plant nutrients and raising the biological and chemical oxygen requirements. A procedure comprising organic extraction, acid and base dissolutions, basic and acidic oxidation, and bleaching produced 16.4% of pure cellulose from chardonnay grape skins. 54.9% of the extracted cellulose had a crystalline and microfibrillar structure, as revealed by Fourier-transform infrared spectroscopy (FTIR), thermal analysis, and X-ray diffraction (XDR). To create cellulose nanocrystals, the extracted grape cellulose was further hydrolyzed using an atypical sulfuric acid hydrolysis process (8.75 mL/g, 65% sulfuric acid, 45°C, 30 min) [15].

Cellulose from coconut coir fibers. Coconut coir is an available in sufficiency and recyclable plant dry matter generated out of outer casing husk of *Cocos nucifera*. Coir fibers have a considerably higher lignin content than cotton stalks. Lignin could be removed using a blend of mechanical and chemical treatments. After washing, coir fibers were milled, powdered, sieved to 100–150 mesh in a milling machine, and dewaxed. The pulverized coir strands were processed in a basic liquid at high temperature with air condenser and heating. The pulping was carried out using 6% sodium hydroxide at a ratio of 15–25 mL/g of coir threads. The pulp was rinsed in deionized water and dissolved in demineralized water with urea. Then, it was sonicated for 30 min and dispersed in a solution of NaOH, NH_2CONH_2, and H_2O. After the removal of sodium-lignin outgrowth, the

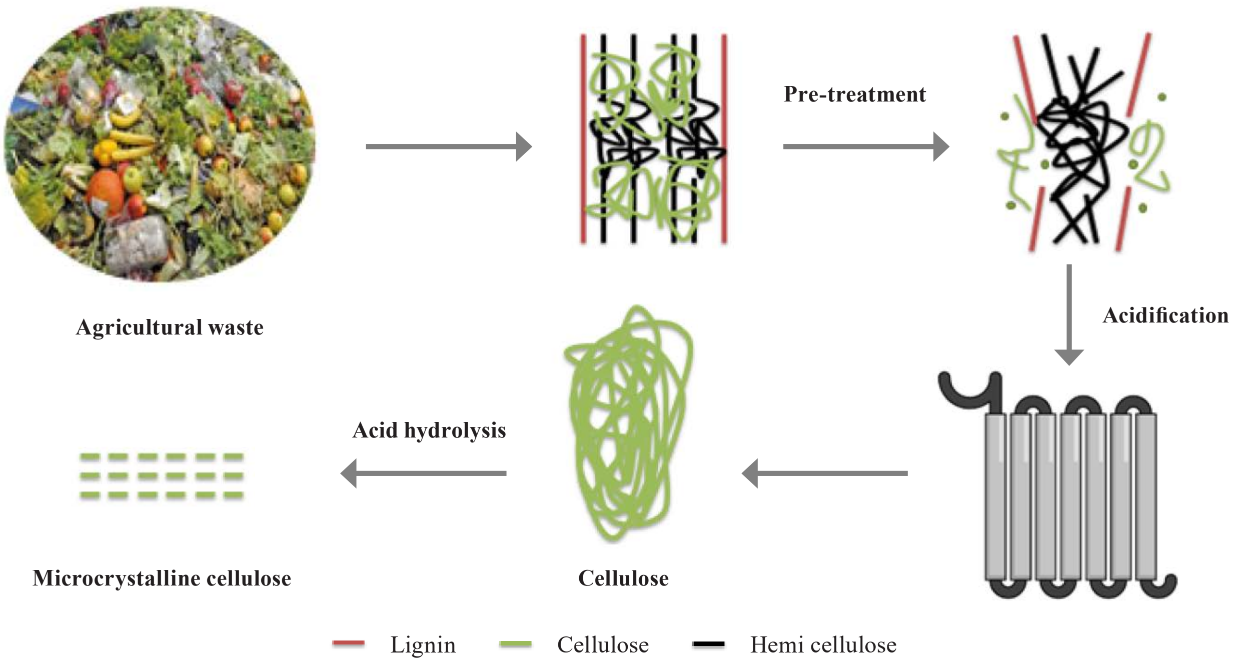

Figure 1 Obtaining microcrystalline cellulose from agricultural waste

reaction mix served as a raw material for cellulose and its derivates, e.g., aerogels [16].

Microcrystalline cellulose from agricultural waste. Microcrystalline cellulose is safe, renewable, and biocompatible. Its high natural strength, huge superficial area, and low bulk have drawn considerable scientific interest during the last twenty years. Microcrystalline cellulose is used as binders and fillers in food products and medicines. More specifically, it serves as a reinforcing agent in the formation of polymers. Besides, microcrystalline cellulose is also a suspension stabilizer, water-holding agent, viscosity maintainer, and emulsifier in pastes and creams. Traditionally, pulpwood and pure *Gossypium herbaceum* fibers were the main cellulose sources serving as an important feedstock for microcrystalline cellulose production. Figure 1 shows a diagrammatic representation of production of microcrystalline cellulose from agricultural waste.

However, new sources of microcrystalline cellulose are reported every day.

Microcrystalline cellulose from tea waste. Deep-processing produces a huge portion of tea waste. Tea leftovers are disposed of by composting, incineration, or dumping. Unfortunately, tea waste is difficult to break down, which puts a stress on the environment, not to mention a severe loss of important components. Controlled acid hydrolysis with good thermal stability is a novel way to extract microcrystalline cellulose from tea waste. Its efficiency depends on hydrochloric acid concentration, acid-to-material ratio, heat, and processing time. An orthogonal experiment design involved the degree of polymerization and tea waste yield as dependent variables. The resulting microcrystalline cellulose had smaller fibers with rough surface morphology and several surface pores [17].

Microcrystalline cellulose from fodder grass. Setaria glauca (L) P. Beauv proved to be another potential source of microcrystalline cellulose [18]. The first stage was to remove lignin and hemicellulose from the dehydrated grass with sodium hydroxide. It was followed by applying bleaching chemicals, i.e., sodium hypochlorite and hydrogen peroxide, in an equal ratio, to remove any traces of lignin and hemicellulose. After that, 10 g cellulose was acid-hydrolyzed with hydrochloric acid (2.5 N) at 100°C for 30 min. The obtained microcrystalline cellulose was properly rinsed with water to remove any traces of acid.

Microcrystalline cellulose from banana fibers. A combination of fermentation and acid hydrolysis yields microcrystalline cellulose from banana fibers. This method is economical and environmentally-safe [19].

Microcrystalline cellulose from sisal fibers. Extraction of microcrystalline cellulose from sisal fibers involves the Soxhlet extraction followed by acid hydrolysis with mineral acid treatment and bleaching. Bhimte and Tayade [20] described a three-stage bleaching procedure:

Stage 1: bleaching with water, buffer solution, and sodium chloride;

Stage 2: bleaching with buffer solution and sodium chloride solution 30 min after Stage 1; and

Stage 3: bleaching with buffer solution and sodium chloride solution 30 min after Stage 2.

The physiochemical analysis of the resulting microcrystalline cellulose showed long thread-like fibers.

Microcrystalline cellulose from mango kernel. Mango kernel is an abundant and accessible agricultural type of waste. Hydrochloric acid hydrolysis of α-cellulose obtained from the mango kernel was reported to produce microcrystalline cellulose with a compact structure and rough surface with 50% crystallinity, as evidenced by a scanning electron microscope. Its physicochemical profile demonstrated excellent flow and compression characteristics [21].

Microcrystalline cellulose from orange peel. Ejikeme obtained microcrystalline cellulose from orange mesocarp extracted after epicarp and endocarp were removed from oranges [22]. The moisture content of the dried mesocarp was 8.3%. With the α-cellulose share in the orange mesocarp being 62.5%, the yield of microcrystalline cellulose was 25.3%. Orange mesocarp underwent acid hydrolysis, and the isolated cellulose was acid-hydrolyzed with dilute mineral acid, which caused partial depolymerization. This strategy could lower the cost of microcrystalline cellulose production in areas where orange peel is easily available.

Microcrystalline cellulose from sugarcane stem pulp. In this case, the isolated cellulose was similarly acid-hydrolyzed with dilute mineral acid to cause partial depolymerization [23].

Microcrystalline cellulose from peanut shell. Peanut shell subjected to acid hydrolysis is another potential source of microcrystalline cellulose. Like in the previous cases, the resulting cellulose has to be acid-hydrolyzed with dilute mineral acid for partial depolymerization [24].

Microcrystalline cellulose from palm oil biomass. Oil palm empty fruit bunch pulp is a common source of biomass in Malaysia. The resulting cellulose has to be hydrolyzed with dilute mineral acid for partial depolymerization to yield microcrystalline cellulose. The Fourier-transform infrared spectroscopy (FTIR) confirmed that acid hydrolysis had no effect on the chemical structure of cellulose fragments. According to the scanning electron microscopy analysis (SEM), the microcrystalline cellulose obtained from oil palm empty fruit bunch had a rough and compact structure. Atomic force microscopy (AFM) revealed spherical particles. The crystallinity index was high, indicating that acid hydrolysis had no effect on the crystal building of the pulp cellulose I allomorph [25].

Starch from agricultural waste. The list of methods for obtaining starch from agricultural waste keeps growing as new research data are published.

Starch from pineapple stem waste. Pineapple properties make it an ideal source of resistant starch or thermoplastic starch in food and non-food applications, respectively. Its physiochemical examination was reported to consist of 34.4% amylose. The amylose content is the most significant factor in defining the valuable assets of type III resistant starch. As a result, pineapple starch can be used as resistant starch in functional foods for anti-diabetic diets [26].

Starch from banana peels. Catering generates high amounts of banana peel, which is an emerging source of starch as it contains 50% of starch. The technique of extraction (generally wet extraction) includes oxidation with ascorbic acid followed by grinding, filtration, and washing. The washing water waste can be processed by employing clotting + flocculation + transferring with aluminum salts, namely Al_2O_3 and $Al_2(SO_4)_3$ (10 000 ppm solution, 15 mL/L) in order to reduce turbidness and carbon-based amount prior to discarding. The yield reported under these conditions was 29% while the purity approached 70% [27].

Starch from turmeric waste. Turmeric rhizomes are rich in starch. The crop is a popular dietary food ingredient. Turmeric waste is an alternative source of starch extraction. Santana *et al.* claimed 50% of starch in turmeric waste [28]. They used supercritical extraction and pressurized fluid extraction to obtain 80% in the final product.

Starch from avocado seed. Avocado seeds (*Persea americana* Miller) are a waste by-product from fruit processing that causes ecological and environmental issues, contributing to the spread of vermin, e.g., flies or rats. Avocado seeds can be an alternative supply of starch as they contain 29% of starch. The two methods reported for starch isolation from avocado seeds are those by enzyme and by sulfite reagent. The amylose content was reported as 16% while the gelatinization temperature fluctuated from 56 to 74°C, peaking at 65.7°C; the transition enthalpy ranged from 11.4 to 11.6 J/g. At 90°C, the water solubility was 19–20% [29].

Starch from jackfruit seed. Jackfruit farming is a rapidly growing sector. Dumping jackfruit seeds is a waste of useful resources and a threat to the environment. Jackfruit seed starch remains understudied; the extraction procedure involves using protease enzyme as a potential supply of starch. After pre-treatments, the obtained product is further processed and purified to remove residues [30].

Silica from agricultural waste. Silicon dioxide is also known as silica. It is a derivative form of silicon obtained from fused quartz, flint, and agate. These methods are costly and hazardous, which indicates an urgent need for an alternative source. Today, silica is extracted from sugarcane bagasse, rice husk, peanut shell, bamboo leaves, etc.

Silica from rice husk. Rice husk is an important agricultural by-product. Its global annual output exceeds 80 million tons. Rice husk yields 72–98% of silica with a particle size of 40–50 nm [31]. Silica is a result of rice husk carbonization, which indicates that a silica amount is a temperature-dependent variable [32]. Other methods include hydrothermal crystallization, sonochemical synthesis, sol-gel technique, and pyrolysis [33–35].

Silica from peanut shell, bamboo leaves, and sugar cane bagasse. Silica can be obtained from peanut (*Arachis hypogaea* L.) shell, bamboo (*Bambusa vulgaris* L.) leaves, and sugarcane (*Saccharum officinarum* L.) bagasse. Large quantities of these waste materials pose a grave ecological threat. In line with the dissolution and precipitation approach, waste materials are dehumidified in a hot plate before being sintered at 900°C for 7 h. The powder is treated first with 1M sodium hydroxide to make sodium silicate, then with 6M sulfuric acid to synthesize silica. Vaibhav *et al.* reported high purity of silicon dioxide (98%, wt.) from rice husk, sugarcane bagasse, and bamboo leaves, with yields of 78, 71, and 52%, respectively [36]. The silica powders were analyzed by such modern analytical instrumentations as Fourier-transforminfrared spectroscopy (FTIR), X-ray diffraction (XRD), and energy dispersive X-ray analysis (SEM-EDAX). All the sources but peanut shell yielded pure silica. The peanut samples generated magnesium-substituted silica, which needed additional procedures to obtain silica.

Chitosan from agricultural waste (mushrooms). Chitosan is a bioactive polysaccharide derived from chitin, a natural polymer used in the food industry and biomedicine. Currently, almost all commercial chitosan is derived from crustacean shellfish, e.g., shrimps and crabs. Vegetarianism, allergy, and religious beliefs prevent many people from consuming fruits and vegetables coated with animal-sourced chitosan. Mushrooms are consumed as food or added as taste modifiers all over the world. In this regard, mushroom waste may become a source of chitosan because cell walls in mushrooms are made up of chitin. Chitosan can be obtained from mushroom waste by a combination of alkalinization, oxidation, and acidification. The thickness of chitosan-based coatings was measured to be 25 µm by a laser scanning confocal microscope [37]. Another technique for procurement of chitosan is deacetylation, where chitin is isolated from mushroom waste and transformed into chitosan by *N*-deacetylation. The density, porosity, and water vapor barrier of mushroom chitosan films were similar to those of animal chitosan [38].

Enzymes from waste. Agricultural waste is a source of cellulase, amylase, protease, tannase, xylanase, etc. Microbes become a solution to the major problem of agricultural waste disposal. The enzymes obtained by microbes are more stable than those of animal or plant origin. Enzymes are basically obtained by fermentation.

Amylase from agricultural waste. Wheat bran, rice husk, and coconut oil cake are alternative sources of amylase. In case of wheat bran, the fermentation involved *Gibberella fujikuroi*, followed by enzyme extraction with acetate buffer filtration. Rice husk was fermented with *Bacillus subtilis* and extracted by phosphate buffer filtration. Coconut oil cake is a by-product of oil extraction from dried copra; it was fermented with *Aspergillus oryzae*, extracted with distilled water containing Tween 80 polysorbate, and centrifuged. Amylase production often relies on solid state fermentation because of its simplicity, minimal capital asset, low wastewater output, minimal end-product inhibition, improved product retrieval, and high-quality production. As a result, solid state fermentation is usually preferred over submerged fermentation [39–41].

Cellulase from agricultural waste. Cellulase is a plant-produced enzyme that contributes to the breakdown of polymer cellulose. Potato peels could be fermented with bacteria *Aspergillus niger* to produce cellulase. Paddy straw, sugarcane bagasse, sugarcane *barbojo*, grass powder, sorghum husks, and corn straw were fermented with *Klebsiella* sp. [42, 43].

Tannase from agricultural waste. This enzyme belongs to the hydrolase family, which includes enzymes that act on carboxylic ester bonds. Tannin acylhydrolase is the scientific name for this enzyme class. Tannase is an enzyme that aids in the breakdown of gallotannins, which are a form of hydrolysable tannin. Tannase is found in many microbes, including rumen bacteria. Effective tannin utilization requires solid state fermentation technology with non-pathogenic microorganisms that can generate hydrolytic enzymes, i.e., tannase.

Tannase was isolated from palm kernel cake and powdered tamarind seed by solid state fermentation using *A. niger*; the yield was 13.03 IU/g dry solids from palm kernel and 6.44 IU/g dry solids from tamarind seed powder. Coffee pulp is a by-product of coffee processing that accounts for 30% of coffee fruit dry solids. Coffee pulp provides tannase using *Penicillium verrucosum*. Coffee pulp was used as the only carbon source for solid state fermentation, yielding 28.173 ± 1.4 U/g dry solids of tannase. A 3.93-fold increase in tannase production (115.995 U/g dry solids) was also achieved utilizing a statistical approach called central composite rotatable design. Various wastes were fermented with *Aspergillus terreus* to produce tannase, including red gramme husk, green gramme husk, ground nut waste, cotton seed waste, wheat bran, rice bran, coffee husk, tamarind seed powder, cashew apple bagasse, coconut powder, and corn powder [44–46].

Xylanase from agricultural waste. Xylanase comes from various sources, e.g., wheat bran, rice straw, sugarcane bagasse, and soyabean hull. In some studies, it was obtained by fermenting with *A. terreus* strain 5 and *A. niger* strain 44. Wheat bran showed the maximal yield, with the bacterial strain producing less by-product cellulose. Hemicellulose fractions were selectively separated during the saccharification of lignocellulosic substrates, enhancing the commercial viability of xylanase production. Other sources included sorghum straw fermented by *Thermomyces lanuginosus*. In submerged culture using corncobs as carbon source, a thermophilic fungus was reported to produce large amounts of cellulase-free xylanase. This process yielded 11 855 U/g of xylanase free from cellulase and hemicellulose [47, 48].

Protease from agricultural waste. Proteolytic enzymes make up about 60% of the industrial enzyme market. They are used in the food industry for cheese ripening, meat tenderizing, protein hydrolysate manufacturing, and bread making. Protease could be produced using such cheap substrate as defatted soybean cake by solid-state fermentation; it was found suitable for industrial use as a commercial detergent. Defatted soya cake produced protease using *Penicillium* sp. The fermentation of coffee pulp and corn cob involved *Bacillus* sp. and showed a maximal yield (920 U/mL) with the BT MASC 3 strain. Such variables as pH, incubation time, coffee pulp waste, and corncob substrate content could be optimized using the Box-Behnken design [49, 50].

Pharmaceutically useful excipients from industrial waste. Various industrial wastes may yield such pharmaceutically demanding excipients as cellulose, chitosan, and gelatin [51].

Cellulose from industrial waste. One of the major sources of cellulose is the leather and garment industry. Other sources include foods, beer, fabrics, and cotton.

Cellulose from cotton fabric. The global fiber output for textiles exceeds 70.5 million tons per year, with cotton fiber accounting for 40% and polyester fiber accounting for 45.2%. Cellulose is obtained from waste cotton fabrics by acetylation with 1-allyl-3-methylimidazolium chloride (AMIMCl) as a catalyst. It disintegrates cotton-based fabrics before enzymatic hydrolysis. Acid hydrolysis was used to grow *Gluconacetobacter xylinus*, which then produced biopolymer-cellulose pellicle. The resulting cellulose demonstrated satisfactory toughness, dry mass, and moisture holding capacity [52]. Cellulose acetate is a form of cellulose that can be obtained by using ionic liquid *N*-methyl-imidazoliumbisulfate [Hmim]. The yield of cellulose acetate was reported as 49.3%, with the conversion to cellulose at the rate of 84. Waste cotton cloth was utilized to make cellulose nanocrystals with degreasing cotton as control. Cellulose was removed by alkali and bleaching treatments, and cellulose nanocrystals were isolated by controlled acid solution hydrolysis. Cellulose nanocrystals produced from discarded cotton material had a strong crystalline phase index of 55.76 ± 7.82%, indicating that they were more thermostable [53].

Cellulose from rice husk. Rice husk is the most available cellulosic source in global agricultural crop waste. The temperature of 45°C was reported as optimal for acid hydrolysis because it was comparatively low and controllable. The hydrolysis lasted for 30 and 45 min, producing cellulose nanocrystals CNC30 and CNC45, respectively. The yields for CNC30 and CNC45 decreased as the length of hydrolysis increased, amounting 6.43 and 4.83%, respectively. Both CNC30 and CNC45 appeared on individual isotropic transmission electron microscopy (TEM) images as distributed rod-like crystals formed by air-drying dilute suspension of cellulose nanocrystals [54–57].

Cellulose from citrus peel. Citrus peel is another potential source of cellulose. Fan *et al.* produced bacterial cellulose by fermentation using *Komagataeibacter xylinus* CICC No. 10529 [58]. They used Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), and differential scanning calorimetry (DSC) to analyze its properties. The steam explosion technique, which involved sodium hydroxide, a bleaching reagent, and subsequent hydrothermal compressing, proved to be the most effective preparation for plant fibers based on incomplete lignin and hemicellulose separation. *Xanthomonas axonopodis pv.*

citri (strain 306) was able to produce cellulose from citrus waste biomass, which demonstrated a good potential for important nano biomaterials, e.g., nanofibers [59].

Cellulose from beer waste. Beer waste is an alternative potential source of nanocellulose, which is obtained by alkaline treatment, bleaching with sodium chlorite, and controlled acid hydrolyzation. Shahabi-Ghahfarrokhi *et al.* [60] described the visual, thermal, and physical properties of the final product, which was crystalline in nature.

Chitosan from industrial waste. Chitin and its metabolite chitosan are one of the most popular of all carbohydrate natural polymers. Chitosan is a linear polysaccharide obtained mainly form animal sources, with chitin as a basic exoskeleton building block. Chemically, chitosan consists of 2-amino-2-deoxy-D-glucose (deacetylated, D-unit) and *β*-(1-4)-linked *N*-acetyl-2-amino-2-deoxy-D-glucose (acetylated, A-unit). Chitin has different concentrations of A- and D-units. The amount of A-unit exceeds that of D-unit, resulting in water insolubility. In chitosan, the high amount of D-unit makes it water soluble. Chitosan is the key module of the outer shell in crustaceans and other species. Fish factories discard crustacean and shrimp shells as waste, thus losing a potential source of chitosan.

Chitosan from crustacean waste. Crustacean waste is a traditional source of chitosan, which is obtained by demineralization, deproteinization, and deacetylation [61].

Chitosan from shrimp waste. Microbiological fermentation is a good option for chitin production. Demineralization and deproteinization are the two main processes of chitin extraction. Shrimp waste undergoes lactic acid fermentation and is utilized for chitosan isolation by *Pseudomonas aeruginosa.* Lactic acid ($C_3H_6O_3$) is formed in the process of glucose degradation. As a result, exoskeletons shells yield calcium carbonate in a water-soluble form and various minerals. Enzymes or proteases found in biowaste break down crustacean shell proteins into water-soluble protein hydrolysates. Sedaghat *et al.* studied the effect of three parameters on demineralization and deproteinization of crustacean biowaste, i.e., glucose content, inoculation volume, and fermentation time [62]. They produced chitosan by microwave, autoclave, and conventional methods. The autoclave method yielded 87% of chitosan. Fermentation proved to be a simple and effective method for chitosan isolation from shrimp waste.

Chitosan from squid bone plate. Chitosan can be obtained from squid bone plates both chemically and by fermentation. The procedure involves demineralization and deproteination, followed by decarboxylation to form chitosan. Nwe *et al.* [63] obtained chitosan of various qualities by treating chitin with strong sodium hydroxide under various circumstances. The demineralization process of squid bone plate required only 3 h with 3M sodium hydroxide at room temperature.

Chitosan from lobster waste. Chitin was extracted by protease-assisted extraction from Norway lobster (*Nephrops norvegicus* L.). Sayari *et al.* produced chitosan by deacetylating chitin and described its antibacterial, antiproliferative, and physicochemical properties [64].

Chitosan from blue crab waste. Deacetylation of chitin derived from blue crab (*Callinectes sapidus* L.) waste also was reported to yield chitosan. Carapace, hooks, chest, legs, guts, and eggs made up 80% of the raw matter. Baron *et al.* defined the deacetylation amount and the viscos metric of chitosan, as well as described the properties of chitosan film, i.e., opacity, gloss, color parameter, water vapor permeability, moisture content, thickness, and swelling [65].

Gelatin from industrial waste. Gelatin is the key component of pharmaceutical capsules. This hydrocolloid is a popular non-carbohydrate gelling agent in foods, pharmacy, and skincare products.

Gelatin from meat waste. Gelatin usually comes from the tendons of slain cattle (*Flexor digitorum*, *Flexor digitorum profundus*, and *Extensor communis*). Acid or alkaline treatment of collagen prior to water extraction was reported to facilitate gelatine production. Gelatin obtained from short tendons was processed by enzymatic refinement and acidic treatment followed by extraction. The reported Bloom strength was 360–410°C with a yield of 55–60% [66].

Gelatin from pollock skin. Fish skin is composed of collagen, which can be turned into gelatin through mild heat denaturation. Cindy *et al.* dehydrated, pre-treated, and dissolved pollock skin in water to obtain gelatin solution [67]. This solution was cast to form gelatin film; its physicochemical profile included gel strength, tensile strength, physical and mechanical properties, molecular weight, and amino acid content.

Gelatin from fish skin. Gelatin can also be produced from fish skin with the 71.8–97% gelatin purity and 78.1–98.8% yield. Boran and Regenstein [68] studied such properties as protein recovery, gelatin recovery, viscosity, gel strength, etc. Although other processing elements such as acid strength had an impact on the gelatin quality, extraction temperature and pre-treatment time appeared to be the most important variables. However, the extraction temperature and pre-treatment method also affected the quality and strength of the fish skin gelatin.

Pharmaceutically useful materials from municipal waste. Co-combustion with electricity generation by coal represent a unique method of municipal waste disposal.

Silica from municipal waste. Different grades of silica are used in thin layer chromatography and column chromatography. Other applications involve a lubricant for granules, desiccant, etc.

Silica from incinerated municipal waste. The alkaline fusion method is commonly used for silica extraction. The obtained silica demonstrated high porosity with a pore size of 2–3.8 nm. Mining ash and municipal incinerator ash undergo hydrothermal or fusing processes to produce a variety of zeolites. Zeolites have ion exchange capabilities and selective adsorption capacities, which makes it possible to use them as molecular sieves [69, 70].

Cellulose from municipal waste. Municipal waste includes a lot of newspaper and corrugated boxes that can be used as a source of cellulose.

Cellulose from newspaper. Newspaper waste yields pure cellulose of good fiber uniformity [71].

Cellulose from corrugated boxes. Enzymatic hydrolysis proved successful in increasing the yield of cellulose nanocrystals following phosphoric acid hydrolysis, which would significantly improve the industrial production. The crystallinity and thermal stability of cellulose nanocrystals improved after enzymatic treatment. Tang *et al.* [72] reported the particle size, rheological properties, and thermal stability of cellulose nanocrystals obtained from corrugated boxes.

Pharmaceutically useful materials from waste recycling. Isolation of pharmaceutically useful material from waste is an alternative to traditional waste management. Waste recycling for pharmaceutical materials should be encouraged only based on the applicability of the obtained material and the rationality of the method. Recycling produces ethanol, lactic acid, acetic acid, etc.

Ethanol from waste recycling. Ethanol serves as a solvent and co-solvent in the pharmaceutical industry, both as a solubility enhancer and as a vehicle. Due to its bactericidal activity, ethanol is also used as a tropical disinfectant. Traditionally, ethanol was obtained from grape juice fermentation or by fermenting any other sugar-containing substrate.

Ethanol from fiber waste recycling. Ethanol was successfully obtained from fiber waste using enzymatic treatment followed by fermentation with *Saccharomyces cerevisiae*. With a high dry weight concentration of fiber sludge, fermentation with *S. cerevisiae* was conducted as simultaneous saccharification and fermentation [73].

Ethanol from food waste recycling. Developing nations are responsible for a greater proportion of food waste in the total municipal solid waste. Enzymatic treatment, flocculation, and biological fermentation employ food waste fermentation to make ethanol. Ethanol production is increased continuously with the increasing cycles of reflux fermentation; the maximal yield was obtained at cycle five [74].

Lactic acid from waste recycling. Lactic acid fermentation employs renewable carbohydrates as a carbon source.

Lactic acid from food stillage. Ma *et al.* developed the protocol for lactic acid production by employing ethanol fermentation stillage from food waste [75]. Suspended particles can be eliminated by centrifugation and ultrafiltration during pre-treatment, which is followed by electrodialysis. The membranes of electrodialysis have fairly low contamination retention; therefore, stillage pretreatment is necessary before electrodialysis. The maximal lactic acid recovery rate from stillage was 71.2%.

Lactic acid from food waste. Diet food production results in waste with a high biological content, e.g., sugars, which can be used to produce lactic acid by fermentation. Kim *et al.* utilized a native mixed culture to obtain lactic acid from food waste by gradually raising the temperature up to 50°C [76]. The methodology involved fermentation and nanofiltration, followed by electrodialysis. The final fermented broth contained lactic acid of high purity.

Lactic acid from grass silage. Danner *et al.* rationalized the method of recovering lactic acid from grass silage by testing a variety of silages with various levels of organic acids [77]. They used the method of mono-polar electrodialysis to purify the crude liquid extract after it had been pre-treated with ultra-filtration membranes to yield lactic acid from silage preparations. The unrefined lactic acid extract was isolated from the remaining solid pulp by filtration. The press-filtering of the moistened silage produced a fairly unrefined extract with plant mucilage. Lactic acid was eventually recovered by centrifugation, ultrafiltration, and electrodialysis.

Acetic acid from waste recycling. Acetic acid is generally utilized as a starting material for pure terephthalic acid, vinyl acetate monomer, and acetic anhydride. Acetic acid is usually obtained from discarded liquid crystal displays, which are extensively used in TVs, computer monitors, and other devices due to its benefits of good light quality, compact size, and low power consumption. Wang *et al.* presented an ecologically friendly method of recycling organic materials before indium recovery [78]. The method reduces the consumption of fossil fuels. Acetic acid was obtained from expired liquid crystal panels by sub/supercritical fluid extraction, which involves supercritical water. The methods of gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) yielded a comprehensive qualitative and quantitative analysis of the resulting product: 78.23% acetic acid was gained at 400°C and 23 MPa.

CONCLUSION

Wastes of various kind are responsible for environmental pollution worldwide. However, they contain useful excipients. Sustainable recovery of these excipients and materials reduces the environmental burden, thus providing a cleaner and safer environment. The derivation of harmful wastes for food or pharmaceutical applications solves a multifaceted challenge that intersects environmental science, public health, and regulatory compliance. By understanding the sources and types of harmful wastes and their implications, the food and pharmaceutical industries can develop more sustainable practices to minimize environmental and health hazards while maintaining the essential advancements.

Based on our interest in pharmaceutical sciences, we reviewed a significant number of publications that described methods of obtaining various pharmaceutically important excipients from different types of waste [79–87]. Waste proved to be a potential source of pharmaceutically useful components. The final products complied with the standards applicable for the pharmaceutical materials while the novel and sustainable methods proved more economical than traditional ones. The yield of the final product was mentioned in most studies as an imperative criterion in the selection of the waste as raw material.

CONTRIBUTION

All the authors participated in developing the concept and writing of the manuscript.

CONFLICT OF INTEREST

The authors declared no conflict of interests regarding the publication of this article.

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