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Review

Unlocking the Potential of Agrifood Waste for Sustainable Innovation in Agriculture

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Abstract: The United Nations Environment Programme's (UNEP's) Food Waste Index Report 2021 highlights a global annual food waste of 1 billion tons. The UNEP plays a crucial role in achieving Sustainable Development Goal (SDG) 12.3, which aims to halve per capita global food waste (FW) at the retail and consumer levels and reduce food losses along production and supply chains globally by 2030. On the other hand, the agricultural sector faces the challenge of increasing productivity to feed the world's growing population while reducing the environmental impact on ecosystems and human health. In this context, the conversion of agri-food waste (AFW) into biocides, bio-based fertilizers (BBFs) and biostimulants could represent a successful approach to tackle all these issues. This review shows the latest findings on the different sources of AFW and the application of their bioactive compounds in agriculture. Increasing crop yields and improving plant physiology through the utilization of AFW-derived value products aligns with a circular economy approach, bolstering people's confidence in managing food waste for improved food production.

Keywords: agri-food waste; biocides; biostimulants; bio-based fertilizers; agriculture; biomass

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1. Introduction

The United Nations Environment Programme's (UNEP's) [1] and European Union policies and initiatives to develop an industry based on the use and processing of renewable raw materials, known as bio-based, aim to achieve independence from non-renewable resources. This objective is geared towards establishing economic autonomy by reducing reliance on raw materials sourced externally. The bio-based industry represents an emerging sector with the goal of converting renewable biological feedstocks into bio-based products, materials, fuels, energy, biocides, biostimulants and bio-based fertilizers to replace their fossil-based counterparts. Potential biobased feedstocks include forestry, agrifood waste, food waste, agricultural, and aquatic biomass, as well as side streams and byproducts from industrial bioprocessing. Additionally, other residues such as sludge and municipal waste play a role, with particular emphasis on agri-food waste (AFW) [2].

The sustainable intensification of agri-food production to feed nine billion people by 2050 will increase the amount of AFW that is composed of the fractions of field waste, process waste generated by agricultural production, industrial processing and animal products [3–5].

The growth of the world population requires greater food production and increased productivity linked to agriculture. In the last 50 years worldwide, agriculture has significantly increased its productivity, reaching 23.7 million tons of food per day [6]. Consequently, the extension of agriculture has impacted the environment, including air, soil, and water, raising concerns about sustainability in the industry, because these companies produce a large amount of biomass that cannot be used as a food and for this reason it is considered a waste.

The recovery and replacement of nutrients from AFW, including crop residues, fruit and vegetable scraps, and post-harvest by-products in biocides (Section 2), bio-based fertilizers (Section 3) and biostimulants (Section 4), that are introduced into the soil environment, plants, fruits, and vegetables, will minimize the consumption of fossil resources and contribute to reducing the amount of waste deposited in landfills, contributing to waste reduction and recycling efforts. Additionally, it is our aim to lessen the dependency on chemical inputs and mitigate the environmental implications of waste [3,7,8].

In the literature, it is possible to find reviews that evaluate the production methods and application of biocides, biostimulants and biofertilizers. However, the present study describes the methods for obtaining the extracts, as well as their yield, using green extraction techniques to obtain the extracts used as biocides. Furthermore, the present work demonstrates applications both on a laboratory scale and in field studies of the use of biostimulants and biofertilizers, in addition to reporting the impact on agricultural crops after their application, such as plant growth, yield and quality. These factors differentiate this review from others found in the literature [2,7,8].

Moreover, the purpose of this revision is to define and investigate the promising potential of AFW to produce bio-based materials such as biocides, biostimulants and bio-based fertilizers. The proposed methodology includes, on the one hand, the identification of sustainable strategies to mitigate the pressure related to waste disposal. On the other hand, the use of biostimulants, bio-based fertilizers and biocides can lead to higher crop yields, better soil condition, and improved quality of fruits and vegetables, among other benefits.

2. Biocides: From Plants, for Plants

The widespread use of synthetic herbicides, pesticides and antimicrobials has caused increasing environmental pollution [9], which has ultimately led to compromised crop yields and human diseases; this urges an investigation of new sustainable and convenient alternatives [10].

A lot of plant-derived bioactive substances have already been proven to have biocidal activity, but the cultivation of dedicated crops for the obtainment of those compounds is not a sustainable solution; biocidal substances that are naturally present in AFW represent an economically convenient and environmentally conscious reservoir of biocides [11].

Plants are an extensive source of biocides since their portfolio of bioactive compounds is very vast. Polyphenols, terpenes, alkaloids, and other secondary metabolites can be obtained through extraction from AFW such as peels, leaves, roots, cobs, stalks and be used under the form of essential oils and crude extracts [12]. Moreover, AFW can be used directly without treatment to fulfil their biocidal function, or they can be used as substrates to grow antagonistic microorganisms as a form of biocontrol [13].

2.1. A Sustainable and Less Toxic Alternative to Traditional Pesticides

The growing resistance of insects to existing insecticides and increasingly rigorous regulatory requirements have prompted the need for the exploration of new, environmentally friendly, and cost-effective insecticides with favorable toxicological profiles and AFW represents a vast and cheap source of natural insecticidal compounds [14].

Neem oil is a known biocide that has been traditionally used as it contains numerous biological active substances, the most relevant being the limonoid azadirachtin, a known insecticide that interferes with egg-laying, molting, pupation, the development of adults, respiration, and consumption [15]. The oil-extraction process leaves behind neem cake as a by-product, which is a substrate that still contains pesticide compounds, as demonstrated by Nicoletti et al. [16], who successfully used neem cakes to obtain a crude extract rich in azadirachtin, nimbin and salannin, observing that the composition and the concentration of these compounds was highly variable between the different cakes screened. Azadirachtin has been found to have a pesticidal action on *Helicoverpa armigera* and *Spodoptera exigua*, two lepidopteran pests of tomato crops [15]. Besides limonoids, neem cake also contains saponins [17], which are known to interfere with the waxy covering of insects and to cover their spiracles, blocking respiration [18]. Neem seed cake can be also used as it is in combination with the insect pathogenic fungus *Metarhizium anisopliae*, a fungus that is pathogenic to insects, to control of black vine weevil (*Otiorhynuchs sulcatus*), as Shah et al. [19] found a synergistic effect between these two agents. Neem seed cake can also be employed as substrate for the growth of *Paecilomyces lilacinus*, a nematocidal fungus that can be used as biocontrol agent [17].

Essential oils and crude extracts have also been reported to have an insecticidal activity: hop essential oils obtained from brewery's hop wastes can be combined with several synthetic insecticides to make them act as an insecticidal synergistic repellent against *Spodoptera frugiperda*, an invasive insect pest [20]; ethanolic and aqueous extracts of avocado kernels (*Persea americana*) have an insecticidal activity against silverleaf whitefly nymphs [21]; nanoemulsions of a terpene-rich byproduct of commercial cannabidiol (CBD) production were found to have and effective insecticidal activity against the legume pest *Callosobruchus maculatus*, decreasing the quantity of insect eggs per bean, the proportion of beans containing eggs and the percentage of seed loss attributed to hatched adults [22].

Allium sativum L. is notoriously a source of insecticidal and nematocidal sulfur compounds which are mainly found in garlic cloves [23] but are also present in *Allium* waste such as husk [24] and straw [25]. It has been found that the use of raw garlic straw water extract in tomato cultivation increases the immobility and the mortality of *Meloidogyne incognita* juveniles [26]. *Allium fistulosum* leaf water extract has been found effective in the inhibition of insect pest of *Vigna unguiculata* L., increasing grain yield [27].

2.2. Secondary Metabolites, Proteins, and Biopolymers as Antimicrobials

Plants naturally adopt a lot of strategies to protect themselves from microbial attacks. Those tactics usually involve secondary metabolites such as polyphenols, terpenes and terpenoids, but can also comprehend proteins and peptides [12].

For instance, lignin is a strong antimicrobial compound, as its moieties have a natural bactericidal action associated with having the capacity to damage the cell membrane and cause subsequent bacterial cell lysis and leakage of cell content [28]. If nanosized, lignin can also have an added antimicrobial activity by directly entering the cell and cause further damage. Moreover, phenolic compounds commonly found in lignin, such as cinnamaldehyde, were found to be capable of crossing the cell membrane thanks to the hydroxyl-lipid interactions they can have with it [29–32]. Once in the cell, lignin causes a cascade that ultimately causes the lowering of the internal pH of the cell and the subsequent depletion of ATP [33]. Kraft lignin has been demonstrated to successfully inhibit bacterial plant pathogens, probably because of its high antiradical activity [31]. Indeed, it has been hypothesized that lignin could alter the physiological redox process and cause oxidative stress in microorganisms [33].

Yang et al. [33] (Table 1, Entry 1) created PLA (Polylactic Acid) films functionalized with lignin nanoparticles and cellulose nanocrystals; these composites were proven to have an antibacterial efficacy which resulted in a proliferation decrease in the bacterial plant pathogen *P. syringae* pv. *tomato* (Pst), the causal agent of tomato (*Lycopersicon esculentum* Mill.) bacterial speck. The best inhibiting activity was obtained using a PLA nanocomposite with 3 wt% lignin nanoparticles (PLA/3LNP). The same research group (Table 1, Entry 2) created polymeric films with PLA, chitosan and lignin nanoparticles that were able to inhibit the growth of *E. carotovora* subsp. *carotovora* and *X. arboricola* pv. *pruni*, chitosan with 3 wt% lignin nanoparticles (Ch/3LNP) were found to be the best performing polymeric film against bacterial growth. Moreover, nanocomposites with both chitosan and lignin were able to maintain the antibacterial activity over time [34]. These works prove that lignin is an effective antimicrobial toward plant/fruit infecting bacteria and that it can be used in antibacterial nanocomposites, hence it is a useful ally for crop protection and fruit preservation after harvesting. An et al. [35] (Table 1, Entry 3) prepared polyvinyl alcohol

(PVA)/lignin quaternary ammonium salts nanofibers that were able to successfully inhibit the growth of *L. monocytogenes*, a bacterium found in soil, water, and vegetation that can contaminate vegetables and is responsible for causing listeriosis.

Table 1. Antibacterial activity of agri-food waste derived materials and extracts.

Entry	Agri-Food Waste/ Agri-Food Waste Derived Material	Microorganism	Antibacterial Activity Testing	Ref.
1	Composite PLA film with lignin and cellulose nanostructures	*Pseudomonas syringae* pv. *tomato*	In vitro (Liquid medium test)	[33]
2	PLA film with chitosan and lignin nanoparticles	*Erwinia carotovora* subsp. *carotovora* *Xanthomonas arboricola* pv. *pruni*	In vitro (Liquid medium test)	[34]
3	PVA/lignin quaternary ammonium salts nanofibers	*Listeria monocytogenes*	In vitro (Turbidity and disc diffusion methods)	[35]
4	Lignin (from bagasse pulp black liquor) nanoparticles casted on a cellulose nanofibril	*Listeria monocytogenes*	In vitro (Inhibition zone method and shaking flask method)	[36]
5	Lignin@Cu nanoparticles	*Listeria monocytogenes* *Xanthomonas campestris* *Pseudomonas syringae* pv. *actinidiae*	In vitro (Agar dilution method)	[37]
6	Lignin@Cu nanoparticles	*Erwinia amylovora* *Pseudomonas syringae* *Xantomonas campestris* *Xantomonas arboricola*	In vitro (Agar dilution method)	[38]
7	*Salvia sclarea* L., *Salvia rosmarinus* Schleid, *Salvia officinalis* L., *Helichrysum italicum* and leaves of *Cupressus sempervirens* L.	*Clavibacter michiganensis* subsp. *nebraskense* ATCC 27822	In vitro (Microdilution method using 96-well microtiter plates)	[39]
8	HTyr-enriched olive mill wastewater	*Pseudomonas savastanoi* pv. *savastanoi* *Agrobacterium tumefaciens*	In vitro (Halo inhibition assay)	[40]
9	Protein hydrolysates (<3 kDa) derived from rice (*Oryza sativa*) straw, bagasse (*Saccharum* sp.), peanut (*Arachis hypogaea*) seed coat, and coconut (*Cocos nucifera* L.) residue	*Xanthomonas oryzae* pv. *Oryzae* *Xanthomonas citri* *Pectobacterium carotovorum* *Agrobacterium rhizogenes*	In vitro (Broth dilution method—microplate reader)	[41]

Nanocomposites of lignin have a proven antibacterial effect. Wang et al. [36] (Table 1, Entry 4) created a cellulose nanofibril film with lignin nanoparticles casted on it that successfully reached a 93% inhibition of *Listeria monocytogenes.* Gazzurelli et al. [37] demonstrated in vitro the antibacterial activity of composed by lignin and copper (lignin@Cu) on *L. monocytogenes* and *X. campestris*, meanwhile, *P. syringae* pv. *actinidiae* was not affected by it (Table 1, Entry 5). Other lignin@Cu nanoparticles have also been tested and found effective on *E. Amylovora*, *P. syringae*, *X. campestris* and *X. arboricola*. In this study, it was observed that nanoparticles containing high molecular weight lignin had a more marked antibacterial effect compared to the ones containing medium molecular weight lignin (Table 1, Entry 6) [38]. Besides lignin, crude extracts and protein hydrolysates obtained from plant waste can exert an antimicrobial activity, moreover, wastewaters rich in plant-derived compounds have been also found active against bacteria. Chiocchio et al. [39] (Table 1, Entry 7) screened thirty-seven methanolic extracts of plant by-products for in vitro antibacterial activity against phytopathogenic bacteria and found that only five of them (*Salvia sclarea* L., *Salvia rosmarinus* Schleid, *Salvia officinalis* L., *Helichrysum italicum* and leaves of *Cupressus sempervirens* L.) possessed adequate antimicrobial activity against the Gram-positive specie *C. michiganensis,* which is the cause of wilt in maize. Surprisingly, all the active biomasses were post-distillation waste, three of them from the *Salvia* genus; this indicates that this kind of biomass is still able to be re-used. Notably, the matrices subjected to testing showed no inhibitory effects on the Gram-negative bacterium *P. syringae*.

Hydroxytyrosol (HTyr) enriched olive mill wastewater (OMWW) (Table 1, Entry 8) was obtained through membrane treatment and tested for antimicrobial activity on *P. savastanoi* pv. *savastanoi* and *A. tumefaciens*. For both species, OMWW had a higher efficacy in the reduction of colony forming units (CFU) compared to HTyr alone, meaning that other compounds present in the water also possessed antimicrobial activity [40].

Protein hydrolysates derived from rice straw, bagasse, peanut seed coat, and coconut residue demonstrated antibacterial activity against bacterial plant pathogens such as *X. oryzae* pv. *oryzae*, *X. citri*, *P. carotovorum*, and *A. rhizogenes.* Protein hydrolysate derived from bagasse exhibited the most antibacterial efficacy; further investigation revealed it contained "ATP-binding cassette domain-containing protein" and "Expansin" among the peptides, while other peptides present in the hydrolysate (PQLAVF and MDRFL) were found to cause cell leakage and interfere with DNA-related processes in *X. oryzae* pv. *oryzae*, and peptide VQLMNSL interfered with the biological processes of *P. carotovorum* and *A. rhizogenes* (Table 1, Entry 9) [41].

Besides bacteria, fungi are a crucial threat to crop cultivation worldwide, which is why there is also a pressing need for novel antifungals [42–50].

Giorni et al. [42] (Table 2, Entry 1) investigated the antifungal activity of extracts of red and white grape marc, grape seeds and stalks, red grapevine leaves, apple, pear, tomato, spent hops and green beans obtained with green extraction protocols (Naviglio® extraction, Ultrasound-assisted extraction (UAE), and steam distillation) on mycotoxigenic fungi such as *A. flavus*, *A. carbonarius*, *F. graminearum*, *F. verticillioides* and *A. alternata.* It was found that extracts from different sources had different inhibition efficacy in the fungal species; a substantial reduction in mycotoxin production was also observed. These extracts could find application in agricultural processes where the control of fungal growth and mycotoxin creation control is a fundamental requirement, such as winemaking or during food storage. Similarly, red, pink, and white wine grape marcs hydrolysates had antifungal activity against *F. oxysporum* and *Alternaria* spp. (Table 2, Entry 2); all the extracts contained high concentrations phenolic acids such as vanillic acid, hydroxybenzoic acid, gallic acid and *p*-coumaric acid and exhibited a considerable antifungal activity [43]. *F. oxysporum* was more inhibited by the extracts compared to *Alternaria.*

Table 2. Antifungal activity agri-food waste biomass derived materials and extracts.

Entry	Agri-Food Waste/ Agri-Food Waste Derived Material	Microorganism	Antifungal Activity Testing	Ref.
1	Extracts of red and white grape (*Vitis vinifera* L.) marc, grape seeds and stalks, red grapevine leaves, apple (*Malus* sp.), pear (*Pyrus communis*), tomato (*Solanum lycopersicum*), spent hops (*Humulus lupulus*) and green beans (*Phaseolus vulgaris*)	*Aspergillus flavus* *Aspergillus carbonarius* *Fusarium graminearum* *Fusarium verticillioides* *Alternaria alternata*	In vitro (Fungal growth and mycotoxin production in Petri dishes)	[42]
2	Red, pink, and white wine grape marcs hydrolysates	*Fusarium oxysporum* *Alternaria* spp.	In vitro (Growth inhibition on Petri dishes)	[43]

Table 2. *Cont.*

Entry	Agri-Food Waste/ Agri-Food Waste Derived Material	Microorganism	Antifungal Activity Testing	Ref.
3	Crude extracts of peels from banana (*Musa* spp.), garlic (*Allium sativum*), brown onion (*Allium cepa* L.), orange (*Citrus* × *sinensis* L.), lemon (*Citrus* × *limon* L.), white potatoes (*Solanum tuberosum*) and pomegranate (*Punica granatum*), barks from *Eucalyptus* sp. and pine (*Pinus* sp.), olive (*Olea europaea*) leaves and pine (*Pinus* sp.) needles	*Diplodia corticola* *Botrytis cinerea* *Colletotrichum nymphaeae* *Phytophthora cinnamomi*	In vitro (Growth inhibition on Petri dishes)	[44]
4	Garlic (*Allium sativum*) peels crude extract	*Colletotrichum acutatum*	In vivo (Apple from "Golden"cultivar protection evaluation)	
5	Potato protease inhibitors I and II from starch manufacture effluent	*Fusarium solani* CCM 8079 *Fusarium solani* CCM 8014 *Fusarium solani* CCM 1036 *Fusarium oxysporum* CCM 17 *Fusarium oxysporum* CCM F65	In vitro (Incorporation of hydrolysate in agar-media)	[45]
6	Extracts from *Crocus sativus* L. flower waste	*Penicillium expansum* *Penicillium digitatum* *Botrytis cinerea* *Fusarium solani*	In vitro (Disc-plate diffusion method)	[46]
7	Nanoemulsions derived from essential oil extracted from *Citrus sinensis* peel and *Citrus sinensis* essential oil alone	*Fusarium* spp. *Aspergillus niger* *Penicillium* spp. *Aspergillus ochraceus*	In vitro (Disc plate diffusion method)	[47]
8	Lignin@Cu nanoparticles	*Botrytis cinerea* *Rhizoctonia solani*	In vitro (Disc plate diffusion method)	[37]
		Rhizoctonia solani	In vivo (In field on "Kero" variety tomato crop)	
9	Lignin@Cu nanoparticles	*Erwinia amylovora* *Monilinia laxa* *Alternaria solani* *Fusarium solani* *Botrytis cinerea* *Septoria tritici* *Rhizoctonia solani*	In vitro (Agar dilution method)	[38]
		Rhizoctonia solani	In vivo (Greenhouse italian tomato "cuore di ponente")	
10	Post extraction lavender (*Lavandula angustifolia*) and lavandin (*Lavandula* × *intermedia*) as soil amendment	*Verticillium dahliae*	In vivo (Field application Strawberry cv. Elsanta)	[48]
11	Agricultural Jiaosu derived from officinal plants	*Fusarium oxysporum*	In vitro (Agar plate diffusion method)	[13]
			In vivo (Greenhouse Pot Experiment on *Astragalus membranaceus*)	
12	Agricultural Jiaosu derived from brown sugar and jujube (*Ziziphus jujuba* Mill.) wastes	*Botrytis cinerea*	In vitro (Colony inhibition on agar plates)	[49]

Palazzolo et al. [51] proved that one of the antifungal mechanisms of grape stalks extracts is based on gamma-sitosterol; this compound could also contribute to the antifungal activity displayed by grape by-products in aforementioned articles. In all the works mentioned, *Alternaria* spp. has demonstrated to be more resistant to the antimicrobial effects of plant extracts compared to other fungal species.

Teixeira et al. [44] (Table 2, Entry 3) obtained crude extracts from various AFW (peels from banana, garlic, brown onion, orange, lemon, white potatoes and pomegranate, barks from eucalyptus and pine, olive leaves and pine needles) and subsequently tested them against phytopathogenic fungi: garlic peel extract was found to be the most effective, followed by onion peel extract. Thanks to a comparison resistance test of different mutant strains of *S. cerevisiae*, researchers could hypothesize that garlic peel extract directly interfered with ergosterol synthesis; moreover, it affected the cell wall integrity. Garlic peel was then directly tested on apples infected by *C. acutatum* and was found to delay the fungus propagation inside the fruit (Table 2, Entry 4) [44].

Potato protease inhibitors I and II obtained from the effluent of a starch manufacture industry successfully inhibited *F. solani* and *F. oxysporum* (Table 2, Entry 5) [45].

Different saffron (*Crocus sativus* L.) flower waste antioxidant extracts were tested against fungal species responsible of crop yield losses and post-harvest mold: they were found to be effective on all of them, with *B. cinerea* expressing a higher susceptibility (Table 2, Entry 6) [46].

The essential oil extracted from *Citrus sinensis* peel, rich in limonene, was used to create antifungal nanoemulsions and exhibited a high antifungal activity toward *Fusarium* spp., *A. niger*, *Penicillium* spp., and *A. ochraceus*, but the direct application essential oils was found to have more efficacy compared to nanoemulsions created with them, probably because of a degradation of essential oil components during the creation of nanoemulsions (Table 2, Entry 7) [47].

The Lignin@Cu nanoparticles created by Gazzurelli et al. [37] (Table 2, Entry 8) were also tested against *B. cinerea* and *R. solani* in vitro; antimicrobial activity was only observed against the latter. The nanoparticles were also tested on crops directly in field against *R. solani* on "Kero" variety of tomato plants and it was found that nanoparticles containing high molecular weight lignin displayed a more marked fungicidal effect compared to others. Sinisi et al. [38] (Table 2, Entry 9) also observed antifungal activity testing Lignin@Cu nanoparticles on *E. amylovora*, *M. laxa*, *A. solani*, *F. solani*, *B. cinerea*, *S. tritici* and *R. solani* in vitro. The nanoparticles were also tested in a greenhouse directly on the leaves of Italian "cuore di ponente" tomatoes infected by *R. solani* and it was again observed that nanoparticles created with high molecular weight lignin were more effective than copper hydroxide alone both in vitro and on field, where nanoparticles were found to be more effective than the reference commercial product. Both works demonstrate that the coupling of lignin with Cu nanoparticles can help diminish the usage of Cu in agriculture without diminishing the biocidal effect.

Another strategy to employ the antimicrobial effect of AFW is using them without further treatment for soil amendment; for instance, the incorporation of post-extraction lavender and lavandin in fields that were naturally infested with *V. dahliae* (the biological cause of wilt) was associated with a large reduction in viable microsclerotia. In particular, lavandin was found to be more effective than lavender in reducing the inoculum size (Table 2, Entry 10) [48].

Another antimicrobial strategy is, as mentioned before, biocontrol by other microorganisms. Agricultural Jiaosu (AJ) is a microbial consortium produced via the fermentation of AFW which has been demonstrated to enhance the yield of plant biomass and increase soil nutrients. Gao et al. [13] (Table 2, Entry 11) demonstrated that Jiaosu developed on officinal plants wastes had an antifungal activity on *F. oxysporum*; in addition, it was observed that both bacteria grown on Jiaosu and acids produced by them inhibited the fungal growth. In particular, the bacterial species that exhibited the most antagonistic activity were of the genuses *Bacillus* spp. and *Lysinibacillus* spp. When tested directly in field AJ treatments significantly increased plant height, root length, root diameter, chlorophyll content, and fresh and dry weights of *Astragalus.* Zhang et al. [49] (Table 2, Entry 12) came to a similar conclusion, observing that AJ grown on brown sugar and jujube wastes provided antifungal activity by both providing beneficial biocontrol bacteria (mainly *Lactobacillus* and *Acetobacter*), and an acid environment, which inhibited fungal growth and created a perfect habitat for the growth biocontrol bacteria.

2.3. Allelopathy of By-Products: Plant Waste-Derived Herbicides for a Sustainable Agriculture

Plants naturally compete with other plants for resources such as nutrients, water and sunlight in a mechanism called allelopathy. To diminish the competition, they produce biochemicals capable of influencing the growth, development, reproduction and, subsequently, survival of other species [52]. The allelopathic compounds created naturally by plants are still present in plants by-products, therefore, they can be used to inhibit the growth of unwanted weeds in agricultural fields.

Plant by-products can exploit the dual function of soil amendment and weed control agents. Lorenzo et al. [53] assessed the herbicidal activity of several AFW biomasses and found that *Urtica dioica* waste, *Vicia faba* pod waste, coffee (*Coffea arabica*) grounds and corn (*Zea mays*) cobs were effective in inhibiting weed growth. Mallek et al. [54] reported that the application of dried and milled crop residues of different *Allium* species inhibited the germination of weeds in a concentration-dependent manner.

Beside antimicrobial and insecticidal activities, plant waste crude extracts and essential oils can also exhibit an herbicidal activity; in fact, chicory (*Cichorium intybus* L.) root extract displayed inhibitory effects on the germination of seeds, as well as the growth of roots and shoots in both *Echinochloa crus-galli* L. Beauv and Amaranthus retroflexus L. [55], and neem oil extracted from *Azadirachta indica* seed waste was found to be an effective bioherbicide against *Senna occidentalis,* retarding its germination and altering the normal development of the weed [56].

Agri-food by-products can also act as herbicides when used for mulching. El-Metwally et al. [57] tested several AFW as mulching material for weed control and found wheat hay, rice straw, peanut straw and mango leaves to be the best materials for a reduction in weed and increase in root and sugar yields in sugar beet (*Beta vulgaris* L.) cultivation; *Plectranthus amboinicus* L. extract was also applied directly in field to assess its herbicide action. Shehata et al. [58] tested mango peel waste, olive oil processing waste and orange peel waste as soil mulches and found the latter to be more effective in weed control when applied to onion crop (*Allium cepa* L.) cultivation. Both studies also investigated the herbicidal activity of the extracts of tested AFW and did not find them effective enough to have an adequate herbicidal function in open field conditions; on the other hand, solid by-products acted also as sunlight-blocking agents, enhancing the growth inhibition of unwanted weeds.

3. Importance to Convert Agri-Food Waste into Bio-Based Fertilizers

The conversion of AFW into bio-based fertilizers (BBFs) is important for several reasons, as it addresses both environmental and agricultural sustainability challenges. The agricultural food supply chain, such as the distribution of products, consumption, post-harvest, processing and production, generates substantial quantities of AFW. Unfortunately, there are still challenges to produce organic fertilizers, as chemical fertilizers are more prominent. In addition, developing countries have limited infrastructure and limited subsidy programs, which further worsens this situation [4,5].

Therefore, using waste from the food industry is gaining prominence, as its use brings economic and environmental benefits, mitigating the problems associated with its conventional disposal [3]. Increased yield in food production and improved soil stability are positive aspects linked to the use of BBFs, which contain high levels of nutrients and organic matter. This is gaining attention from researchers, as its use is associated with minimizing environmental impacts, reducing costs and following the principles of the circular economy. The conversion of AFW into BBFs promotes the return of nutrients to the soil and consequently increases the activity of microorganisms, increases the bioavailability of nutrients and the absorption and retention of water in the soil. In this way, there is a reduction in the need for the use of synthetic fertilizers and other inputs, as the nutrients present in the residues are sufficient for nutrition and increased crop yield [59,60].

Furthermore, BBFs can also assist in the biological remediation of soils contaminated with hydrocarbons and pesticides. Therefore, to preserve the environment and reduce AFW, organic fertilizers are being combined with chemical fertilizers and this nutrient management is increasing the sustainability of agricultural production [61]. Organic matter in AFW can act as a carbon sink when incorporated into the soil, contributing to climate change mitigation efforts [62].

Therefore, the conversion of biomass into BBFs offers a versatile approach to tackle environmental challenges, support sustainable agriculture and create a more circular and resource-efficient food production system. This is a crucial step towards a more sustainable and resilient agricultural ecosystem.

3.1. Bio-Based Fertilizers: General Aspects

Bio-based fertilizers can have different functions, types, actions and availability. They can be divided into the supply mixture of nutrients (it provides essential nutrients to plants, such as nitrogen, phosphorus, and potassium, either directly or indirectly through microbial activities and ensuring optimal conditions for nutrient availability), improved soil health (it contributes to soil health by enhancing its structure, water retention, regulate soil pH, and microbial diversity), the maintenance of symbiotic relationships, the suppression of soil born pathogenic diseases in crops, enhanced crop and maintain microbial consortia in soil [7,61].

A high demand for standard fertilizer production is observed for those that are commonly known as NPK fertilizers and macronutrients (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg)), available along with numerous micronutrients (zinc (Zn), copper (Cu), iron (Fe), boron (B) and molybdenum (Mo) to plants [61].

The fertilizers can be divided in bio-based and chemical. Chemical ones are used more because there is no need to convert nutrients so that they are available to plants; in addition, the concentration of nutrients is high, resulting in a smaller quantity of product applied for crop growth. However, they have some disadvantages, such as (i) excessive N will cause the softening of plant tissues, and diseases and pests may occur; (ii) the loss of soil quality due to decomposition and degradation of its structure; (iii) soil pH correction (acid or alkali) and the elimination of beneficial bacterium; (iv) the loss of nutrients through leaching, which reduces the efficiency of the fertilizer [63].

For this reason, the BBFs can be applied in the soil treatment to improve the plants growth because they have many advantages front of chemical fertilizers (some of characteristics and advantages of the bio-based fertilizers and biostimulants are shown in Figure 1), such as (i) maintaining residual levels of organic nitrogen (N) and phosphorus (P) in the soil, thereby mitigating nitrogen loss via leaching and preventing phosphorus fixation; (ii) promoting the mobilization of nutrients that can improve the biological activity of the soil; (iii) increasing the organic matter content of the soil, consequently increasing the nutrient exchange capacity; (iv) supplying nutrients conducive to fostering the proliferation of advantageous microorganisms; (v) improving soil quality in terms of structure, helping with root development and reducing diseases; (vi) increasing water retention in the soil; (vii) conferring economic and ecological advantages by increasing soil vitality and fertility; and (viii) representing an advantageous option (cheap, environmentally friendly) for the reuse of renewable resources [64–68]. However, BFFs may present reduced and variable concentrations of nutrients necessary for crop growth and development. Therefore, it is necessary to use greater quantities of them, to minimize nutritional deficiencies that may occur due to the gradual rate of absorption and transfer of micro and macronutrients to plants. Despite these limitations, BFFs are an effective example of circular economy applied in agricultural practices [64–68].

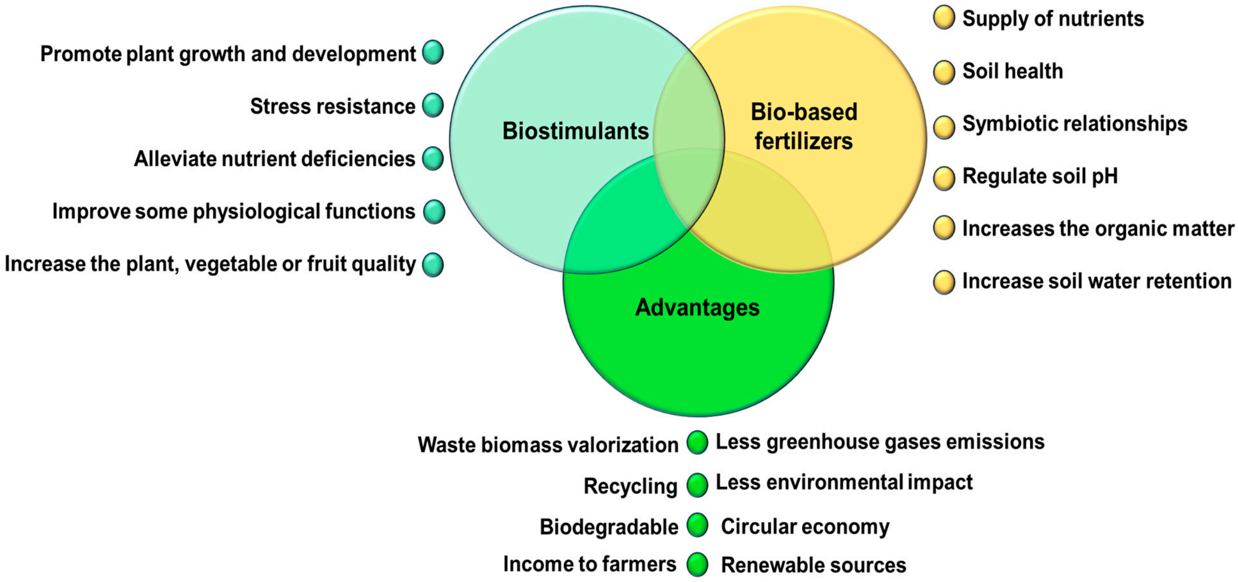

Figure 1. Characteristics of bio-based fertilizers and biostimulants and the advantage of converting AFW into these products.

Therefore, the use of BBFs in agriculture offers a sustainable and environmentally friendly approach to soil enrichment and crop nutrition. BBFs contribute to the principles of sustainable agriculture through recycling organic waste, reducing dependence on chemical inputs, and promoting ecosystem balance. While bio-based fertilizers offer numerous advantages, their efficacy may vary based on factors such as soil type, climate, and crop requirements. The utilization of bio-based fertilizers represents a promising avenue for achieving sustainable agriculture. As research continues to explore innovative formulations and applications, the agricultural sector can further harness the potential of bio-based fertilizers to address food security, environmental conservation, and the long-term health of agricultural ecosystems [64–68].

3.2. Methods for Converting Agri-Food Waste into Bio-Based Fertilizers

The most common AFW treatment processes include anaerobic digestion, composting and pyrolysis; these methods are in accordance with the circular economy perspective [69–71]. These processes generate products from different conversion processes and have different physical, chemical, and biological properties [7].

Anaerobic digestion (AD) consists of a three-stage process (hydrolysis, acetogenesis, and methanogenesis), and its main products are methane, carbon dioxide and digestate [72]. AD treatment can be provided for agricultural waste and various organic matrices to produce digestate and biogas. After the AD, two products can be obtained: liquid digestate (can be applied directly to crops as a liquid fertilizer, providing essential nutrients for plant growth) and solid digestate (used as a soil conditioner or incorporated into compost blends to enhance nutrient content). Digestate is safe to use directly in the field, as it contains a high percentage of organic matter and low heavy metal content. These BBFs can increase the yield and nutrition of the crops on which it is applied, as it is rich in micro and macronutrients and is also beneficial from the point of view of climate mitigation [73,74]. Moreover, BFF contains high concentrations and bioavailability of NPK (nitrogen, phosphorus and potassium), 60% of which is in the form of total nitrogen [75]. AD stands out as a versatile and sustainable method for converting AFW into BBFs, offering benefits such as nutrient recycling, improved soil health, and renewable energy production. However, successful implementation requires careful consideration of feedstock characteristics, system design, and management practices to optimize the process for specific agricultural.

AFW can also be managed using composting treatment that consists of a biological process in which it breaks down organic matter and humic substances by microorganisms under aerobic conditions (oxygen presence) as well as water presence, and this process results in the release of dissolved organic matter (humus). Moreover, this procedure can be improved through the addition of biological inoculants such as bacteria and fungi [7]. The decomposition process, conditions, addition of nutrients and raw materials used directly affect the final quality of the compost [61]. During the composting process, organic materials undergo microbial decomposition, resulting in the generation of various compounds, such as humic substances (fulvic acid, humic acid, and humin), carbon dioxide (CO_2) (as a byproduct of their metabolic processes, that indicates the microbial activity), water (composting involves the release of water through microbial metabolism and the breakdown of organic materials), nitrogen compounds (ammonium (NH_4^+), nitrites and nitrates (ammonium is converted into nitrites and nitrates through nitrification by bacteria), phosphorus compounds (phosphate), potassium compounds (soluble potassium), micronutrients (Fe, Zn, Cu, Mg, among others), volatile organic compounds (alcohols, aldehydes, acids), cellulose and hemicellulose breakdown products (simple sugars), proteins and amino acids (ammonia (NH_3)), and enzymes (cellulases, proteases, lipases, among others). These enzymes are from the microorganisms that produce enzymes to break down complex organic molecules into simpler forms during composting [61].

It is vital to notice that the composting procedure aims to transform organic waste into a stable and nutrient-rich material. The product, compost, is characterized by improved nutrient content, reduced volume, and enhanced stability compared to the initial organic waste. The compost can then be applied as a BBF to improve soil fertility and support plant growth in agriculture.

Through composting, AFW is transformed into stable organic matter that can be used in agriculture as soil amendment [76], bio-based fertilizer [77,78] and other applications. This biomass transformation process produces water, CO_2, and makes nutrients, such as NPK, accessible to plants, in addition to obtaining stable and sterile solid substrates [79]. Composting requires the monitoring of certain parameters such as pH, oxygen, particle size, temperature, time, curing, moisture content, and C/N ratio to optimize its potential to be used as a bio-based fertilizer [79,80].

To obtain biochar, biomass is thermally carbonized (pyrolysis) inside a sealed chamber under limited oxygen, controlled temperature and holding time conditions. However, if these conditions have been modified it can obtain biochar with different characteristics. This thermochemical transformation is accompanied by functional modifications resulting in the production of biochar, which is a carbonaceous product characterized by a substantial surface area, a porous structure, and an abundance of functional groups. Various processing techniques can be applied to biochar, resulting in a diverse range of physical and chemical characteristics [81–83].

After converting organic matter into BBFs, they can be applied to the soil or directly to crops, to evaluate their benefits. Therefore, several studies report these applications in literature.

3.3. Bio-Based Fertilizers Applied in Crops and Soil

BBFs can be defined as materials or products derived from biomaterials (plant, animal or microbial origin, often wastes, residues or side-streams from agriculture, industry or society) with a content of bioavailable plant nutrients suitable to serve as a fertilizer for crops [84]. The agri-food waste or biowaste materials utilized to produce the BBF, the principal macro and micronutrients found in BBFs, and the method for converting agri-food waste into bio-based fertilizers and applications in agriculture can be seen in Table 3. Multiple processing techniques exist for synthesizing organic fertilizers, and the effective managing of these AFWs is crucial for establishing a sustainable cycle encompassing manageability, fertilizer value, soil amelioration value, and plants growth [84].

Table 3. Characteristics of bio-based fertilizer produced from different types of agri-food waste.

Method of Valorization	Source of Biomass	Type of Fertilizer	Crop Application	Principal Nutrients Found in the BBF	Ref.
Pyrolysis	Rice husks, peanut shells and sugarcane	Liquid fertilizer	* Chinese Cabbage seeds (*Brassica pekinensis*)	Silicon carbide	[85]
	Sugarcane exocarp, peanut shells and rice husks	Hybrid mineral-hydrothermal fertilizer	* Rice seeds	Macro and micronutrients (carbon; oxygen; potassium; aluminum; magnesium; calcium; sodium; nickel; silicon)	[86]
	Biosolids (urban wastewater treatment, cattle manure coffee grounds)	Biochar	Lettuce (*Lactuca sativa* L.)	N.I.	[82]
	Sunflower seed shells, peanut shells and *Spirulina* algae	Biochar	Lettuce (*Lactuca sativa* L.)	Carbon; nitrogen; hydrogen; oxygen; fixed carbon	[87]
Composting	Olive mill waste	Compost	Lettuce (*Lactuca sativa* L.) and tomato (*Lycopersicon esculentum*)	Total nitrogen; total phosphorus, potassium; total organic carbon	[88]
	Food waste (onion, potato, cabbage) with cattle manure	Compost	* Maize	Organic carbon; available phosphorus and potassium; total nitrogen	[76]
	Fruit and vegetable waste	Compost (leachate part)	Cress (*Lepidium sativum*) and sweet corn (*Zea mays cv. Luscious*)	NH_4; total nitrogen; total inorganic and organic nitrogen; phosphorus; phosphate; sulphate; potassium; calcium; magnesium; sodium; copper; zinc	[89]
	Banana peel (used as the fermentation liquid) and whilst soil and coconut husk (used as the composting medium)	Compost	N.I. (applied in soil to evaluate the nitrogen, phosphorus and potassium concentration)	Nitrogen; phosphorus; potassium	[90]
	Banana fruit waste with cow dung and cow urine	Compost (liquid fertilizer)	Mung bean (*Vigna radiata* L.) seeds	Total nitrogen; potassium, calcium; phosphorus; magnesium; iron; copper; zinc; manganese	[91]
Grinding and Mincing process	Food waste	Liquid fertilizer	Not applied	Total nitrogen; nitrate; total phosphorus; calcium; magnesium; sodium; potassium	[92]
Grinding and mincing process	Food waste	Liquid fertilizer	Lettuce (*Lactuca sativa* L.) and cucumber (*Cucumis sativus* L.)	Total nitrogen; nitrate; total phosphorus; calcium, magnesium; sodium; potassium	[93]
Pyrolysis + composting	Pig manure and rice straw	Biochar (rice straw) and compost (pig manure)	* Watermelon	Organic carbon; nitrogen total; phosphorus available; potassium available	[94]
No treatments for conversion	Food waste	Liquid fertilizer	Chinese cabbage (*Brassica pekinensis*)	N.I.	[95]

* The variety of species was not identified or mentioned in the article.

Despite their comparatively lower economic valuation, agricultural residues constitute a significant and renewable repository of minerals and carbon for soil. Upon reintroduction into the soil, these residues undergo a transformative process, converting into bio-based fertilizers. The judicious and strategic utilization of agricultural residues as biofertilizers has yielded notable improvements in soil particle structure, heightened soil organic content, enhanced activities of specialized microorganisms, diminished water evaporation, and minimized fertilizer loss [3,96,97]. The approach adopted by Kadir et al. [90] used banana peels as biomass to produce BBF using the decomposition method. It contains nitrogen (35.32 mg/L to 78.77 mg/L), phosphorus (195.83 mg/L to 471 mg/L), and potassium (422.3 mg/L to 2046 mg/L), which are suitable for application as soil conditioners [90]. Another study also used banana waste but combined with cow dung and cow urine to prepare a liquid fertilizer and apply it in bean seeds. BBF presented 30.09 C:N ratio which can accelerate decomposition by microbes and prevents low nitrogen loss [91]. Fermented banana waste, when supplemented with soil, can serve as a good source of soil microbes in the production of hormones to stimulate plant growth and it is a rich bioinoculum that enriches the nutrient status of the soil by increasing organic matter and mobilizing Fe in soil [98].

In the same sense of using food waste (onion, potato, cabbage) with cattle manure, Wolka and Melaku [76] observed higher yields from corn crops. The diverse concentrations of food waste led to distinct NPK concentrations resulting from microbial activity and microbial biomass production. This investigation highlights the potential utility of organic food waste derived from composting as an organic fertilizer. Despite the relatively diminished NPK content when juxtaposed with conventional chemical fertilizers, the NPK values derived from this study demonstrate comparability with those of established organic fertilizers [90].

Moreover, olive mill waste can be used in soils that have a low amount of organic matter and that are susceptible to mineralization; in addition, in this case, the compound can be used for amending soil and increasing the lettuce and tomato germination index [88]. The germination and rootlet growth, leaf area, shoot and root biomass of cress and sweet corn increased using a diluted compost leachate [89].

The orange residue used as organic fertilizer had a direct impact on the growth of *durum* wheat, presenting results similar to those obtained with chemical fertilization when the correct dosage of BFF was used [99].

Spent coffee grounds possess the potential for valorization through judicious management and reutilization, yielding valuable products for agricultural applications while concurrently enhancing soil structure and fertility [100]. An experimental investigation involved the assessment of a fertilizer derived from used coffee grounds combined with ash from biomass combustion across distinct plant species. No adverse effects on germination were detected in the tested plants, except for cress [101]. The utilization of an organic fertilizer resulting from the amalgamation of organic and mineral waste is viable, contingent upon meticulous adjustment of the mixture's composition to meet the specific needs of the respective plant. It was observed that a given fertilizer mixture may exert adverse effects on root development in certain plants while concurrently stimulating growth in others [101].

The presence of plant growth-promoting bacteria in fermented banana residues increased the nutrient content and organic content of the soil. Promoting plant growth evidenced by the stimulation of shoot and root growth increased root length (3.6 cm) and wet and dry weight. In addition, there was an increase in the germination percentage and the germination rate of mung bean after the application of biofertilizer diluted 50 times. The fermentation process releases organic molecules like amino acids and carbohydrates from the banana waste, which in turn are converted into hormones, enzymes, and amino acids. Fermented banana residues serve as a source of nutrients and microbes that help plants access nutrients and improve soil health [91].

Sangamithirai et al. [102] compared a mixture of organic matter with chemical fertilizers in potato and sweet corn plants. The findings of this investigation reveal that the compost employed exhibited phosphorus (P) content comparable to that of an inorganic fertilizer. However, it demonstrated lower nitrogen content in comparison to both manure and biofertilizer derived from food waste in the context of tomato processing. In contrast to tomatoes subjected to synthetic fertilization, those cultivated with biofertilizer derived from food waste compost exhibited significantly elevated levels of both total and soluble solids content. Furthermore, BFF from the digestion process helped crop yields and especially the quality of harvested tomato fruit quality [103]. Given the diverse nutrient demands of distinct crops, a meticulous evaluation of the compost's nutrient composition is imperative, facilitating the precise calibration of application rates. Crops encompassing rice, tomato, *Pakchoi*, and common bean manifest tangible advantages upon the application of food waste, leading to enhancements in the physical, chemical, and biological attributes of the soil [104–107].

Recently, it was reported in the literature that AFW fertilizer is effective in growing ornamental plants like *Stachytarpheta jamaicensis* [108]. Siddiqui et al. [109] compared FW-derived organic liquid fertilizer with commercial liquid fertilizer for the hydroponic cultivation of lettuce, cucumbers, and cherry tomatoes. The bio-based fertilizer showed similar concentrations of N and P in the structural parts of lettuce (N 50 to 260 g/kg and P 11 to 88 g/kg) and the structural parts of fruits and plants (from N 1 to P 36 g/kg) of cucumber when compared to the commercial fertilizer. However, for the cherry tomato the commercial fertilizer showed a higher concentration of nitrogen. In addition, the concentrations K, Ca and Mg showed significant differences among the plants, respectively [109]. The effects of organic fertilizer mixed with dry FW powder were evaluated on the growth of *Chinese* cabbage seedlings, which proved to be an excellent fertilizer, [95] and the bio-based fertilizer can be applied to promote the growth of plants in hydroponic systems, such as the lettuce and cucumber crops, because when the BFF was applied for the lettuce hydroponic system and compared with chemical fertilizers, no significative differences were found in number of leaves (25), shoots height (206 mm), plant height (305 mm) and fresh and dried weight (156 g/plant and 30 g/plant). However, for the cucumber crop, the fresh and dried weight were better when applied with chemical fertilizer, thus the number of cucumber fruit per plant (20–22) was similar with both fertilizers [92,93].

Combined bio-based fertilizers from different conversion methods showed good results when the compost was combined with biochar. Using this combination, a reduction in nutrient leaching occurred as well as greater retention of P, K, and ammonium available in the soil, consequently increasing yield in watermelon production. There was a significant positive correlation between watermelon yield and soil nutrients, microbial diversity or microbial evenness in the continuous watermelon monocropping system. The application of biochar with compost significantly increased the hydrolysis activities of β-glucosidase and fluorescein diacetate 1.5 and 1.3 times, respectively. The alkaline phosphatase activity of the soil in chemical fertilizers plus the compost and biochar treatment was more than doubled compared to the chemical fertilizer with the compost. The addition of biochar alone increased the activities of β-glucosidase, protease, and alkaline phosphatase, although the differences were not significant. These results indicate that the addition of biochar can increase the activities of soil enzymes involved in the C, N and P cycles, and the combined addition of compost and biochar has more significant effects compared to chemical fertilizer treatment [94].

Additionally, potassium-enriched banana waste, conjoined with sewage sludge characterized by a substantial phosphorus content, was subjected to biochar production through thermal methodologies, specifically slow pyrolysis and thermal plasma treatment. Both techniques demonstrate efficacy in generating biochar endowed with plant-accessible nutrients. However, a notable concern arises with the presence of arsenic, necessitating its elimination prior to the process due to its prohibitive implications for the use of biochar as a fertilizer for edible plants [110].

Fish meat and fish waste, after composting with an addition of a bulking agent, is a valuable fertilizer material rich in N, P, and Ca [111]. Waste keratin materials, including feathers, after hydrolysis, is a cocktail of amino acids, which digested with sulfuric acid is a source of N and can be given directly to plants as foliar BBFs [112].

Bones can also serve as a valuable and concentrated reservoir of phosphorus [113]. The incorporation of bones as a partial substitute for phosphate rock introduces novel technological challenges, notably an escalated demand for sulfuric acid essential for the solubilization of hydroxyapatite in the wet-process phosphoric acid production. In the case of utilizing bones as a feedstock, a portion of the acids becomes requisite for the solubilization of the organic matrix within the bones. The production of phosphate fertilizers can be realized through the pyrolysis of slaughter waste, involving the participation of other biomass components such as meat residue, wood, and corn [114].

In this regard, Chang and Huang et al. [85] evaluated the use of rice husks, peanut shells and sugarcane in the germination of cabbage seeds and concluded that using a mixture of 6% peanut hull together with silicon carbide, it presented pH to 7.0–7.5 and had a significant effect on cabbage seed germination, significantly improving plant height, leaf number, and the weight of fresh and dry matter. The same organic matter base was also tested, however, in rice seeds. There was an increase in the pH value of the soil as reported in the previous work, as well as an improvement in the botanical aspect (ear with more grains and improved panicle) when compared to the treatment using only water. In addition, the application of BFF significantly improves rice yield, as well as ensuring the robustness of the crop and its resistance to pests and diseases, thus improving the economy [86].

Biochar is mainly used as a soil corrector; Christou et al. [82] evaluated the effects of applying different biochar, from biosolids, cattle manure and coffee grounds. The lettuce crop grown in the soil treated with these BBFs showed a significant increase in the biomass production rate, evident through high average values of fresh and dry weight. However, the BBFs did not impact the photosynthetic pigment content, but reduced the nitrate content in the leaves by around 44%. There was also a reduction in the soluble solids content, but there was an increase in sucrose and fructose present in the lettuce leaves, in addition to the increase in the concentration of total phenolics (451.26 and 414.12 mg GAE/100 g FW). Overall, the results showed that BBF applied as soil amendments can serve to improve the growth and, partially, the nutrition value of lettuce plants [82].

In this sense, biochar from sunflower seed shells, peanut shells and Spirulina algae were tested separately in lettuce. The results showed that when peanut shells were used (pyrolysis at 280 °C) it did not affect germination and exhibited a remarkable growth-promoting effect on the roots and stems of lettuce, as the presence of carbonyl derivatives and aromatics in the water-extractable substances of peanut shell biochar may be linked to the stimulating effects of this extract [87]. In contrast, the water-extractable substances from the biochar of both bio-waste produced at 350 °C inhibited the growth of lettuce, posing a risk of direct application as soil amendment. In this case, aromatics may be responsible for growth inhibition in the water-extractable substances of the biochar from the sunflower seed shells, while the organic nitrogen compounds would enhance the inhibitory effect in the water-extractable substances of the biochar of the Spirulina algae [87].

Sánchez et al. [115] reported the higher concentration of potassium oxide and other nutrient components (nitrogen and phosphorus pentoxide) in sunflower residue biochar compared with grape residues biochar. Similar results are also found by Ain Shafiq [116], where the nutrient contents (Na, K, Mg) in *Parthenium hysterophorus* biochar were found for rice-wheat cultivation. In this way, the biochar produced from *Flourensia oolepis* also had a great potential in improving the germination and growth bioassays of lettuce plant. The biochar promoted the growth of roots and shoots up to 225% and inhibited the of germination when a high level of dose (7.5% w/v)) was applied in this crop [117].

Compared with other biochar produced from rice straw and cow manure, biochar from sunflower straw was demonstrated to have a smaller proportion of the most detrimental ions of both sodium and bicarbonate in the soil, showing that sunflower straw might be a highly potential amendment of saline soils [118].

The use of BFFs is a very promising alternative, as it is an effective strategy for managing compostable waste.

4. Biostimulants: General Aspects

Biostimulants before being used in sustainable agriculture practices and integrated cropping systems were used for organic production, but due to their benefits this has been changed [119]. Biostimulants, although not classified as nutrients, ref. [120], do not serve as complete substitutes for inorganic fertilizers across all situations. Nevertheless, their application in modest quantities can effectively mitigate the requirement for mineral nutrient supplementation, alleviate nutrient deficiencies, ameliorate abiotic stress conditions, promote plant growth and development, stress resistance, alleviate nutrient deficiencies, improve some physiological functions, and increase the plant and vegetable or fruit quality. All these advantages from biostimulants are in accordance with the circular economy and with the mitigation of the reduction in greenhouse gases [121] (Figure 1).

Biostimulants are extracts derived from organic raw materials containing bioactive compounds such as humic substances, amino acids, chitin, chitosan, vitamins, poly and oligosaccharides, phytohormones proteins, phenolic compounds, amino acids, phenols, humic and fulvic acid, salicylic acid, protein hydrolases and mineral elements, which can stimulate beneficial effects in crops and improve some physiological functions [121–123].

Modernized agricultural practices focus on sustainable environmental systems with the main challenges being improving the quality of crops and resistance to stress using the smallest number of inputs, to be in accordance with environmental sustainability [8,122]. For this reason, developing biostimulants from by-products paves the path to waste recycling and reduction, generating benefits for growers, the food industry, registration and distribution companies, as well as consumers [124]. Plant biostimulants (PBs) may have different biological functions, due to the different matrices used and the procedure used to obtain them. Therefore, converting AFW into biostimulants contributes to the concept of a circular economy. Instead of treating waste as a problem, it is transformed into a valuable resource for agriculture, closing the nutrient loop and reducing the environmental impact associated with waste disposal.

Influence on Crop Productivity with the Use of Biostimulants from Agri-Food Waste

BFs can improve plant growth through increasing chlorophyll synthesis, which occurs due to an increase in mineral status, synthesis and accumulation of antioxidant metabolites [119]. It was reported by Rehim et al. that vegetables developed greater tolerance against biotic and abiotic stresses, in addition to improving crop quality, after the use of BFs, consequently reducing the use of chemical fertilizers [125]. Table 4 shows the main residues used in the production of biostimulants, their application, as well as the main groups that act as biostimulants on crops and the main responses generated by crops after application.

Table 4. Agri-food waste used for the extraction of plant growth biostimulators and plant responses in different crops.

Agri-Food Waste	Application Crop	Group	Application Method	Plant Response	Ref.
Vegetal and seaweed (commercial biostimulants)	Lettuce (*Lactuca sativa* L.)	Protein hydrolysates	Hydroponic	Increased yield of leafy vegetables and improved physiology and biochemical composition.	[126]
Seaweeds	Soybean (*Glycine max* (L.) Merrill.)	Phytohormones (auxins, cytokinins) Amino acids, vitamin B1, B2, C and E. Minerals (N, P, K, Mg, Fe, Mn, B, Zn, and Cu)	Foliar	Alteration of the nutraceutical and antioxidative potential and improved the growth and yield	[127]

Table 4. *Cont.*

Agri-Food Waste	Application Crop	Group	Application Method	Plant Response	Ref.
Ten biostimulants from different biological sources (alfalfa and seaweeds)	Strawberry (*Fragaria × ananassa Duch.*) cv. Elsant	Humic acids, alfalfa hydrolysate, macro seaweed extract and microalga hydrolysate, amino acids alone or in combination with zinc, B-group vitamins, chitosan, and a commercial product containing silicon (10 different biostimulants)	Foliar	Greater pulp consistency, yield and improved fruit quality	[128]
Vegetal based	Radish (*Raphanus sativus* L.)	Vitamin B12, and CoQ10	Soil	Increased root and shoot biomass	[125]
Rape seed, apple seeds, and rice husks	Kiwi fruit (*Actinidia deliciosa*, c.v Hayward and Green Light)	Auxins, cytokinins, gibberellins, amino acids, protein, and minerals.	Foliar	Increased the fruit weight Increase of the vitamin C content in the fruits	[129]
Mycorrhizal Fungi, Tea Wastes, and Algal Biomass	Corn (*Zea mays* L.)	Polyphenols acids, protein, nutrients, carbohydrates, amino acids and organic carbon	Soil	Improved soil microbial activity; increased resistance to saline environments; highly efficient in improving soil mean weight diameter; increased soil-organic carbon, microbiota and increased grain productivity.	[130]
Plants	Corn (*Zea mays* L.)	Nitrogen, protein hydrolysate, amino acids (alanine, arginine, aspartic acid, cysteine, glutamic acid, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tryptophan, tyrosine and valine) and soluble peptides	Stem was immersed for few minutes into the biostimulant solution	Increase the shoot length, total biomass, root and nitrogen content.	[131]
Red grape, blueberry fruits and hawthorn leaves	Corn (*Zea mays* L.)	Indoleacetic acid and isopentenyladenosine auxin and gibberellin Nitrogen	Soil	Increased protein and fructose content in the roots; Increased protein and glucose in leaves; increased the maize plant dry weight was found in both roots and leaves; the treatments with the extracts in separated or together increased the phenolic acids in the plants (p-coumaric, gallic acids, vanillic, caffeic).	[132]

Table 4. *Cont.*

Agri-Food Waste	Application Crop	Group	Application Method	Plant Response	Ref.
Legumes	Tomato (*Solanum lycopersicum* L.)	Protein hydrolysate	Foliar	Improvement in yield (fruit weight); foliar nutrition (K and Mg); Greater assimilation of CO_2; increase in antioxidant activity; total soluble solids and increase in lycopene and ascorbic acid.	[133]
Seaweed	Grapes (*Vitis vinifera* L.) cv. 'Perlette)	Amino acids	Foliar	Higher leaf size, chlorophyll content, berry setting, number of bunches per cane, rachis length, berry weight, berry size, soluble solid concentrations, total sugars and reducing sugars with reduced berry drop and ascorbic acid.	[134]
Fennel processing residues, lemon processing residues and brewer's spent grain	Tomato (*Solanum lycopersicum* L.)	Organic acids; sugars and flavonoids; organic acids (citric, gallic, malic, fumaric and tartaric acids) and their conjugates (lactates); free amino acids (proline, glutamine and asparagine).	Irrigation (soil)	Increased the shoot growth and dry matter; increased fresh fruit yield; increased the vitamin C concentration on the fruit.	[135]
Vine-shoot wastes	Lettuce (*Lactuca sativa* L.)	Phenolic compounds (phenolic acids, stilbenes, flavanols, (+)-catechin and (−)-epicatechin pyrogallol and hydroxybenzoic acids (ellagic and gallic)).	N.I.	The tested extracts did not affect the germination of lettuce seeds, but the extracts stimulated root elongation.	[115]
Spelt (*Triticum dicoccum* L.) husks	Maize (*Zea mays* L.)	Polyphenol (*p*-hydroxybenzoic, syringic acids, ferulic, *p*-coumaric, and caffeic).	Soil	Recovery of shoot growth to control levels and reduction in stress-induced proline accumulation; mitigating salt and oxidative stress.	[136]
Sorghum leaves	Maize (*Zea mays* L.)	Phenolic compounds	Foliar	Improved germination and plant growth and when the extract was applied (0.75 mL/L) in the tenuous absence of water increased stem diameter as well as leaf area.	[137]

Table 4. *Cont.*

Agri-Food Waste	Application Crop	Group	Application Method	Plant Response	Ref.
Giant Reed	Tomato (*Solanum lycopersicum* L. cv. MT), watercress (*Lepidium sativum* L.) and chicory seeds (*Cichorium intybus* L.)	Humic-like lignins	Seeds hydration	Positively seed development by either directly acting as gibberellin (GA) molecules or by positively perturbing GA-related hormonal balances and, thus, influencing GA-mediated physiological mechanisms.	[138]
Vegetal	Tomato (*Solanum lycopersicum* L.), basil (*Ocimum basilicum* L.), and Chrysanthemum (*Chrysanthemum indicum* L.)	Auxin	Stem was immersed into the biostimulant solution	Enhances Adventitious Rooting	[123]

N.I. = no information found in the articles.

In their study, Donno et al. [129] analyzed the influence of a hydrolyzed extract obtained from residues of apple seeds, rapeseed, and rice husks on growth parameters, antioxidant capacity, and ascorbic acid levels in kiwi fruit. The extract elicited an increase in fruit weight ranging between 5% and 6%, attributable to its noteworthy concentration of auxins, cytokinins, and gibberellins, primarily sourced from apple seeds. The application of the product significantly influenced the antioxidant activity of fruits from both cultivars, particularly evident in *cv*. Hayward, while *cv*. Green Light fruits exhibited slightly elevated values compared to the control. Moreover, the treatment markedly enhanced the ascorbic acid (AA) content in both cultivars across all locations investigated. In cv. Hayward, the median AA content of fruits increased from 32 to 41.73 mg/100 g_{ffw} in Piedmont and from 38.10 to 45.52 mg/100 g_{ffw} in Latium. For cv. Green Light, the AA content of fruits increased from 45.05 to 51.22 mg/100 g_{ffw}. This stimulatory effect can be attributed to the high amino acid, protein, and mineral content present in rapeseed and rice husks.

Crops treated with phytohormones and amino acids showed significant effects on their productivity [130,139]. For example, using apple seed extract, rapeseed extract, and rice husk waste as biomass to obtain PB, and then applied to the crops, increased the ascorbic acid in kiwi; this vitamin is essential for maintaining human heath [129]. During the cultivation of corn, peas and tomatoes, both in the laboratory and in a greenhouse, vegetable protein hydrolate was applied, which induced rooting due to the presence of auxin, resulting in an increase in dry mass and root area. In addition, the extract also positively affected shoot length, total biomass, and nitrogen content. These facts were related with the high number of proteins, amino acids and other compounds present in the extract such as alanine, arginine, aspartic acid, cysteine, glutamic acid, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tryptophan, tyrosine and valine, which exerted a phytohormones-like activity. Furthermore, the biosynthesis of hydrolytic enzymes was stimulated because of the gibberellins present in the extracts and this helps the seedling's development [131].

Biostimulators can contribute to increasing crop quality, in addition to improving the mechanical resistance of vegetables and fruits, such as firmness. This was reported by Soppelsa et al. [128]; in this work different biostimulants were used for strawberry crop, but the biostimulants that showed a significant effect for increasing yield, pulp firmness, increasing nutritional value and fruit quality were alfalfa protein hydrolysate, seaweed extracts, chitosan and amino acids and B-group vitamins. The treatment with alfalfa protein hydrolysate improved the accumulation of biomass in the roots, the leaf area and the chlorophyll concentration. Similar results were found in other studies reported in the literature; due to the stimulation of the activities of ATP *sulfurylase* and *O-acetyl serine sulfhydrylase,* there was an increase in chlorophyll and protein in the corn crop, in addition to the increase in protein content, which probably occurred due to the increase in nitrogen absorption and protein hydrolysate being used as biostimulator for the tomato cultivation and complementing high crop productivity with optimal fruit quality, respectively [132,133]. The increase in pulp firmness is correlated with chitosan, thus increasing the shelf-life of the fruits. It was observed after treatment using amino acids and vitamins that there were changes in the ripening stage of strawberries as well as an increase in the sugar content. This was also found by Khan et al. [134] in grapefruits, but by using a mix of amino acids and seaweed (*Ascophylum nodosum*) extract. The final coloration and the phenolic concentration in strawberry fruit at harvest was increased after applied alfalfa protein hydrolysate and seaweed extracts on the fruit [122,128].

Moreover, there is an increase in the biomass of the aerial part and roots of the radish after the application of PBs [125]. In addition to using AFW biomass to obtain PBs, it was found that the use of seaweed extract as a foliar biostimulant influenced the growth of soybean crops, as this extract contained plant growth regulators [127].

AFW from lemon, fennel, and brewer's spent grain were combined to create a biostimulants extract. Chehade and collaborators [135] evaluated the effect of this biostimulants extract on the conditions of cultivation and physiological maturity and the quality effect of tomatoes; the authors observed that in BFs extract, there was bioactive compounds, sugar, organic acids, amino acids (principally asparagine, glutamine and proline), and phenols [135], and in another crop (maize), the use of BFs improved leaf and root [139].

Vegetal biomass, characterized by a notable abundance of phenolic compounds, has been posited as a viable resource to produce biostimulants. Thus, viticulture is an attractive agricultural sector that produces over 60 thousand tons of grapes annually; this AFW can cause environmental problems if disposed of incorrectly, even in landfills [140].

The valorization of this agrifood waste or bio-waste is a significant opportunity and a strategic avenue for the creation of materials applicable in agriculture. Such residues, owing to their typically high content of phenolic compounds, can be utilized to produce plant biostimulants [141]. In lettuce, some were observed, in terms of radicle extension when applied to wine-shoot aqueous extracts; in this extract, different phenolic compounds, such as flavanols, stilbenes, (+)-catechin and (−)-epicatechin pyrogallol and hydroxybenzoic acids (ellagic and gallic) were found [115].

Within this framework, Ertani et al. [132] conducted a study examining the impact of red grape skin, hawthorn leaf, and blueberry fruit residues on maize crop. The observed favorable results on agronomic and metabolic ways, accompanied by high levels of protein, chlorophylls, and nitrogen, were attributed to the plant growth-promoting substances and diverse phenolic compounds present in the extracts. Notably, these extracts enhanced phenylpropanoid metabolism and stimulated phenylalanine ammonia-lyase activity, leading to the retention of specific phenolics compounds in the leaves.

The impacts of extract contain soluble and insoluble phenolic fractions were investigated, derived from spelt husks on enhancing maize resilience to saline stress [136]. The insoluble phenolic fraction exhibited notable efficacy in facilitating the recovery of maize subjected to salt stress, thereby promoting plant growth, pigment content, and antioxidant defenses. Moreover, maize plants treated with the insoluble phenolic fraction displayed reductions in hydrogen peroxide, malondialdehyde, glutathione, and proline content. In contrast, non-biostimulated and salt-stressed maize samples exhibited an accumulation of hydrogen peroxide and malondialdehyde. The observed positive effects of the biostimulants were attributed to the abundance and diversity of phenols (p-hydroxybenzoic, syringic acids, ferulic, *p*-coumaric, and caffeic) present in the spelt husks extract. This study underscores the potential valorization of certain raw materials through the development of effective biostimulants capable of enhancing plant performance and resistance to various prevailing stresses in cultivation systems [136]. Another factor that can alter plant development is water stress. However, when the phenolic extracts obtained from sorghum leaves were applied to the maize crop to improve agronomic characteristics in conditions of water deprivation, this extract stimulated the growth of shoots and roots and increased the plant's ability to assimilate CO_2 and some nutrients [137]. The effects concurrently elevated photosynthetic activity and mitigated the oxidative stress induced by water scarceness [137].

Another biostimulant found in the literature is the humic-like lignin derived from Giant Reed, which underwent multiple bioassays to assess the potential hormone-mimetic activity, specifically regarding auxin- and gibberellin-like effects. Water-soluble lignins were administered to tomato seeds, which contained the auxin marker (β-glucuronidase), facilitating the visualization of auxin responses in the roots. The water-soluble lignins demonstrated the capacity to either directly emulate gibberellic acid (GA) in plant and seed development or positively influence GA-related hormonal balances, thereby impacting GA-mediated physiological mechanisms. These findings imply that humic-like residual lignins obtained from energy crops hold promise for application in intensified sustainable agriculture, functioning as seed germination enhancers and biostimulants for plant growth [138].

"Seaweed extracts" are another recognized plant biostimulant. Owing to its difficult biochemical composition encompassing minerals, antioxidants, polysaccharides, hormones, vitamins, pigments, fats, oils, and acids, deciphering its mechanism proves highly challenging. However, when the hydrolysis is applied, it can produce hydrolysates and these are known as signaling compounds (free amino acids and small peptides); it can have a beneficial effect on plants, as they can improve the use of nutrients in their metabolic cycle, in addition to promoting resistance to oxidative stress [142–144].

The implementation of a sustainable agricultural management system is imperative to counter adverse climatic conditions. Plant growth stimulators play a constructive role in modern agriculture. They can increase crop yields, promote plant growth and development, manage biotic and abiotic stress, mitigate the translocation of heavy metals and contribute to the reduction in greenhouse gas emissions. Biostimulants (Section 3), which are characterized by a variety of nutrients, cannot serve as a direct substitute for fertilizers. Nevertheless, they have the potential to improve soil quality and increase plant productivity, especially under stressful conditions. Therefore, an optimal application method is contingent upon the specific plant species under consideration and the desired outcomes. Discerning the appropriate timing and dosage is pivotal for maximizing the impact on plants while mitigating the risk of product wastage, thereby averting an escalation in treatment costs [8].

5. Conclusions

Nowadays, research strives to align with UN Sustainable Development Goals, emphasizing methodologies promoting sustainability and technological innovation in food production. This review highlights the feasibility of converting agri-food waste into value-added products like biocides, biostimulants, and bio-based fertilizers for reuse in agriculture. These products integrate into the food production chain, aligning with circular economy principles.

The effective use of various agricultural waste as biocides (Section 2) against plant pathogens, insects, and weeds has been highlighted. In addition, residual biomasses serve as substrates for the cultivation of biocontrol microorganisms, offering an economical and eco-friendly support to agriculture against biological threats. However, most antimicrobial studies focus on human bacteria, with limited research on plant pathogenic bacteria. Specific compounds causing antimicrobial, insecticidal, or herbicidal activity are rarely investigated, and biological mechanisms lack coverage in many articles. The primary limitation in extensively employing AFW and its extracts as biocides lies in the lack of in-field investigation, as the literature reports plenty of in vitro studies, but only a few studies have been conducted in the field.

Despite these challenges, the utilization of residues offers advantages such as higher plant productivity, improved stress resistance and better soil quality. Bio-based fertilizers (Section 4) have the potential to reduce dependence on chemical substances and thus mitigate environmental problems. Biostimulants derived from residual biomass have a positive effect on plant biomass production and CO_2 sequestration, thus contributing to modern agriculture. Although biostimulants (Section 3) are not a complete substitute for fertilizers, they can improve soil quality and plant productivity, even if there is still a research gap in terms of greenhouse gas emissions. Despite all the advantages of biofertilizers and biostimulants, some limitations need to be understood and solutions need to be developed, as they present as limitations to the challenge of developing standardized processes, being free from contamination (pesticides and heavy metals), and a lack of necessary nutrient balance when compared to chemical fertilizers. Furthermore, there are no regulatory standards for its processing and sale, among others. The creation and operation of facilities for converting agri-food waste into biofertilizers may require significant investments in infrastructure, technology and expertise.

The potential replacement of current agricultural products with value-added commodities from agri-food waste holds promise. Nonetheless, addressing the challenge of establishing quality standards for these products is a task that must be tackled soon.

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Abbreviations

AA	Ascorbic Acid
AD	Anaerobic Digestion
AFW	Agri-Food Waste
BBFs	Bio-Based Fertilizers
CFU	Colony Forming Units
Ch	Chitosan
FW	Food Waste
GA	Gibberellic Acid
GGH	Greenhouse Gas Emissions
Htyr	Hydroxytyrosol
LNP	Lignin Nanoparticles
OMWW	Olive Mill Wastewater
PBs	Plant Biostimulants
PLA	Polylactic Acid
PVA	Polyvinyl Alcohol
SDG	Sustainable Development Goal
UAE	Ultrasound-Assisted Extraction
UNEP	United Nations Environment Programme

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