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*Review*

# An Overview of Agro-Waste Management in Light of the Water-Energy-Waste Nexus

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**Abstract:** It is urgent that we increase global food production to support population growth. Food production requires significant resources, amongst them water and energy. Therefore, any losses of food or other agricultural products also means a waste of water and energy resources. A significant amount of these losses occurs during the postharvest stage, primarily during processing and storage. This is considered avoidable food waste. The water-energy-waste nexus (WEW), and its relationship to food production, needs to be investigated from a circular bioeconomy lens. Furthermore, alternative uses of the wastes should be investigated. This review focuses on agro-wastes and their management as sources for bioactive compounds, biofertilizers, biomaterials, nanomaterials, pharmaceuticals and medicinal agents, and growth media, e.g., for plant tissue culture. We also investigated the potential contribution of agro-wastes to bioenergy production (bioethanol, biogas, and biofuel). Proper management of agro-wastes may support the mitigation of climate change, produce innovative bio-ingredients and biodegradable materials, and enhance green growth and a circular bioeconomy. We argue that the management of agro-wastes cannot be discussed without referring to the role of water and energy within the food system. Thus, this review focuses on agricultural wastes and their handling, applications, environmental impacts, and potential benefits in the agricultural and medical industries in light of the WEW nexus.

**Keywords:** agroecology; bioenergy; biorefinery; compost; food security; food waste; nano-management; sustainability

## 1. Introduction

Agricultural wastes (agro-wastes) are defined as the residues that result from growing cultivated crops and/or during the first processing of raw agricultural products including vegetables, fruits, dairy products, meat, poultry, and other products [1]. Agro-wastes are produced during farming activities including horticultural, seed growing, dairy farming, livestock breeding, grazing, nursery plots, market gardens, and forestry or woodland production [2]. Agro-wastes can be classified into liquid, solid, or slurry forms [1]. Nearly 30% of the agricultural goods produced worldwide end up as agro-wastes. The residues of raw agricultural products may include animal and plant residues (e.g., manure, different crop residues, wastes from activities like pruning, harvesting, growing, fertilization) and applied pesticides (as hazardous and toxic agricultural wastes). Several studies have quantified agro-wastes generation and the environmental consequences of these wastes such as global nutritional and environmental losses due to food wastes [3], using digital agricultural technologies [4] and sustainable management with a focus on reducing food wastes as a more eco-friendly and economical option than treatment [5].

Utilization and management of agro-wastes have also been discussed from different points of view, such as production of pharmaceutical ingredients [6], biochar [7,8], nanomaterials like nano-silica and nanocellulose [9,10], agro-composites for packaging purposes [11], asphalt binder or natural aggregate in concrete [12,13], nano-adsorbents [14], composts [15], bioenergy production or biorefining approaches [16–18], and bioactive compounds [19–22]. The sustainable management of agro-wastes should be adapted under the food-energy-water (FEW) nexus, as agro-wastes are critical resources that, if properly used, can underpin human livelihoods and wellbeing. In this review we will argue that how we treat agro-wastes will impact our ability to achieve the *Sustainable Development Goals* of the United Nations [23]. The FEW nexus includes natural resources (e.g., energy, land, and water) and wastes. The global demand on the FEW nexus constantly increasing, as reported by many researchers (e.g., [24–26]).

We believe that simple illustrations may help in understanding complex situations. Based on the concept that "*one photo is worth one thousand words*", we recently published pictorial studies on soil and humans [27], the soil-water-plant-human nexus [28], management of salt-affected soils [29], global soil science education [30], soil restoration and macro-fungi [31], and plant nutrition for human health [32]. Other photographic reviews/mini-reviews were published on agro-practices and activities such as nano-grafting of vegetables [33], sustainable applications of mushrooms [34], nano-farming [35], smart farming [36], smart irrigation [37], and smart-fertilizers [38]. This review is on agro-wastes, their sources, environmental problems, and nano-management. Our main goal is to point at the role that agro-wastes have with a special focus on the water-energy-waste (WEW) nexus. Different applications of agro-wastes will be discussed such as producing bioenergy and biorefinery, and their use in nanotechnology (i.e., nanocellulose, nanoparticles, and nanofertilizers) within the WEW nexus.

## 2. Methodology

This review focuses on agricultural wastes and their handling, applications, environmental impacts, and potential benefits in the medical and agricultural industries in light of the WEW nexus. To achieve this, keywords related to the nexus of water, energy, food and waste were examined using literature searches on ScienceDirect, SpringerLink, Frontiers, MDPI, PubMed, and other scientific databases. Keywords searched included "agricultural residues", "agro-wastes", "water-energy nexus", "climate change and agro-wastes", "agro-wastes and nanotechnology", "agro-wastes and compost", "agro-wastes and foods", "agro-wastes and bioenergy/biorefinery", and "management of agro-wastes". The searches were refined to mainly include the last five years (from 2018 to 2022). After an initial screening of the articles, we sorted the references according to the main ideas communicated, this to allow for a more thorough reading and the creation of figures and tables that summarized the main topics. Our review is divided into sections that first provide an overview of the WEW nexus and its implications. Then, we discuss different types of agro-wastes with a focus on their benefits and challenges. Thereafter, we move into environmental issues related to such wastes, including what it means for climate discussions. We have a large section on management practices that includes recycling and composting, nano-management of wastes, the use of wastes for bioenergy and biorefinery, and finally for plant growth media, e.g., for use in tissue culture multiplication. Throughout the paper we use diagrams and figures to simplify and summarize the topics discussed.

## 3. Water-Energy-Waste Nexus

Water and energy are critical resources for food production, human health, well-being, and social development [39]. Shortages of both water and energy are causing problems in countries all over the world [40]. In 2020 around 3.2 billion people lived in a state of water shortage, with about 1.2 billion living in severely arid regions [41]. Energy and water resources are interdependent and inseparable [42]. The relationship between water and energy is strong and very complex, and both the water and energy-related sectors are essential for production, supply, conversion, utilization and consumption processes [41]. A conceptual model of the different nexuses is shown in Figure 1, and these are related to WEW in different ways such as in the energy-water nexus [43], water–food nexus [44], energy-water-food nexus [45], water-energy-waste nexus [46], water-land–energy–food nexus [47], water–food–energy–climate nexus [48], water–waste–energy–food nexus [24], water, energy, food and forest nexus [49], and finally the energy–water–food–waste-land nexus [26].

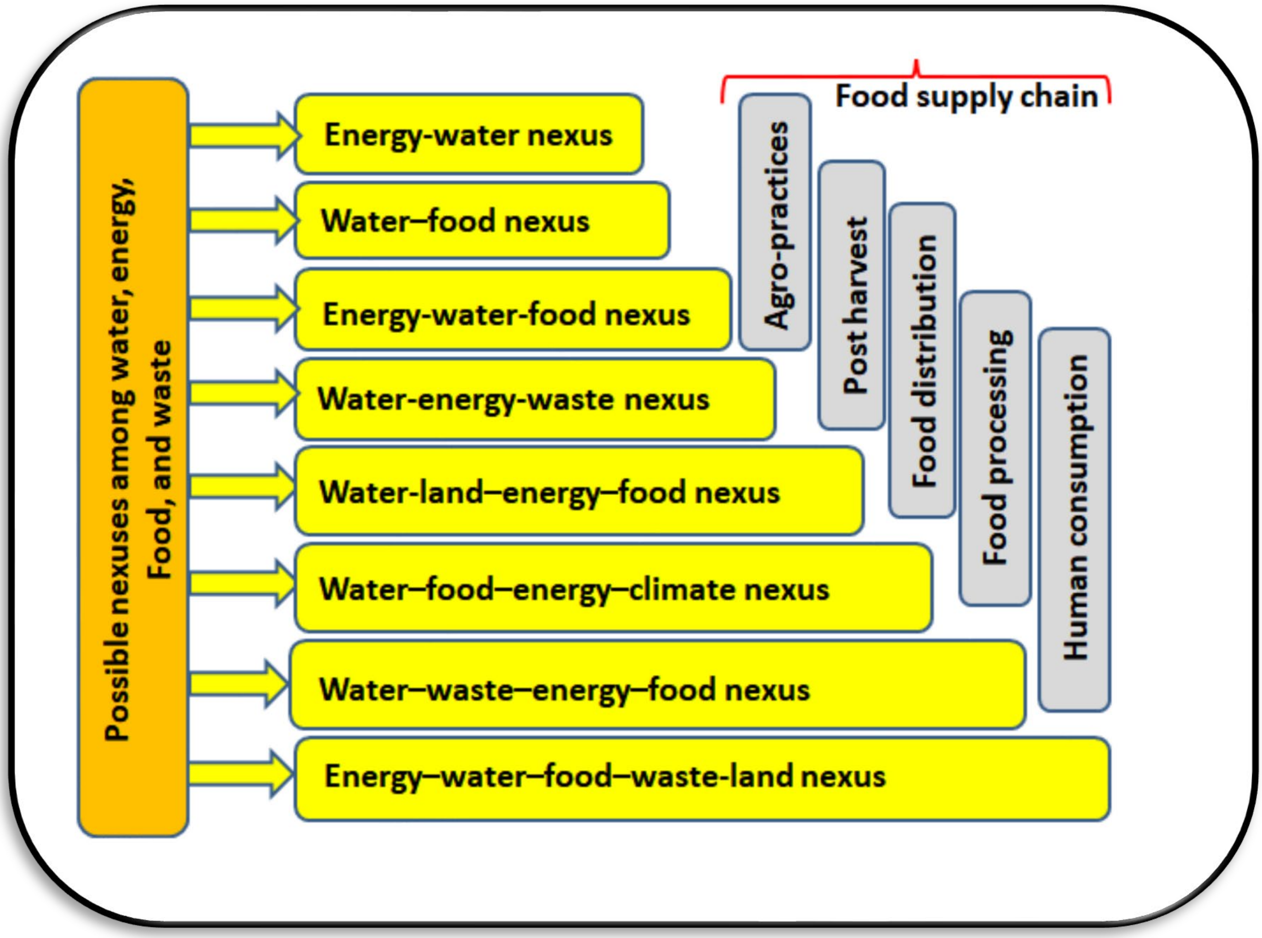


**Figure 1.** Conceptual model of the different nexuses among water, energy, waste, food, land, and climate, and the different factors affecting these nexuses including agricultural practices, post-harvesting, food distribution, food processing and human consumption.

There are several interfaces between each of the components in these nexuses, such as water and energy; health and water; health and energy; food and water; food and energy; food and land; etc. The different combinations among these nexuses in the agroecosystem are presented in Figure 2. The use of polluted irrigation- and wastewater in food production may cause health problems such as "blue baby syndrome", diarrhea, or chemical poisoning [50]. Many health outcomes are associated with the interfaces between energy–health, water–health, food–health, and agroecosystem health, which may impact human health either positively or negatively [50]. Such interactions will be discussed in more depth in the coming sections, but we will also discuss potential benefits of agro-wastes.

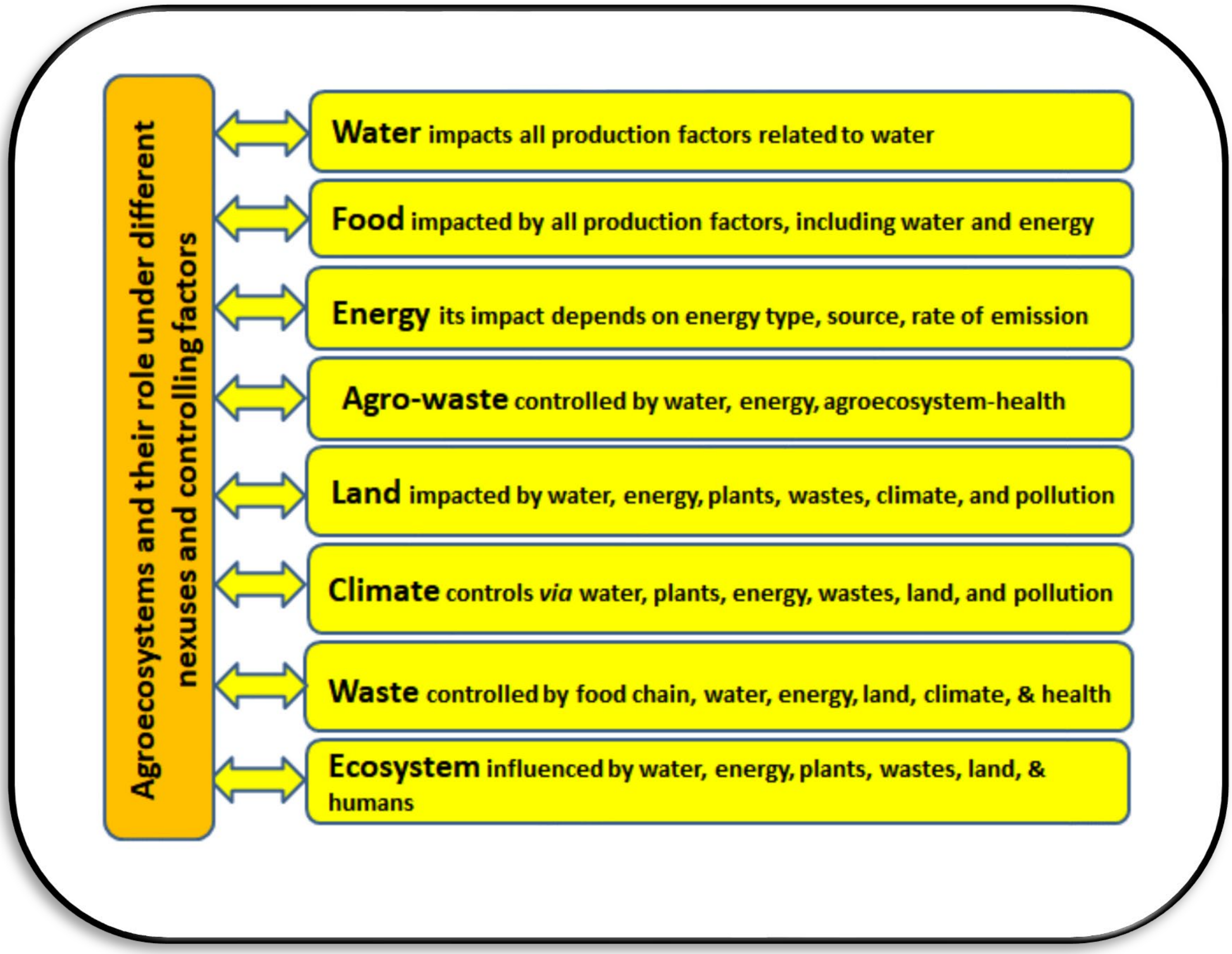


**Figure 2.** Illustration of the relationships between agroecosystem components and the different nexuses as well as the factors controlling these nexuses.

## 4. Agro-Wastes: Their Benefits and Challenges

Agricultural wastes are the residues that result from growing cultivated crops and/or during the first processing of raw agricultural products including vegetables, fruits, dairy products, meat, poultry, and other products (Figure 3 and Table 1; [2,51,52]). These wastes may include crop residues, agro-industry processing wastes, livestock wastes, fruit and vegetable wastes, and industrial waste [52]. Based on a "waste-to-wealth" perception as well as a "zero-wastes" perception, we see that several benefits and applications can be associated with agro-wastes. These include: (1) improved soil fertility and crop yield; (2) reduced dependence on chemical fertilizers; (3) reduced dependence on fossil fuels; (4) production of protein-based feedstock for animal feeds; (5) production of nanomaterials/nanoparticles; (6) production of bioactive compounds; (7) agro-wastes used in fermentation industries;

(8) production of pharmaceutical compounds; (9) production of asphalt binder or as natural aggregate in concrete; and (10) production of nano-adsorbents [2,20,52].

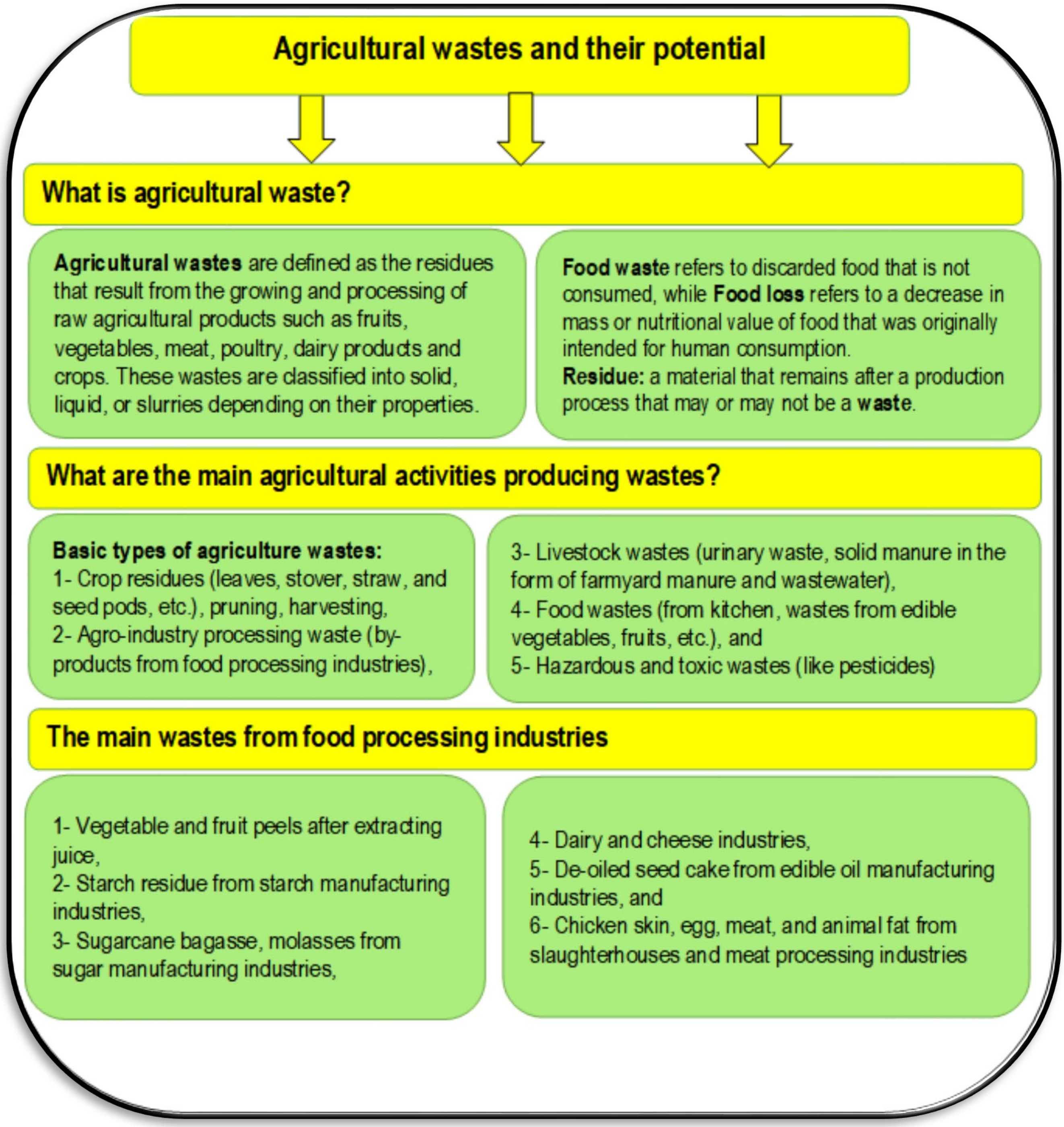


**Figure 3.** Overview of different agro-wastes and their production, including the main wastes resulted from food processing.

**Table 1.** Some suggested management approaches for agro-wastes.

| Main Management Approaches | References |
| --- | --- |
| 1- Producing bioethanol from agro-wastes | Singh et al. [53] |
| 2- Producing biobutanol from agro-wastes | Huzir et al. [54] |
| 3- Generation of biogas from agro-wastes | Devi et al. [55] |
| 4- Producing biohydrogen from agro-wastes | Haque et al. [56] |
| 5- Producing bio-oil from agro-wastes | Nair et al. [57] |
| 6- Producing bio-char from agro-wastes | Ur Rahim et al. [58] |
| 7- Organic fertilizer and compost production | Surendra et al. [59] |
| 8- Producing protein-based feedstock for animal feeds | Asiri and Chu [60] |
| 9- Burning of agricultural waste as fuel | Awogbemi et al. [61] |
| 10- Producing nanomaterials/nanoparticles | Yadav et al. [62] |
| 11- Production of bioactive compounds | Sangpong et al. [63] |
| 12- Agro-wastes for fermentation industries | Leite et al. [64] |

The main challenges facing agro-waste management include: (1) poor or unpredictable nutrient bioavailability for cultivated plants; (2) lack of biorefinery technologies for nutrient re-use and biofuel production; (3) potential pollutants in these wastes that could threaten food safety; (4) lack of knowledge on reducing greenhouse gas (GHG) emissions to mitigate climate change; and (5) lack of knowledge on how to enhance soil health and functions through the application of organic fertilizers [65]. Poor nutrient availability is related to a slow or unpredictable breakdown of organic wastes. Furthermore, the management of agro-wastes is important to minimize the accumulation of wastes in cities or landfills, which may lead to several environmental problems. This applies to wastes from both livestock and crop farming (Figure 4; [65]). A variety of agro-techniques can be applied to manage agro-wastes, such as brown- and green manuring in arable lands, and agroforestry on marginal and degraded lands [66].

Several studies have been published on agro-wastes and their management, revolving around topics such as sustainable management of urban wastes, with publications from India [67], Italy [68], Oman [69], Tanzania [70], the European Union [71], the USA [72], and China [73–75]. Other studies have focused on producing microbial bio-flavor [76], sustainable management of agro-industrial wastes [77], management of olive leaf wastes to include production of biomass, animal feed, and pharmaceutical products [78], producing biomaterials derived from food wastes for the horticulture industry, like biodegradable nursery pots [79], and sustainable use of agro-industrial wastes to produce microbial pigments [80].

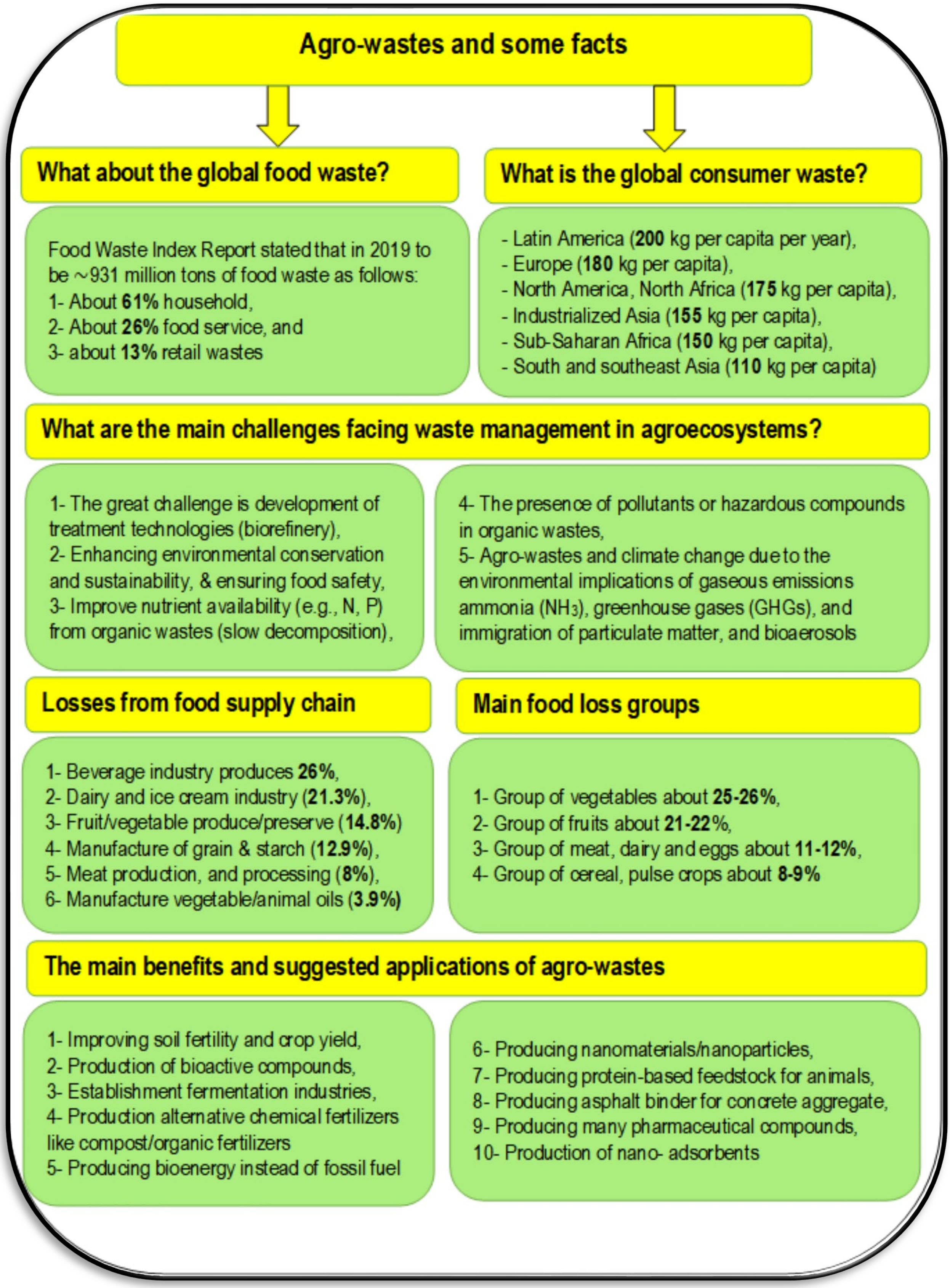


**Figure 4.** Benefits, applications, and challenges related to agro-wastes.

## 5. Environmental Impacts of Agro-Wastes

Agriculture is a primary producer of food, but also contributes to the production of waste, greenhouse gas emissions, and energy consumption on a global scale [81]. Agro-wastes are created in considerable quantities after harvest and such wastes represent significant issues for policymakers and farmers [82]. The environmental impact of agro-wastes has harmed ecosystems and is a huge burden to society due to the high consumption rate of agricultural products and improper disposal procedures [83]. The accumulated agro-wastes and their by-products at farms and processing locations can trigger serious management and disposal issues [84]. Figure 4 illustrates benefits, applications, and challenges related to agro-wastes [3,65,85,86]. The accumulation of mismanaged agro-waste raises environmental concerns, particularly in developing nations. As a result, agro-waste is one of the major issues that needs to be addressed to safeguard the environment and preserve renewable resources [87,88]. Humans obtain a considerable amount of energy from plant parts that may be consumed such as seeds; a preferable route to obtain bioenergy would be the use of agro-wastes that cannot be eaten [81], so long as the utilization of these wastes does not create issues through the denial of organic sources to the soil [89]. Wastes produced in the field or after industrial processing are multiphase and multicomponent, and agro-waste pollutes land, water, and air [52].

If these waste products are not properly disposed of, they can pollute land and water resources. Most of the agro-waste is still being disposed of improperly [81]. For example, burning straw and manure produces a large amount of dust, smoke, and toxic levels of gases, contributing to air pollution and harming human health [90]. Animal manure may contain heavy metals, parasite eggs, pathogens, antimicrobials, hormones, and other contaminants. A portion of these agro-wastes have been directly released into water bodies, resulting in pollution of aquatic ecosystems [82,91]. The use of animal manures in agriculture can contribute to nutrient pollution, i.e., discharging excessive nutrients such as N and P from manure-amended agricultural soils to water bodies and groundwater. Nutrient pollution causes harmful algal blooms, hypoxia, and eutrophication of water bodies, among other problems that may pose health risks as well as economic costs [92]. The growing volume of agro-waste may cause excessive biological and chemical oxygen demands that have an impact on a variety of media, including soil and water [93].

Traditional waste disposal techniques that include thermal treatment, landfills, and composting may also result in negative side effects, such as the emission of CO, $CO_2$, CnHm, NOx, SOx, ashes, foul aromas, and contamination of subsurface water. The random burning of agro-wastes such as straw and livestock manure has also resulted in a variety of environmental issues. It becomes more expensive to dispose of waste as its volume grows, which emphasizes the significance of environmentally friendly (sustainable) processes for recycling waste into valuable goods [93]. The rising amount of these wastes and their improper management, particularly in developing countries, threatens environmental health and safety while also magnifying these countries' contributions to GHG emissions [91].

## 6. Climate Change and Agro-Wastes

Human-induced climate change is a worldwide environmental issue. It is defined as global changes in long-term weather conditions, characterized by increasing atmospheric temperature trends and changes in precipitation amounts and patterns [94,95]. Through altered temperatures, precipitation, and a rise in the intensity and frequency of severe weather events, climate change can have negative impacts on ecosystems, including agroecosystems. These changes will impact human society by changing agricultural yields, with yield losses for most crops in most regions, and thus the agricultural economy worldwide, which will influence global food security for an increasing human population. Climate change can also have an indirect impact on agricultural production through its effects on species that interact with crops. Climate change, for example, has already impacted many insect species that pollinate crops, and rising temperatures are expected to increase the prevalence of agricultural pests and viruses [95,96]. Therefore, climate change is a serious environmental and socioeconomic challenge that represents a serious threat to human health and wellbeing, in the absence of viable mitigation and adaptation procedures [94].

The elements that are largely responsible for climate change are carbon and nitrogen. These elements are abundant in organic agricultural wastes and are responsible for exacerbating global warming in their GHG forms, primarily carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). Moreover, processing such wastes consumes energy, and if urine, animal feces, or slaughterhouse residues are polluted with heavy metals, the finished products still represent a risk to the environment [84]. Because agro-waste is a substantial source of $CO_2$, $CH_4$, $N_2O$, and hydrocarbons, agro-waste and biomass decomposition or burning has a considerable influence on global atmospheric chemistry. Emissions from burning have both negative and positive effects on the climate. Aerosol and smoke particles, for example, have a cooling impact in the atmosphere because they scatter or reflect sunlight. However, as a result of absorbing incoming solar radiation, black carbon particles warm the atmosphere. Some of the gases released by agro-waste burning, such as $CO_2$ and $CH_4$, are GHGs and hence contribute to the greenhouse effect, which warms the atmosphere by absorption of thermal solar radiation [91]. Singh et al. [82] reported that uncontrolled agro-industrial waste burning emits harmful (nitrogen oxides, $SO_2$, respirable particulate matter), carcinogenic (furans, dioxins polycyclic aromatic hydrocarbons), and GHG substances as well as smoke, causing significant haze, global warming, and harming human health.

Following the energy sector, which accounts about 25% of global GHG emissions, livestock and manure (5.8%), burning of agricultural residues (3.5%), and organic waste (3.2%) are other major contributors to GHG emissions [59]. To achieve the Intergovernmental Panel on Climate Change's global target of net-zero emissions, an effective reduction in GHG emissions is required. One of the widely accessible solutions is biomass utilization. Agro-waste, for example, is recognized as renewable biomass that occurs in conjunction with harvesting of crops and removal of $CO_2$ through plant growth. Unutilized chances for innovative and environmentally friendly agro-waste management strategies would narrow the resource cycle for net-zero carbon emissions and achieve sustainable agro-ecosystem resource management [97]. Concerns about the severe effects of global warming and depletion of nonrenewable resources have driven the exploitation of agro-wastes as renewable resources for many applications, including bioenergy generation, over the last decade. To realize the full potential of agro-wastes, especially to protect the environment and confront climate change, researchers have further investigated the use of agro-wastes in valuable applications such as biodegradable packaging materials, biofuel generation, and biomass composites utilized as water pollutant absorbents and dyes [98,99].

## 7. Management of Agro-Wastes

The best approach to waste management is to avoid creating waste. The second-best approach is to recycle and re-use agro-wastes to produce compost, organic fertilizers, and other products. Food wastes can be sustainably managed through the 4 R rule: "reduce, reuse, recovery. and recycle" [86]. The sustainable management of agroforestry wastes can be achieved using the sustainable biorefinery by collecting wastes and valorization, or recycling those wastes into valuable products such as organic fertilizers, biofuel, biochar, and industrial chemicals rather than engaging in traditional approaches, which include thermal management, landfilling, and decomposition [93,100]. Other sustainable utilizations of agro-wastes include producing biodegradable polymers [101,102], or in wastewater treatment as adsorbents such as agro-waste based materials made from potato, tomato, apple, banana, citrus, grape, and mango [103]. The management of agro-industrial wastes using solid state fermentation to produce bioactive compounds has been reported in multiple studies (e.g., [64,104]). Agro-industrial by-products are considered a sustainable source for producing a wide array of bioactive compounds [105]. A survey of selected crop wastes and the bioactive compounds extracted from them is given in Table 2.

**Table 2.** The main bioactive compounds extracted from selected horticultural crops.

| Plant | Family | Agro-Waste | Bioactive Compounds | Refs. |
|---|---|---|---|---|
| Almond: *Prunus dulcis* (Mill.) D. A. Webb | Rosaceae | Seed coat | Catechin, kaempferol, isorhamnetin, naringenin, quercetin | [106] |
| Apple: *Malus domestica* (Suckow) Borkh. | Rosaceae | Pomace, seed, peel | Anthocyanins, catechin, caffeic acid, phloretin glycosides, quercetin glycosides | [107] |
| Banana: *Musa* sp. | Musaceae | Peel, stalk, pulp | Anthocyanins, auroxanthin, cyaniding, catecholamine, delphinidin, flavonoids, hydroxycinnamic, lutein, neoxanthin, α-and β-carotene, β-cryptoxanthin | [108] |
| Date palm: *Phoenix dactylifera* L. | Arecaceae | Pulp, seed | Phenolic acids, fatty acids, flavonols, sphingolipids, steroids | [109] |
| Durian: *Durio zibethinus* L. | Malvaceae | Peel, pulp, rind, seed | Glutathione, γ-glutamyl cysteine, pyridoxamine, cysteine, leucine | [63] |
| Grapefruit: *Citrus × paradisi* Macfad. | Rutaceae | Peel, pulp, seed | Neohesperidosides, naringenin | [110] |
| Lemon: *Citrus limon* (L.) Osbeck | Rutaceae | Seed, peel, pulp | Apigenin-6, caffeic acid, coumarate, ferulate | [111] |
| Mango: *Mangifera indica* L. | Anacardiaceae | Exocarp, pulp, seed | Flavonoids, gallates, hydrolysable tannins, methyl gallate, phenolics | [112] |
| Pineapple: *Ananas comosus* L. Merr. | Bromeliaceae | Stem, pulp, peel | Catechin, epicatechin, ferulate, gallic acid, phenolics | [113] |
| Pomegranate: *Punica granatum* L. | Lythraceae | Pulp, seed, peel | Anthocyanins, flavonoids, gallic acid, punicalagin | [114] |
| Strawberry: *Fragaria × ananassa* | Rosaceae | Sepals and peduncles | Phenolic compounds and antioxidant capacity | [115] |
| Carrot: *Daucus carota* L. | Apiaceae | Peel | Anthocyanidin, α-carotene, carotenoids, β-carotene | [116] |
| Potato: *Solanum tuberosum* L. | Solanaceae | Peel, tuber, leaf | Anthocyanin, caffeic acid, carotenoid, lutein, caffeoylquinic acid | [117] |
| Rice: *Oryza sativa* L. | Poaceae | Husk, straw, bran | Anthocyanins, caffeic acid, phytosterols, pantothenic, niacin, pyridoxine, tricin | [118] |
| Soybean: *Glycine max* L. Merr. | Fabaceae | Husk | Chlorogenic acid, ferulate, gallic acid | [119] |
| Tomato: *Solanum lycopersicum* L. | Solanaceae | Peel, pulp, seed | Caffeic acid, chlorogenic acid, lycopene β-carotene, | [120] |
| Wheat: *Triticum aestivum* L. | Poaceae | Bran | Caffeic acid, ferulate, gallic acid, p-coumaric acid | [121] |

Scientific names were obtained from the website https://powo.science.kew.org/ (accessed on 6 August 2022).

### 7.1. Agro-Wastes for Recycling and Composting

The most common traditional management of agro-wastes is to plough them into the soil, or to bail or otherwise remove them from the field after harvesting [122]. Crop residues can have both positive and negative impacts on an agroecosystem, depending on the chemical composition of the residue. If the crop grew in polluted soil the residues may contain hazardous materials and/or harmful microbial species that threaten human health [123]. However, several positive outcomes can arise from leaving residues in a field, including mineralization, or release of nutrients, into soils and increased nutrient uptake efficiency [124]. In developing countries, landfilling and/or burning agro-residues after harvest is a common practice [125]. About 35, 85 and 45% of N, P, and K, respectively, taken up by rice plants remain in vegetative parts and may be re-used to feed soil and nourish cultivated plants [126].

Composting is a microbial process, by which the decomposition, biodegradation and bioconversion of agro-residues can be accelerated from complex materials into simpler organic and/or inorganic soluble forms [127]. This process mainly depends on factors including the kind of agro-wastes, their C:N ratio, and environmental conditions such as pH, aeration, moisture content, temperature, etc. (Figures 5–7). In general, some essential chemical fertilizers (NPK) need to be applied to start the composting process along with the addition of plant growth-promoting bacteria (PGPB) [126]. The PGPR help decompose and process the compost (i.e., organic matter), forming a bioorganic fertilizer with many bioactive compounds or enzymes that stimulate biological processes that enhance the bioavailability of nutrients to cultivated plants [128]. The role of PGPR may also include enhancing the germination of seeds, growth of plants, soil rehabilitation, and biological suppression of diseases in soil [126]. Furthermore, PGPB can produce phytohormones that mediate nutrient and water uptake and improve plant growth and yield due to high root proliferation [129]. Agro-wastes from horticultural crops are used to extract many bioactive compounds, as reported by Khaksar et al. [130] and in Table 2. The main challenges that face food waste composting include odorous substances and leachate production, which should be collected and treated for pollutants [85].

The accumulation of by-products (wastes) produced from the vegetable and fruit processing industries are a potential pollution hazard, as these wastes contain many bioactive molecules (e.g., coloring pigments, phenolic compounds, essential fatty acid, flavonoids, pectin, proteins, dietary fibers, and vitamins). Instead of releasing these into the environment through landfilling, these bioactives could be utilized in industries including food, cosmetics, pharmaceuticals, and textiles [131]. The extraction of the bioactive compounds mainly depends on the extraction technology, the type of by-products (wastes) and their characteristics, and water and energy inputs. In general, the most common by-products that result from the fruit processing industry are seeds, peels/skin, leaves, roots, tubers, and pomace [22]. These by-products are considered an excellent source of bioactive compounds, which include the phenolic compounds (e.g., carotenoids, phenolic acid, and flavonoids), bioactive proteins (e.g., amino acids and peptide isolate), fibers, fatty acids, etc. The seeds of fruits have high phytochemical, essential oils, and phytosterols content, whereas fruit peels contain valuable fibers, pectin, and minerals [131]. The uses of enzymes and fermentation are considered biological approaches that can be used in the extraction of bioactive compounds from agro-industrial wastes [22].


**Figure 5.** Horticulture and field crops are primary sources for agro-wastes such as date palms. The upper left photo shows waste in a horticultural nursery. The upper right photo shows the same wastes after crushing. The lower photos show maize (left) and citrus (right) residues. Photos courtesy of El-Mahrouk and El-Baily.

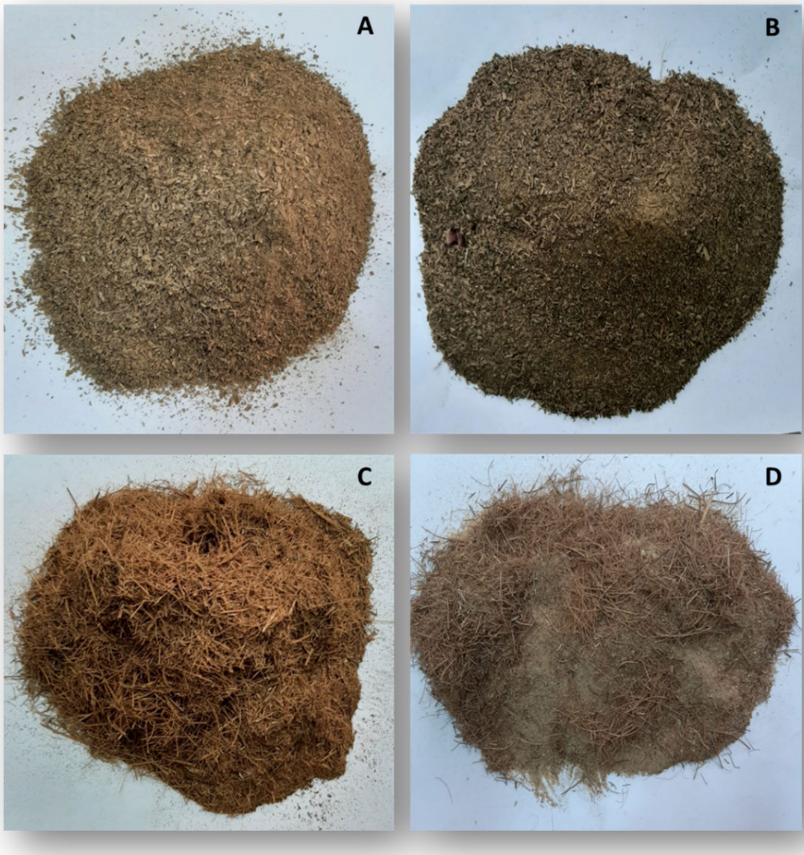


**Figure 6.** Crushed wastes can be used to prepare compost to improve the properties of sandy soil and be used in growing media in horticultural nurseries. Banana compost (**A**); banana compost and sand (1:1) (**B**); date palm compost (**C**); date palm compost and sand (1:1) (**D**). Photos courtesy of El-Mahrouk.


**Figure 7.** *Cont*.


**Figure 7.** Different kinds of banana wastes, including leaf wastes (**A**), peduncle wastes (**B**) (upper photos), pseudo-stem wastes (**C**,**D**) (middle photos), and wastes belong in vitro seedlings, which harvested this year (photo **E**) and last year (photo **F**). Photos courtesy of El-Mahrouk and El-Baily.

### 7.2. Nano-Management of Agro-Wastes

Management of agro-wastes is considered a major challenge. This management may include many processes, starting with the production and collection, transportation, and disposal of wastes. The management of agro-wastes has become a global issue, which may include options from composting to forming biochar. Some agro-wastes, such as oil crop wastes, cannot be composted because of their low economic value [131], although there can be benefits to applying oil crop wastes to soil [132]. Agro-wastes can be left in the field after harvest, which may protect soil from erosion and/or provide nutrients. Other common practices involving agro-wastes include burning or dumping in landfills, which may cause pollution of soil, water, and air [133]. Nanotechnology is one of the most promising new applications for the management of agro-wastes [134]. Agro-wastes can be used to produce materials like nano-composites, nano silica, nano-cellulose, and as nano-adsorbent or nano-cementitious additives (Table 3). These applications of agro-wastes are promising to address environmental and health issues through the removal of pollutants from soil and water environments [124,135]. Modern agriculture can promote sustainability and resilience by converting agro-wastes into nano-enabled materials [136]. Several studies have been published this year (2022) that focus on agro-wastes and their potential for biorefinery (Table 4).

**Table 3.** Examples of using agro-wastes as a bio/nano-adsorbent to remove pollutants from soil and water.

| Agro-Waste | Type of Adsorbent | Capacity Rate | Pollutant/Media | Application/Removal Mechanism | Refs. |
|---|---|---|---|---|---|
| Leaves of *Saccharum officinarum* | Nano-adsorbent | 148 and 137 mg $g^{-1}$, for Pb, Zn | $Pb^{2+}$ and $Zn^{2+}$ in aqueous solution | Nano-silica used as a nano-adsorbent to remove $Pb^{2+}$ and $Zn^{2+}$ from aqueous solution | [137] |
| Barley and wheat grass wastes | Nano-adsorbent | 95% for nano-silica barley | $Ni^{2+}$ in agri-wastewater | Nano-silica used in extraction of about 93% of nickel ions from agricultural wastewater | [138] |
| Sawdust from tree wood *Cinnamomum camphora* | Nano-composite | 88.2 mg $g^{-1}$ | Hexa-valent Cr (batch technique) | Nano-silica coated biochar removed Cr (VI) under studied conditions | [139] |
| Almond and walnut shells | Nano-adsorbent | By loading iron oxide NPs onto the shell surface | Wastewater (dye solution) | Cationic dye adsorption and rapid separation by converting solid agro-wastes to magnetic activated-carbon | [140] |
| Olive pomace and rice husk | Nano-composite | Up to 90% for $^{226}Ra$ | Radionuclide pollutants in batch work | Treatments worked as nano-adsorbents to remove radionuclides (i.e., $^{226}Ra$, $^{210}Po$, and $^{228}Th$) | [141] |
| Kitchen waste converted into charcoal | Nano-adsorbent | 81–100% ($F^-$); 13–100% ($As^{3+}$) | Arsenic and fluoride ($F^-$) in drinking water | Pollutant adsorption by iron-NPs doped kitchen waste in water samples | [142] |
| Food waste (eggshell) | Magnetic nano-adsorbent | 94.6% | Cr(VI) in batch solution | Eggshell coated with magnetic nano-adsorbent removed Cr from a 18.24 mg $g^{-1}$ aquatic solution | [143] |
| Agricultural and garden wastes | Nano-composite | Adsorbed 10 mg $L^{-1}$ for 70 min | $Pb^{2+}$, $Cd^{2+}$, $Ni^{2+}$, $Cu^{2+}$, $Zn^{2+}$ in a bath study | Biosynthesized silica-supported iron oxide used as a nano-adsorbent for the rapid sequestration of heavy metal ions from wastewater | [144] |
| Natural cellulose and waste tires | Nano-absorbant | 47.61 mg $g^{-1}$ for 90 min | Malachite green dye in wastewater | $\gamma$-$Fe_2O_3$/MWCNTs/cellulose removed malachite dye by the chemical vapor deposition technique in wastewater | [145] |
| Tobacco leaves coated with iron oxide-NPs | Nano-adsorbent using continuous fixed bed column | Cr, Pb, and Zn were 92.26, 75.57, and 89.36%, respectively | Cr (VI), Pb (II) and Zn (II) ions from industrial effluent | Removal of toxic heavy metal pollutants by fixed bed column adsorption process using tobacco leaves coated with iron oxides | [146] |
| Silica-NPs using waste aquatic weeds | Nano-absorbant | 96.54 mg $g^{-1}$ after 60 min | Cr(VI) removal from industrial effluents | In batch experimental study, adsorbed Cr(VI) by ion exchange and electrostatic interaction | [147] |
| Orange peel extract | Nano-composite (PGHN) | Removed 98% of Cs within 110 min | Cesium (Cs) ions in aqueous solution | Nano-composite had super-paramagnetic action | [148] |
| Waste tea leaves | Green graphene oxide iron-NPs (GSGO@FeNPs) | 387.59 mg $g^{-1}$ in solution | Remove Cr(VI) from waste-water | High removal rate of Cr (VI) by chemisorption phenomenon | [149] |
| Pistachio shell agro-wastes | Iron-modified activated carbon derived from agro-waste | 99.99% | Removed 99% of dye at 516 mg $g^{-1}$ | Activated carbon derived from pistachio shells had high efficiency in removing dye from aqueous solution | [150] |
| Walnut shells and rice husk waste | Carbon nano-composite | Removed 78% of Cd(II) | Removing heavy metals from water | Magnetic activated carbon nano-composite removed Cd(II) from aqueous system | [151] |

Abbreviation: Multi-Walled Carbon Nanotubes (MWCNTs), Polyphenols functionalized graphitic hematite nano-composite (PGHN).

**Table 4.** Recently published articles on agro-wastes and their potential for biorefinery.

| The Main Findings of the Study | References |
|---|---|
| The biorefinery of agro-wastes through fermentation produced biofertilizer and biological formation of Ag-nanoparticles. | [152] |
| Spent coffee grounds were biorefined to produce fuel pellets. The grounds were divided into defatted spent coffee grounds and coffee ground oil that could be used to produce fuel pellets with excellent heating values. | [153] |
| Peach seeds were used in a zero waste biorefinery to extract oils/lipids and pyrolysis to generate gas, bio-oil, and biochar under different pyrolysis conditions. | [154] |
| Bioproducts were formed for use in the food and pharmaceutical industries through the integrated biorefinery of pineapple wastes. These bioproducts included bromelain, xylo-oligosaccharides, glucose, and residual hemicellulose. | [155] |
| A study on the biorefinery of crop residues and their applications. The main biorefineries for crop residues include the production of biomaterials, biofuels, enzymes, and nutraceuticals. | [156] |
| Studied the development of agro-waste biorefinery under the circular bioeconomy, which could be used to produce higher-value chemicals with high marketability. | [157] |
| Biorefinery approaches using fungi (mycology) through bioconversion and valorization via recovery, recycling and reusing of food wastes was studied. Food wastes could be processed for the recovery of oils, fatty acids, pectin, phenolic compounds through microbial bioconversion to produce biogas, bioethanol, enzymes, organic acids, and biopolymers, as well as biofertilizer and biomaterials like biofilms and 3D edible foods. | [158] |
| Different pretreatment techniques (i.e., chemical, physical, biological, and physico-chemical) for pretreatment of agro-wastes to improve the digestibility and biodegradability of agricultural lignocellulosic biomass were studied. Physical methods include mechanical pretreatment and ultrasonics; chemical methods include thermal, acid, and alkali pretreatments; and biological methods include oxidation, fungal, and organic solvent pretreatment. | [159] |
| The study investigated different approaches of sustainable biorefinery under the circular bioeconomy for conversion of biowaste for cleaner low-carbon environments. | [160] |
| Focused on establishing a circular bioeconomy through an integrated system of anaerobic digestion and pyrolysis for valorization of agro- and food wastes to produce biochar via sustainable approaches for carbon storage and capture in soil. | [161] |

### *7.3. Agro-Wastes to Produce Bioenergy and Biorefinery*

Energy demand is expected to increase worldwide due to rapid population growth and urbanization. To avoid continued and increased use of fossil fuels, new sources of energy need to be utilized. Renewable energy resources are considered the best options to alleviate environmental pollution and climate change risks while fulfilling future energy demands. Bio-based energy (e.g., biodiesel, bioethanol, etc.) is considered a sustainable, safe, cost effective, and eco-friendly source. Converting agro-wastes to energy is a promising alternative to fossil fuels [162]. Many studies have discussed the positive and negative aspects of converting agro-wastes and/or agro-industrial wastes into products such as chemicals, fuels, and by-products (e.g., [99,158–160]). Agro-wastes are considered an important resource for the generation of renewable energy through new methodologies [161]. The extraction methods used depend on the type of agro-wastes being processed (Figure 8).

Water and energy security both have a close relationship with food security. Moreover, the ever-increasing global population puts more demand on water and energy resources. Bioenergy (e.g., biogas, biohydrogen, bioethanol, biodiesel, etc.) can be generated from several agricultural and related wastes. Biofuels produced from agro-wastes have many advantages over fossil fuels like lower pollution rates (Figures 9 and 10; [57]). Due to high efficiency, negligible $CO_2$ emissions during combustion, sustainability, economic feasibility, and biodegradability, additional research and development of biofuels should be undertaken [57].

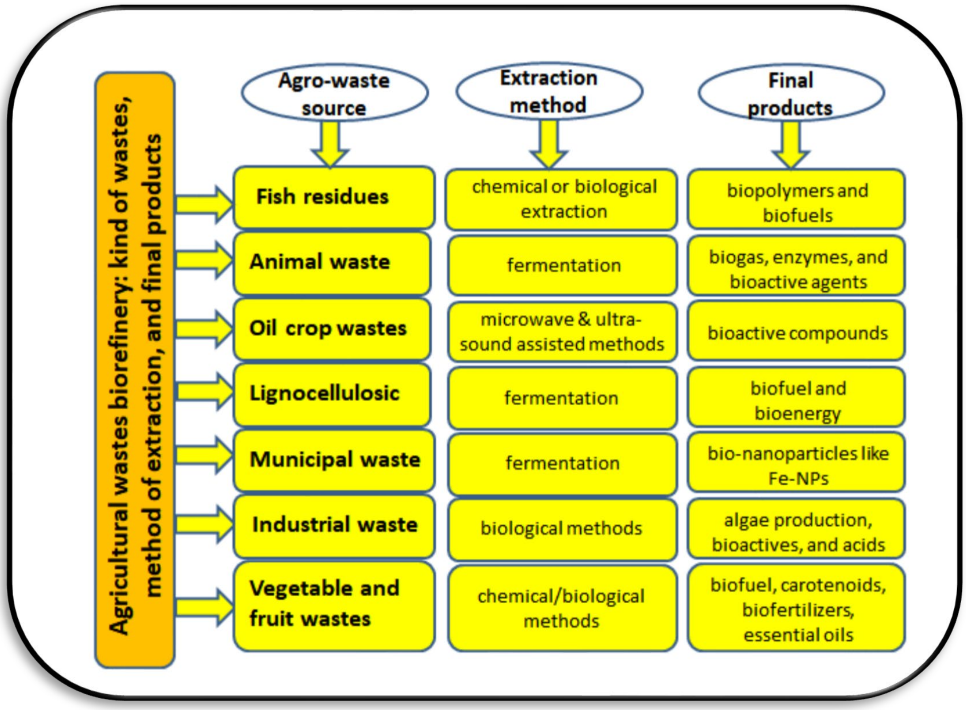


**Figure 8.** Common methods used in the processing and biorefinery of agro-wastes to produce bioproducts.

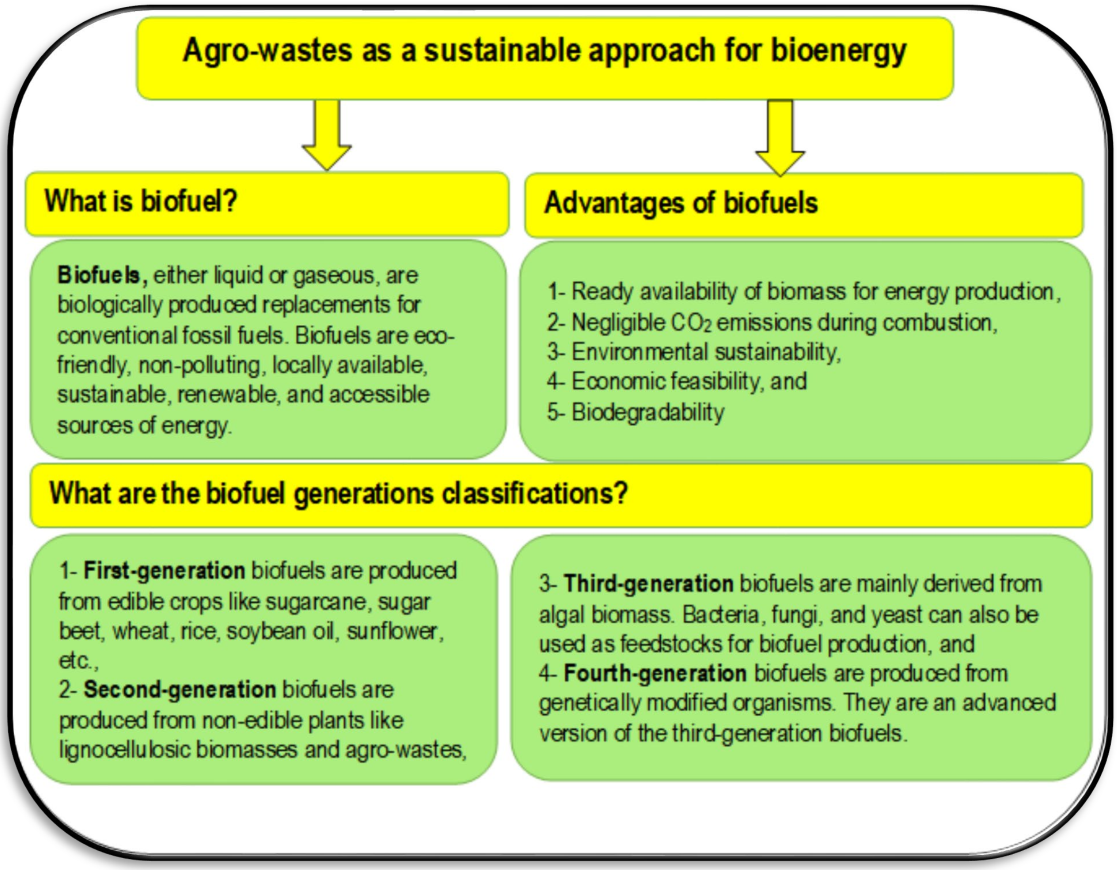


**Figure 9.** A general classification of biofuels along with applications and mechanisms for generating these biofuels.

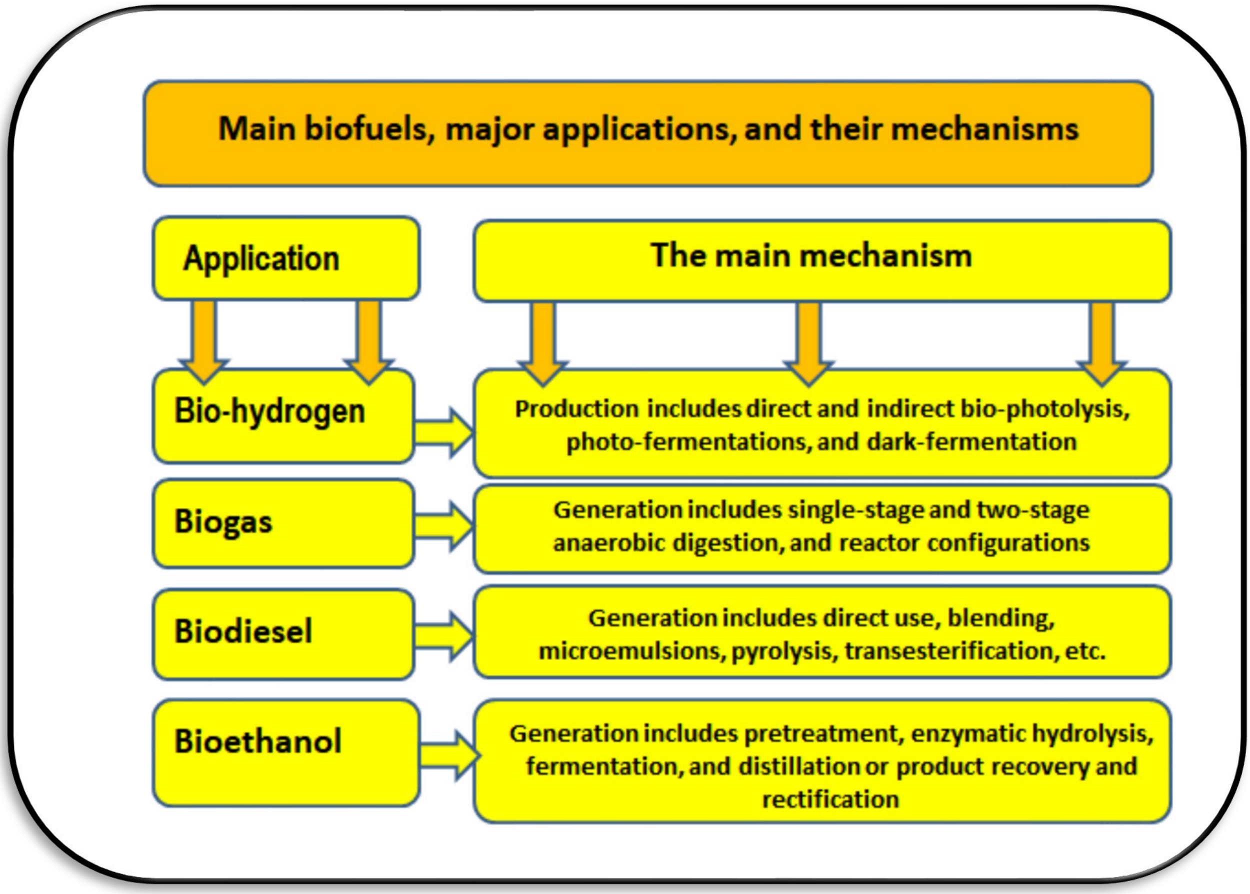


**Figure 10.** The main biofuels and the primary mechanisms for manufacturing them.

*7.4. Agro-Wastes for Plant Tissue Culture Media*

The agricultural industry has been fundamental for human survival for thousands of years [163]. However, modern agriculture generates tons of organic agricultural wastes such as inedible plant tissues (shells, peels, stalks, etc.) [164]. The rapid expansion of cities and human population has led to millions of tons of solid waste generation annually, which has serious implications for pollution of the global environment. Waste management systems that include storage, collection, transportation, segregation, processing and disposal of waste are very expensive and require technology that is not readily available in poor developing countries. Proper management of these wastes is essential to protect the environment and practice sustainable utilization of the available resources. This may include making compost for soil application or substitutional media for microorganisms. Agro-wastes can be used to prepare environmentally safe alternative plant tissue culture media that is less expensive than current commercial artificial media [165].

For example, cost-effective media for plant tissue culture have been formulated using the wastes of cabbage, beetroot, and onion. The agro-wastes were dried, then ground to powder. Coconut water was added as a source of natural hormone (cytokinin). This alternative medium could be used to grow plants because it contains micro and macronutrients within required ranges. It is useful for laboratory applications and at the industrial level for large scale production of plants [165]. It is a new strategy to produce the components of tissue culture media from farm wastes. This is a possible sustainable solution to protect the environment and preserve natural resources.

## 8. General Discussion

This section will address some of the many questions that emphasize the potential of water and energy in human activities, with a focus on environmental and biotechnological aspects of agro-wastes. However, before answering these questions, it is crucial to focus on energy and water as they relate to the United Nation's *Sustainable Development Goals* (SDGs). Energy and water are required for any agricultural, industrial, or social human activity. As the global population increases, we face the "*food* vs. *fuel*" conflict. Depending on the feedstock and technology or method used for biofuel production, there are four types of biofuels: (1) produced from food crops (mainly starch, sugar, and vegetable oil crops like maize, sunflower, sugarcane) grown on farmland, also known as "conventional biofuels"; (2) biofuels produced from animal or cellulosic biomass that represents non-food biomass (e.g., Arundo, Miscanthus), also known as "*cellulosic-ethanol*" or "*olive green*" fuel; (3) biofuels made from aquatic plant biomass (mainly algae), called "*algae fuel*" or "*oilage*"; and (4) the fourth generation of biofuel includes the highly advanced and novel technologies of genetically modified organisms or specific engineering of plants or microorganisms to provide higher yields of biofuels [161]. There is an urgent need to maximize the multifaceted environmental benefits of agro-wastes for both bioenergy and bioproducts production [164].

Are agro-wastes a blessing or a curse? Why are agro-wastes a global issue? Simply, food loss and waste represent a loss of financial, energy, and water resources, which negatively impacts our ability to meet the SDGs [165]. The importance of water and energy to food can be understood through their security (water, energy and food security), as elucidated in the SDGs. The UN included water and energy in 3 SDGs: in SDG 6 "*clean water and sanitation*", SDG 7 "*affordable and clean energy*", and SDG 14 "*life below water*". Therefore, there are strong links between water, energy, and the SDGs. Food is also emphasized in the SDGs, as seen in SDG 2 "*zero hunger*", SDG 3 "*good health and wellbeing*", and SDG 12 "*responsible consumption and production*" [166]. Therefore, a sustainable food system is a crucial strategy that requires linking farmers to markets, the optimization of food processing, and streamlining the food supply chain [167].

What are the environmental threats from the accumulation of agro-wastes? What are the expected benefits from sustainable agro-waste management? The accumulation of agro-wastes in the environment causes several health and environmental problems, which depend on many factors such as population awareness, degree of financial development of a country, public policies, education, and overexploitation of natural resources [22]. Management of agro-wastes is often accomplished through burning, land dumping, or landfilling. Burning wastes can cause adverse effects on the environment including increases in GHG and atmospheric temperature [100]. According to European environmental regulations, the management of organic residual matter (like agro-wastes) in agroecosystems has five dimensions of constraint: (1) water quality; (2) soil preservation; (3) gaseous emissions; (4) resource efficiency; and (5) human health [71]. Agro-industrial wastes should be handled using eco-friendly strategies instead of traditional processes (burning, landfilling, etc.) and follow the optimizing process conditions [168]. Biological approaches for handling agro-wastes are the most effective and include using enzymes for extraction via bio-decomposition, and fermentation for bio- transformation of wastes into products such as proteins, ethanol, peptides, enzymes, and pigments [22].

What are the main possibilities for agro-wastes management? Agro-wastes should be managed under the 4Rs rule within the food, water, energy, waste nexus (Figure 11). Natural and anthropogenic resources that are important in the agriculture sector include seeds, seedlings, land/soil, water, applied nutrients (fertilizers), energy, and labor. Utilization and management of agro-wastes may involve recycling, composting, forming nanoproducts, bioactives, food additives, pharmaceuticals, etc., which may impact the food-energy-water-waste nexus and other combined interactions. The cycle of agro-wastes due to human activities may start at the micro- (farm), meso- (company/industrial), or macro- (city to country) levels with different pathways under the 4Rs rule and different possible applications as well as management under different nexuses. The main factors that control the processing, transformation, converting and production of by-products or new products from agro-wastes include water, energy, and microbes (Figure 12).

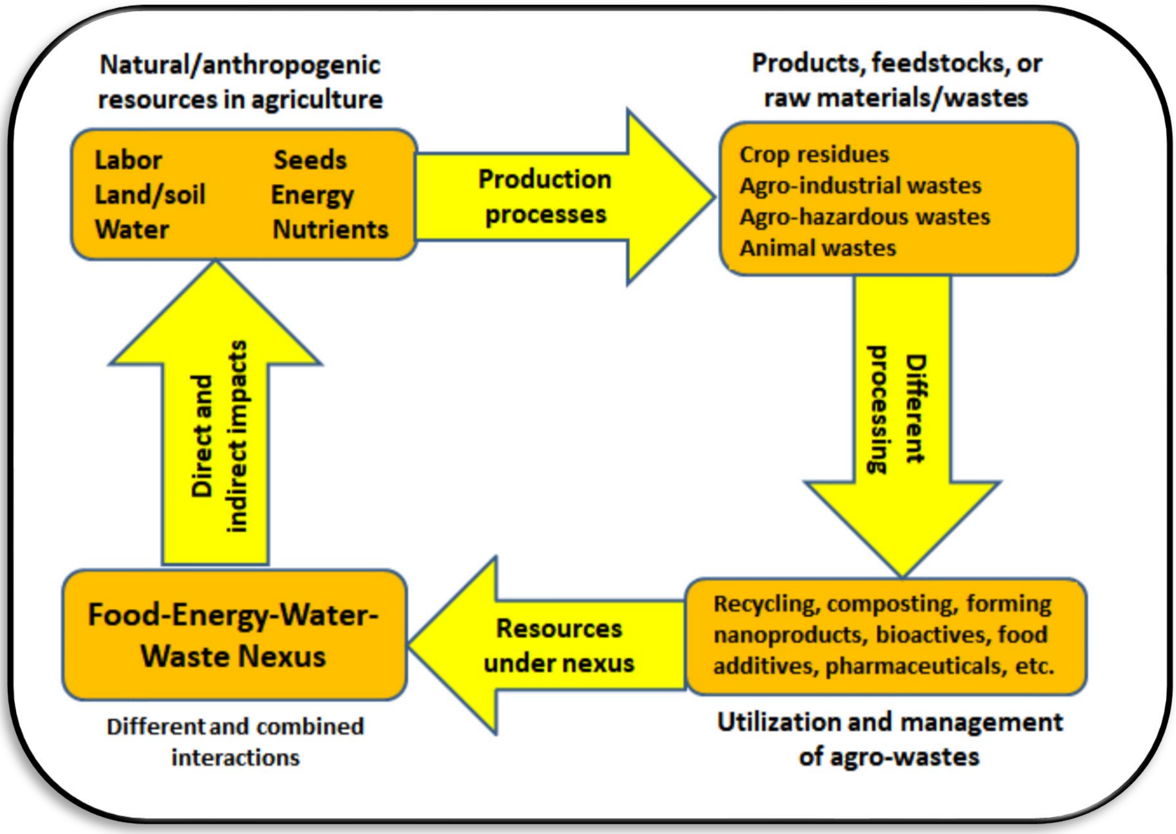


**Figure 11.** Generalized cycle of agro-wastes illustrating different pathways followed under the 4Rs (reduce, recovery, reuse, and recycle) rule and different possible applications, as well as suggested management under different nexuses.

What are the novel applications for the biorefinery of agro-wastes? To answer this question, it is important to review the main methods of agro-waste conversion into value-added bioproducts or energy during the biorefinery process, which includes combustion, gasification, pyrolysis, fermentation, anaerobic digestion, and transesterification [100]. The major products from agro-industrial wastes are biofuel, biogas, antibiotics, enzymes, phytochemicals, and biofertilizers [100]. Novel approaches to the biorefinery of agro-wastes include the use of nanotechnology and biotechnology to valorize agro-food wastes and improve their stability and applicability. There is an increased demand to develop novel tools and outcomes for examining and analyzing the valorization of agro-industrial wastes in a circular bioeconomy system. There is a critical need to renovate current methodologies in agro-waste biorefinery, and/or create a sustainable approach using agro-industrial waste biorefinery and expediting the production of biofuel on a large-scale [100].

It is important to produce innovative bio-ingredients (e.g., fiber, pigments, and polyphenols) from agro-wastes under the circular bioeconomy to open and exploit different market opportunities. Furthermore, urgent integrated/sustainable technologies are needed, at both the lab and industrial scale, for efficient extraction of biomaterials or bioactives from agro-wastes, especially fruit and vegetable wastes [69,169]. Mapelli et al. [79] reviewed novel possibilities for production of bio-based biodegradable nursery pots and development of biomaterials (e.g., bio-stimulant extracts, plant-growth promoting microbes) derived from food wastes. These novel biomaterials are an emerging industry that can generate new business and promote green jobs [79].

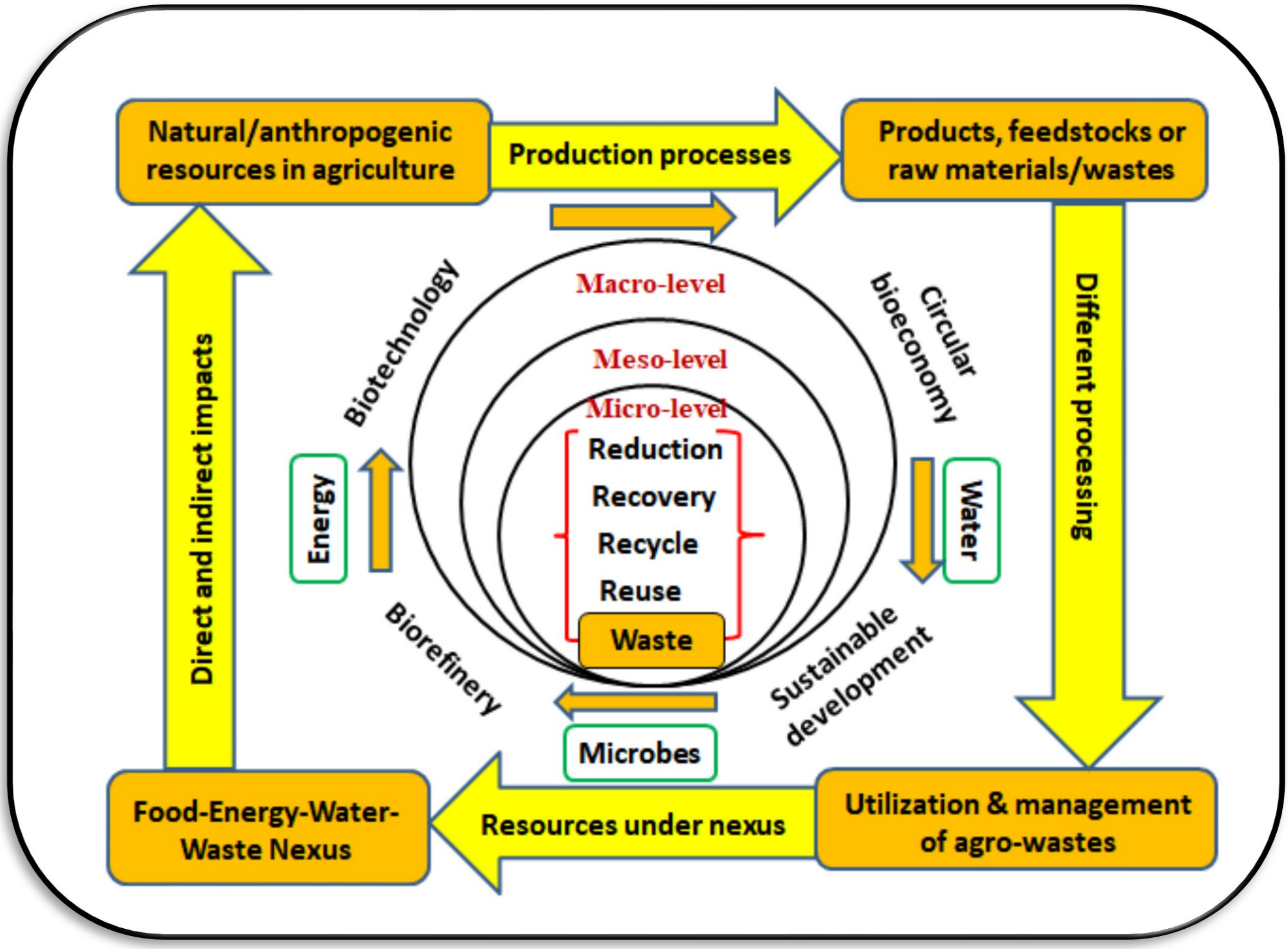


**Figure 12.** The cycle of agro-wastes starts with formation after human activity at the micro- (farm), meso- (company/industrial), or macro- (city to country) level with different pathways under the 4Rs (reduce, recovery, reuse, and recycle) rule with different possible applications and suggested management under different nexuses. The main factors that control the processing, transformation, conversion, and production of by-products or new products from agro-wastes include water, energy, and microbes.

To what extent can nanotechnological solutions for agro-wastes manage soil and water, especially under polluted conditions? Several biorefinery processes can be used to manage agro-wastes to produce value-added products [169]. Sustainable processes operating within the circular bioeconomy using chemical and biological conversion have been applied in nanotechnology, material engineering, pharmaceuticals, medicine, and remediation of polluted environments. Nanotechnology can be used to create biogenic iron oxide-NPs from paddy rice and wheat straw agro-wastes [170] using Azolla as a nano-catalyst [171], to remove pollutants from soil and water using nanomaterials derived from agro-wastes [151], and to produce biodegradable nano fibers derived from coconut wastes [172]. Producing nanomaterials using agro-waste as a substrate is a sustainable approach with economic, environmental, and technological benefits.

What is the relationship between food waste and water/energy? What are the open questions that still need to be answered? All food production needs water and energy, including practices such as seeding, tilling, harvesting, and producing and applying fertilizers and/or pesticides [173]. The energy footprint of the global food system is estimated to be greater than 70 Exa-joules ($10^{18}$ J) and about 70% of global water use is by the agricultural sector, with 40% of food produced from irrigated soils [173]. This shows there is a very strong relationship between agro-wastes and water and/or energy. A total of 82 billion cubic meters of water and 4 trillion megajoules of energy are lost globally during food consumption, including the post and retail phases of the food system [173]. Food wastes should be recovered or recycled to reuse water and energy, which can reduce the burden on existing systems [174]. It has been estimated that 344 million tons of avoidable food wastes squander $4 \times 10^{18}$ J of energy and $82 \times 10^{9}$ $m^3$ of water worldwide each year [173]. Thus, the water-energy-food system nexus is important to achieve zero-waste [175]. Several questions still need to be answered about the water-energy-waste nexus, including the environmental and societal dimensions linked to water, energy, food, wastes, climate, land, etc.

## 9. Future Research Recommendations

There are many additional areas that need to be investigated within the studied topic. This work could be strengthened through research collaborations among research institutes, universities, key research laboratories, and the industrial sector. It is also important that these collaborations are international in their scope, as these are challenges that face the entire global community and solutions will need to be global in their implementation. The main reason for this challenge is that water and energy are two components of any human activity, and of life itself. The main obstacle in agro-wastes management is the availability of facilities and the transfer of information from academics/researchers to farmers/other members of the agricultural industrial complex. Transferring innovative technologies and knowledge to farmers is a particular challenge in developing countries. Agro-wastes research is essential to secure energy and water security, especially under climate change, and to meet the needs of an ever-increasing population, which puts a large burden on energy and water resources. The valorization of agro-wastes and their management are essential for sustainable development. There is no circular economy without a thorough understanding of water and energy resources. The agro-food industry, which generates massive amounts of organic waste and wastewater, should be utilized as a valuable source of energy and resources recovery. Finally, intensive research is needed to move towards more sustainable management of existing water and energy resources. Evaluating agro-wastes and bringing them back into the production process means solving two very important problems in the modern world: environmental pollution; and the sustainability of economic activities. More recommendations could be listed in the following issues:

(1) It needs to be determined how much crop residue can be removed from a field to make cellulosic biofuels and other resources from renewable biologic sources, without denying the soil the levels of organic additions needed to sustain healthy soils;
(2) Complete life-cycle analyses need to be conducted for multiple aspects of the WEW;
(3) Soil scientists, agronomists, horticulturalists, chemists, engineers, economists, and others need to work together to define the major areas of missing knowledge, and design research to fill those gaps;
(4) We need to investigate ways to generate more uniform biofertilizers with more predicable decomposition and nutrient release characteristics to maximize nutrient management planning when these biofertilizers are used.

## 10. Conclusions

The agricultural sector is a major supplier of food, feed, fiber, and fuel. A huge volume of agro-wastes is generated as a result of agricultural activities and food processing, and this waste represents a major threat to the environment. At the same time, this waste can be seen as an opportunity for reuse in a more circular bioeconomy. An accumulation of these wastes could cause several human health problems, due to issues such as the outbreak of diseases, air pollution, or the release of GHGs. There are five main sources of agro-wastes: (1) crop residues; (2) agro-industry processing wastes; (3) animal wastes; (4) food wastes; and (5) hazardous and toxic wastes like pesticides. Food wastes can represent a direct threat to the environment due to increased GHG emissions, landfilling, and consumption or pollution of water resources. The main sources of food waste are industrial, retail, and household or consumer wastes. The management of agro-wastes to maximize benefits can be achieved through approaches such as composting, producing bioactives, nanomaterials, and/or using biorefinery tools. Many questions about the management of agro-wastes remain, especially about novel technologies for agro-waste composting, handling of food waste, biorefinery of agro-wastes, the regenerated role of nanotechnology in handling agro-wastes, etc. Expected developments in agro-wastes biorefining include valorizing these wastes into bio-based energy, converting cellulolytic/lignocellulosic materials into bio-alcohols, and producing advanced biogas systems. In this review, we have condensed information from various sources on a complex and evolving topic on how we handle our waste with a particular focus on agro-wastes. Finally, it could be concluded that the management of agro-wastes cannot be discussed without referring to the role of water and energy within the food system, as confirmed by many published studies.

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