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Review article

Pretreatment and composting technology of agricultural organic waste for sustainable agricultural development

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ABSTRACT

With the continuous development of agriculture, Agricultural organic waste (AOW) has become the most abundant renewable energy on earth, and it is a hot spot of research in recent years to realize the recycling of AOW to achieve sustainable development of agricultural production. However, lignocellulose, which is difficult to degrade in AOW, greenhouse gas emissions, and pile pathogenic fungi and insect eggs are the biggest obstacles to its return to land use. In response to the above problems researchers promote organic waste recycling by pretreating AOW, controlling composting conditions and adding other substances to achieve green return of AOW to the field and promote the development of agricultural production. This review summarizes the ways of organic waste treatment, factors affecting composting and problems in composting by researchers in recent years, with a view to providing research ideas for future related studies.

1. Introduction

The growth of the global population and the improvement in living conditions have led to an increasing demand for food production, putting enormous pressure on agricultural production [1,2]. The negative impact of increasing food production is the use of large amounts of chemical pesticides/fertilizers and the production of agricultural waste, which not only causes pollution and damage to the environment but also poses a potential health hazard to people [3]. According to statistics, 140 billion tons of lignocellulose-related organic agricultural waste are generated each year globally [4]. As a reusable resource, improper disposal of large amounts of agricultural by-products not only causes waste of resources, but also pollutes surface water and groundwater, as well as generates large amounts of greenhouse gases, causing air pollution [5], etc. Therefore, how to correctly and safely disposing AOW is a global challenge [6].

AOW consists mainly composed of lignocellulose - the most abundant organic matter on earth [7]. If it is reasonably treated and returned to the field, it can not only realize the reasonable treatment of AOW, but also reduce the use of chemical pesticides and fertilizers. Composting is one of the most effective methods to promote the recycling of organic waste [8], improve soil fertility and promote crop growth [9]. Composting agricultural waste not only reduces agriculture's dependence on chemical fertilizers but also reduces environmental pollution [10]. Composting AOW back to the field is the use of complementary mechanisms of hydrolytic enzymes secreted among microorganisms, especially those that degrade lignocellulose, to degrade AOW into a nutrient substrate that

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can be absorbed and used by crops [11]. In AOW, through aerobic composting, complex organic compounds will be transformed into small soluble molecules [12,13]. After composting, maturation can eliminate toxic substances, disease-causing microorganisms, and insect eggs [14]. Compost products are rich in C, N, P, K, and other adequate nutrients to meet the needs of crop nutrients [15], so the products of composting can be used as a substrate for plant growth or as a soil conditioner.

AOW recycling is a cycle between vegetation and soil and a material cycle between above and below ground [16]. Microorganisms are essential drivers of this cycle, which can accelerate the degradation process of organic waste, promote the humification of compost, facilitate compost maturation, shorten the composting cycle [17,18], etc. However, this cycle suffers from difficulties in lignocellulose degradation, greenhouse gas emissions and poor quality of compost products [19]. In response to these problems, a lot of research has been done in recent years to promote the recycling of AOW, mainly by controlling the conditions of AOW before and during treatment or by adding additives. Although the treatment conditions of AOW have been mentioned in many reviews, they are only some reviews, perhaps imperfect reviews, of organic waste pretreatment [20,21]. Therefore, this paper not only reviews the pretreatment methods of AOW, but also the factors affecting composting, the problems in composting and the effects of compost products on plant growth, and proposes the idea of "taking from the land and using it for the land" to truly achieve sustainable agricultural production.

2. Lignocellulose

Generally speaking, lignocellulose (Fig. 1 [22]) is mainly composed of cellulose of (38–50%), hemicellulose (15–25%), and lignin (15–25%) [23]. Cellulose molecules are regularly arranged and tightly packed and are the main structure of plant cell walls; hemicellulose is usually a polysaccharide composed of monosaccharides such as pentoses and hexoses; lignin is an aromatic polymer composed of oxygenated phenylpropanoids and their derivatives. These components are intertwined and connected by hydrogen and covalent bonds, forming a complex and dense natural network structure [24].

2.1. Cellulose

Cellulose, as a complex carbohydrate, is the major component of lignocellulose [25], and the major and minor features may vary from species to species, but the overall directions. Cellulose is a linear chain composed of β-1,4 glucose, and the polysaccharide structure of cellulose is composed of a large number of backbone parts linked by hydrogen bonds to form crystalline regions [26]. Its dense network and resistance to chemical and biological hydrolysis lead to physical, enzymatic reactions only from the surface of cellulose, which limits the rate of biodegradation to a large extent [27].

The cellulose molecules are regularly arranged to form the crystalline area of cellulose, and the hydroxyl groups of its glucose molecules combine with hydrogen ions inside and outside the molecule to make the crystalline structure of cellulose stronger, making it difficult for the relevant hydrolytic enzymes and water to invade its interior [28]. Studies have shown that when the area of lignocellulose reaches the nanometer level, the accessible location of degradation enzymes increases dramatically (Fig. 2 [29]), enabling cellulose to be degraded quickly [30]. The related hydrolases that hydrolyze cellulose to monosaccharides are derived from the glycosyl hydrolase family [31].

2.2. Hemicellulose and lignin

The presence of hemicellulose and lignin in agricultural waste essentially hinders the accessibility of cellulose to hydrolytic enzymes and is one of the main reasons why lignocellulose is difficult to degrade [32]. Hemicellulose is the second most abundant polysaccharide after cellulose, a branched heterogeneous polymer formed by 1,4 xylopyranosyl groups linked by β-1,4-glycosidic bonds [33]. Usually, the hemicellulose constituent structural unit consists of a pentose group, hexose group, and acetyl group intermingled with cellulose [34]. When cellulose undergoes hydrolysis, hemicellulose is also hydrolyzed. Unlike cellulose, hemicellulose is non-crystalline and has shorter and highly branched chains, bridging lignin and cellulose [35].

Lignin is a heterogeneous three-dimensional reticulated phenolic non-crystalline polymer tightly bound to hemicellulose (Fig. 3 [36]). It consists of combined oxidative combinations of basal cinnamyl alcohols, coniferyl alcohols, and mustard alcohols [37]. The diversity of these monoalcohols and the randomness of the linkages make the lignin structure more complex and heterogeneous, making it more challenging to utilize lignocellulose [38,39]. Lignin-carbohydrates act as a protective substance that encases cellulose

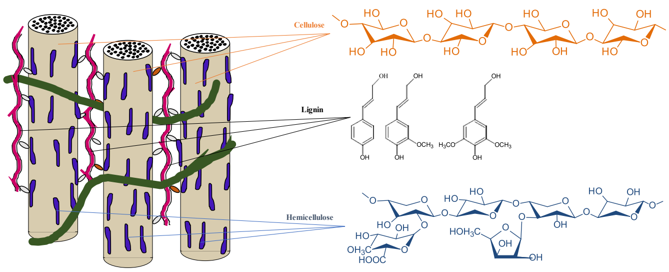

Fig. 1. Schematic diagram of lignocellulose structure.

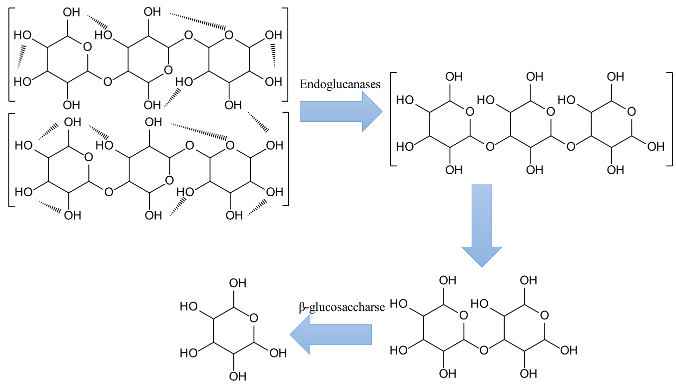

Fig. 2. Cellulose degradation mechanism.

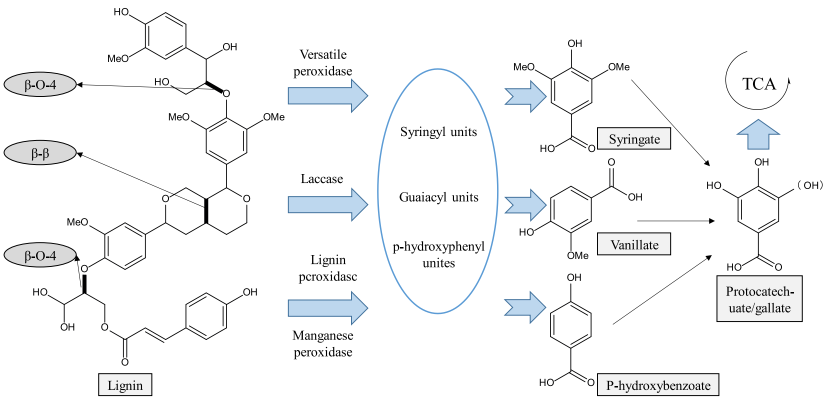

Fig. 3. Mechanism of lignin degradation.

in the plant cell wall and can prevent microbial degradation of lignocellulose [40]. If hemicellulose and lignin are removed, the lignocellulosic pore size can be increased, and the hydrolytic enzymes can be brought into contact with them to perform hydrolysis [41]. Studies have shown that microorganisms degrade lignin by first hydrolyzing the aryl glycerol-β-aryl ether bond, followed by the biphenyl bond, which are essential targets for microbial hydrolase degradation [42].

3. Pretreatment of lignocellulose

The components in lignocellulose form a lignocellulosic matrix through covalent or non-covalent bonds, which gives it a strong natural resistance to hydrolysis by hydrolytic enzymes [43]. This disobedience needs to be overcome by some pretreatment to promote the hydrolysis of lignocellulose [44]. The primary purpose of pretreatment is to promote lignin hydrolysis, disrupt cellulose crystal structure, increase its surface area, and improve hydrolysis efficiency [45].

Pretreatments for lignocellulose include physical, chemical, physicochemical and biological, and combined pretreatments [43]. Combining these pretreatments individually or in some combination can increase the lignocellulosic porosity [26]. Converting it from

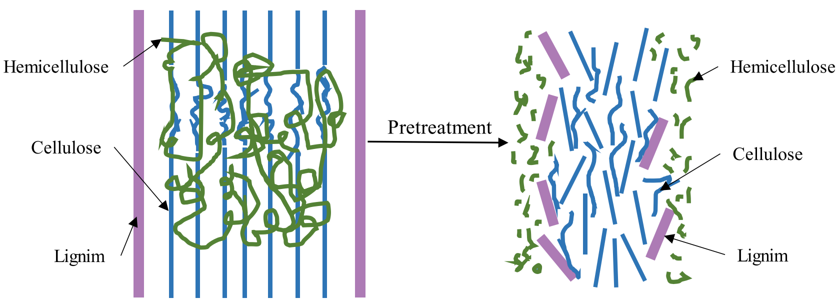

Fig. 4. Effect of pretreatment on the structure of lignocellulose.

Table 1
Partial treatment methods of AOW and their effects.

	Pre-processing	Processing method	Role	Quote
Physical pretreatment	Mechanical crushing	AOW mechanical shredding.	Reducing particle size, loosening material structure, increasing specific surface area and enzyme accessibility.	[46,48]
	Microwave processing	Microwave irradiation heats the material.	The material is uniformly heated, resulting in a loose lignocellulosic structure.	[52]
	Hydrothermal pretreatment	The material is heated for a certain time at 120–180 °C.	Run water molecules through lignocellulose to promote its hydrolysis.	[131,132]
Chemical pretreatment	Alkali pretreatment	105 °C + 2% NaOH	Removal of lignin and hemicellulose and increase of porosity of lignocellulose.	[57]
	Acid pretreatment	0–2% dilute acid treatment	Removal of hemicellulose and lignin	[59,60]
	Organic solvent pretreatment	Washing of materials with organic solvents	Removal of hemicellulose and lignin	[64,65]
	Ionic liquid pretreatment	Salt solution ionic liquid treatment materials	Removal of lignin and reduction of cellulose crystallinity.	[69,133]
	Oxidation pretreatment	Hydrogen peroxide or peroxyacetic acid treated materials	The lignin content of the material was reduced, but the effect on hemicellulose was minimal.	[134,135]
Biological pretreatment	Microbial Bacteria	Compound microorganisms inoculated in AOW composting	The main driver of composting AOW for green, safe and effective treatment.	[89,136,137]
	Insect composting pretreatment	Inoculation of compost before or after high temperature with scavenging insects	Promotion of AOW degradation and decomposition through insect life activities.	[98,99,138]
Combined pretreatment	Steam Blasting	Instantaneous release of pressure under high temperature and pressure saturated steam	Lignocellulose structure rearrangement, lignin and hemicellulose removal, short treatment time and high energy efficiency.	[109]
	Ammonia fiber expansion	Sudden release of pressure under liquid ammonia + low pressure and high temperature to burst the raw material.	Destruction of cellulose crystal structure, degradation of some lignin and hemicellulose, reagents can be recycled, disadvantage: higher cost.	[114]
	Wet oxidation method	120 °C + water and oxygen	Promotes hemicellulose solubilization and increases enzyme accessibility to cellulose.	[118]
	Mechanical + biological treatment	AOW mechanical shredding + microbial composting treatment	Increase the accessibility of hydrolytic enzymes to AOW and promote degradation.	[127]
	Chemical + biological treatment	Acid, alkali and oxidation pretreatment materials + microbial composting	Reduces lignocellulose recalcitrance and promotes degradation of AOW.	[130]
etc.				

its natural form to a more readily hydrolyzed format by hydrolytic enzymes promotes hydrolysis of the substrate (Fig. 4 [24]). And because the various pretreatment treatment methods are different, the resulting characteristics are different, and in practice the appropriate choice is made according to the actual situation and economic losses (Table 1).

The ideal lignocellulosic pretreatment should have the following effectiveness: (1) improve the formation of sugars or the ability to form sugars after enzymatic digestion [21]; (2) avoid carbohydrate loss; (3) prevent the production of inhibitory substances to subsequent hydrolysis and fermentation processes; (4) being cost-effective; (5) being environmentally friendly; (6) being simple to operate and having fewer processes, etc.

3.1. Physical pretreatment

Physical pretreatment reduces cellulose's crystallinity to different degrees by destroying the structure of lignocellulose [46]. The essence is to increase the specific area of the substrate by physical means to increase the contact area between the hydrolytic enzymes and it and improve the degradation efficiency [41]. Many studies have also proved that the surface area, particle size, and porosity of lignocellulose are the key factors affecting the enzymatic degradation of lignocellulose [26,47]. It has the advantages of a simple operation method, is friendly to the environment, and has little loss of carbohydrates [46], but the high power and consumption of this treatment lead to increased production costs.

3.1.1. 3.1.1 Mechanical crushing

Crushing lignocellulose into 0.2–2 mm pieces by mechanical pulverization reduces lignocellulose's degree of polymerization and crystallinity. Wang et al. increased glucose and xylose yield from 25 g/L and 19 g/L to 45 g/L and 40 g/L after mechanical pulverization of corn stover [48].

And Ji et al. found that glucose yield increased from 35.29 to 81.71% when organic waste was crushed to the cellular scale [46]. Therefore, it can be found that the conversion rate of organic waste is proportional to its particle size, but the energy consumed is also proportional to the particle size of lignocellulose, and it is obviously inappropriate to pursue a smaller size with a larger energy consumption. Although mechanical treatment does not produce inhibitory substances, its treatment is predicated on significant energy consumption - the main factor limiting its application in the industry - it is nonetheless a necessary step prior to the treatment of AOW [49].

3.1.2. Microwave processing

Through high-frequency electrons, the polar molecules in lignocellulose vibrate, converting the field energy of microwaves into heat energy. The internal structure of lignocellulose is changed through a series of physicochemical reactions such as heating and expansion. Overcoming the problems of low treatment efficiency and uneven heating in other pretreatment methods [50], so in some studies, microwave pretreatment is usually combined with different pretreatment methods [51]. Chen et al. promoted the removal of lignin and xylan by microwave pretreatment, resulting in a 2-5-fold increase in cellulose removal [52]. Microwave pretreatment has many advantages, such as green, energy efficient use, and low energy requirement, but the most significant disadvantage remains the high cost. For example, the price of a microwave reactor is 1 t/d/$700,000 [53].

3.2. Chemical pretreatment

Chemical pretreatment refers to treating lignocellulose with chemical reagents such as acid, alkali, hydrogen peroxide, etc. It mainly causes hemicellulose and lignin to be dissolved and destroyed in the treatment process, thus promoting the degradation of cellulose, but due to the involvement of chemical reagents, it is easy to lead to environmental pollution and other problems [54].

3.2.1. Alkali pretreatment

Alkali solutions such as sodium hydroxide, sodium carbonate, and calcium hydroxide break the glycosidic bonds of lignocellulose by esterification reactions, resulting in structural changes [55]. The alkali pretreatment can remove lignin and hemicellulose from lignocellulose, increase the porosity of lignocellulose, and promote its hydrolysis [56]. Haque et al. found that a 2% sodium hydroxide solution at 105 °C resulted in 84.8% and 79.5% removal of lignin and hemicellulose [57]. In addition to taking the lignin and hemicellulose away and exposing more cellulose to the enzyme solution, the alkali pretreatment broke the intermolecular hydrogen bonds within the cellulose molecules, resulting in a significant decrease in cellulose crystallinity [58]. Although alkali pretreatment can enhance the enzymatic performance of lignocellulose, there are some problems in practical applications, such as the need to neutralize residual solutions, generation of inhibitory substances, and secondary contamination.

3.2.2. Acid pretreatment

Acid pretreatment is more effective than alkali pretreatment, which can well remove hemicellulose from lignocellulose, destroy the crystalline region of cellulose, and improve the accessibility of hydrolytic enzymes to cellulose [43]. For example, Bukhari et al. achieved 59.5% and 13.3% removal of hemicellulose and lignin after pretreatment of sugarcane bagasse with dilute sulfuric acid [59]. The acid-base pretreatment method is not only able to reduced the crystallinity of lignocellulose, but also increased the yield of sugars [45]. Robak et al. pretreated rye straw using dilute acids at concentrations of 0.5%–2.0% to achieve 69% cellulose saccharification [60]. The disadvantages are that it does not remove lignin and it also produces inhibitory substances such as formic acid and acetic acid [21], and the acid solution tends to cause corrosion of equipment and requires a large amount of alkali to neutralize the treated material [61], which tends to cause chemical contamination and increase the cost of treatment [62].

3.2.3. Organic solvent pretreatment

The organic solvents are mainly methanol, ethanol, formic acid, acetic acid, peracetic acid, and propanol. The organic solvents enable effective lignin removal and better enzymatic accessibility of lignocellulose. It has the characteristics of improving cellulose hydrolysis rate, green and safe, and solvent can be reused [63]. Choi et al. pretreated with 50% ethanol at 160 °C and 1% sulfuric acid for 10 min, Hemicellulose and lignin were separated into hydrolysates to give 80.2% glucose [64]. Karnaouri et al. used isobutanol as an organic solvent for efficient delignification and fractionation of beech wood. The results showed that the removal of hemicellulose and lignin could reach 43.3% and 97.6% [65]. Organic solvents have high penetration efficiency, which can swell and reduce the crystallinity of cellulose and promote the conversion efficiency of lignocellulose, but organic solvents still have the disadvantages of high cost and environmental unfriendliness in practical applications [66].

3.2.4. Ionic liquid pretreatment

Ionic liquid pretreatment is a salt solution in a molten state consisting of anions and cations at room temperature [67], which is suitable for lignin removal and effective in reducing cellulose crystallinity. Lietal et al. pretreated willow branches with ionic liquid and found that it was superior to dilute acid pretreatment in terms of crystallinity, specific surface area, and lignin content [68]. Hashmi et al. pretreated bagasse at 110 °C for 30 min using ionic liquids, and pretreated bagasse had significantly lower lignin content, reduced cellulose crystallinity, and 97.4% and 98.6% digestibility of dextran and xylan [69]. As a green solvent, it has the advantages of chemical stability, non-flammability, chemical conditioning, and high thermal stability [70].

3.2.5. Oxidation pretreatment

The oxidative pretreatment method, which involves treating lignocellulose with hydrogen peroxide or peroxyacetic acid, can reduce the lignin content significantly. However, the effect on hemicellulose is small, and the impact on cellulose is negligible [71]. Therefore, with its high delignification nature, oxidative pretreatment is often used as an adjunct to other pretreatments [72]. Sun & Cheng et al. achieved 89% and 57% enzymatic digestion of wheat and rye straw after oxidative pretreatment [73]. Oxidative pretreatment is a relatively mild process that is difficult to produce inhibitory compounds and is, therefore, more widely used in practice.

Fenton pretreatment is a kind of oxidation pretreatment, using Fe^{2+} and H_2O_2 reagent as the medium to pretreat lignocellulose, which has become a more mainstream treatment method with the advantages of mild conditions, small amount of addition required and low pollution.

3.2.5.1. Fenton pretreatment.

The Fenton reaction was discovered in 1894 by the French scientist Fenton, who discovered that the H_2O_2/Fe^{2+} system could facilitate the oxidation of tartaric acid [74]. In the 1960s HaliWar et al. found that the degradation of lignocellulose by ·OH produced by the Fenton reaction was very similar to microbial degradation [75]. Due to the strong oxidation potential of hydroxyl radicals, they have high electronegativity and electrophilicity, thus they are able to oxidize with difficult-to-degrade organic matter and achieve the purpose of organic matter removal.

The Fenton reaction is a series of phases as follows [76]:

$$H_2O_2 + Fe^{2+} \rightarrow \cdot OH + OH^- + Fe^{3+}$$

$$\cdot OH + \text{Organics} \rightarrow \text{Degradation products / Solids}$$

$$\cdot OH + Fe^{2+} \rightarrow OH^- + Fe^{3+}$$

$$\cdot OH + \cdot OH \rightarrow H_2O_2$$

$$H_2O_2 + \cdot OH \rightarrow H_2O + \cdot HO_2$$

$$Fe^{3+} + H_2O_2 \rightarrow (Fe\text{–}OOH)^{2+} + H^+$$

$$(Fe\text{–}OOH)^{2+} \rightarrow \cdot HO_2 + Fe^{2+}$$

$$\cdot HO_2 + Fe^{2+} \rightarrow Fe^{3+} + HO_2^-$$

$$Fe^{3+} + \cdot HO_2 \rightarrow Fe^{2+} + O_2 + H^+$$

It was found that Fenton's reagent mainly promotes lignin depolymerization by breaking β-O between lignin residues, thus achieving the disruption of lignin structure to promote lignocellulosic enzymatic saccharification [77]. The Fenton reagent has a pH of about 3.0 ± 0.5 under natural conditions [78], and the Fenton reaction can be promoted by adding some reagents, for example, citric acid can promote the production of iron ions and reduce the consumption of whole cellulose by hydroxyl radicals under neutral conditions, which can well promote the Fenton reaction [79]. The reason is that oxalate has a good complexation and fixation effect on Fe^{2+} under acidic conditions [80]. The application of Fenton pretreatment in combination with other pretreatments, e.g. Jeong et al. treated hardwoods with a combination of Fenton and hydrothermal pretreatments, and the experimental group treated with Fenton pretreatment achieved 79.54% conversion of lignocellulose compared to the control group [81]. Wu et al. combined Fenton pretreatment with microbial inoculation for rice straw composting and found that the humus content increased to 32.62% after Fenton treatment relative to the initial stage, and also had a strong conversion capacity for humic acids [2]. Fenton pretreatment can be performed at room temperature and has the advantages of mild reaction conditions, low cost, environmental friendliness and no inhibition of enzymatic and fermentation inhibitors, but the reaction process is very time consuming [82].

3.3. Biological pretreatment

Biological pretreatment methods can be traced back as far as the 1890s [3]. The biological pretreatment method mainly includes microbial bacteria and scavenging insects (black gadfly and earthworms, etc.). Compared to other pretreatment methods, biological pretreatment is a relatively gentle process and the treatment process does not lead to the production of inhibitory substances, making it a relatively green method.

3.3.1. Microbial agent treatment

Bacteria and fungi are used to secrete relevant hydrolytic enzymes for the degradation of AOW [83]. And most of the hydrolytic enzymes secreted by microorganisms are extracellular enzymes, which are more conducive to the degradation of lignin and other compounds [84]. Some of the microorganisms present in AOW also have some degradation capacity for lignocellulose, but the small number and poor degradation capacity of such microorganisms lead to problems such as low composting efficiency and poor quality of compost products [85]. Therefore, in the composting treatment of AOW, the degradation of macromolecular organic matter is generally carried out by inoculating the AOW pile with relevant degrading microorganisms by secreting extracellular enzymes through the use of exotic single or complex colonies of bacteria capable of secreting relevant hydrolytic enzymes [86]. The conversion of biopolymers into smaller fragments changes the structure of the microbial composition of the pile, promotes the composting process and the quality of decomposition [18,87]. Sajid et al. showed significant effect on lignocellulose degradation of rice straw (84%) using fungal pretreatment with higher lignocellulolytic enzymes than chemical pretreatment (79%) or control (61%), and fungal pretreatment of rice straw compost showed significantly higher composting temperature at late thermophilic stage, which enhanced lignocellulose degradation [88]. Suthar & Kishore Singh et al. composting of waste paperboard by pretreatment with mixed culture of fungi reduced cellulose, hemicellulose and lignin in waste paperboard by 35.8%, 68.4% and 69.3%, respectively, with a total dry matter loss of 38.8% [89]. The inoculation of microbial agents can increase the diversity of microbial community functions, increase the complementarity of resource utilization among communities [90], prolong the thermophilic phase of composting, increase the abundance of relevant degrading microorganisms, promote the secretion of relevant hydrolytic enzymes, and improve the degradation efficiency of composting materials [91]. Since the microbial degradation process is mild and no toxic substances are produced, it is considered as one of the safest, green, and most effective methods [92], providing a green way to degrade AOW [93].

3.3.2. Insect composting treatment

To date, a large number of researchers have studied the effectiveness of earthworms in composting applications [94,95]. Vermicomposting relies mainly on the hydrolytic enzymes present in the earthworm gut and, due to the presence of some nitrogenous compounds in the mucus of the earthworm gut, increases the activity of microorganisms and promotes the degradation of organic waste [96]. Secondly, earthworm activity in organic waste life increases the looseness of the pile, which further facilitates the composting process [97]. Yu et al. concentrated earthworms in waste mushroom compost and found that vermicomposting improved ion exchange capacity (139.8%), pH (6.9%) and nitrate (71.1%) as well as reduced total carbon (31.2%) and carbon to nitrogen ratio (32.1%), indicating that earthworm inoculation can promote compost product quality and facilitate compost decay [98] Gong et al. used earthworms to compost corn stalks and found that they could reduce greenhouse gas emissions by 66.23% and 55.12% with vermicomposting [99]. Therefore, it can be said that vermicomposting is a greener, safer and more economical way of treatment.

Numerous studies have applied black gadfly to composting studies of municipal solid waste, food/kitchen waste, and animal manure, and found good results [100–102]. Bortolini et al. added black gadfly to chicken manure compost and found that the compost dry matter (DM) was reduced by 75% and the end product became an excellent substrate for cultivation in agriculture [103]. The black gadfly performed well in degrading some high protein and lipid wastes, as black gadfly larvae mainly feed on these substances, but was less effective in degrading some AOWs such as plant straw [104]. However, researchers have also begun to experiment with inoculating black gadfly in AOW composts, and good results have been achieved through some measures of improvement. Menino et al. inoculated black gadfly in ryegrass compost and found that the inoculation of black gadfly increased the activity of relevant degradation enzymes and increased the organic matter, N, P and K content in compost products [105]. The black gadfly not only promotes the degradation of organic waste, but also reduces greenhouse gas emissions during the composting process. For example, adding black gadfly compost to pig manure compost can reduce greenhouse gas emissions by about 90% [106]. The disadvantage is that black gadfly has certain requirements for the surrounding environment, and the products obtained from black gadfly composting are less biochemically stable and easily create conditions for mosquitoes and fruit flies to breed and survive [107].

3.4. Combined pretreatment

There are various pretreatment methods for lignocellulose, but each pretreatment can only have a good effect on the part of the structure of lignocellulose, and if various pretreatments are combined so that their advantages and disadvantages complement each other, then the degradation rate of lignocellulose can be significantly increased. Combined pretreatments not only overcome the disadvantages of single pretreatment but also can improve the efficiency of sugar production, reduce the production of inhibitors and shorten the pretreatment time. Although combined pretreatment improves the conversion efficiency of organic waste, the treatment process is also more complicated and the cost increases.

3.4.1. Combined physicochemical pretreatment

Steam blasting pretreatment is the quick release of pressure from lignocellulose under high temperature and pressure-saturated steam conditions, which causes mechanical fracture and structural rearrangement. During this process, hemicellulose and lignin are separated and removed from it to varying degrees [108]. Sulzenbacher et al. subjected wheat straw to steam blasting at 200 °C and found a significant increase in sugar yield and a decrease in the production of inhibitory substances [109]. The optimum treatment condition was blasting at 210 °C for 10 min with the highest lignocellulose enzymatic rate, although a further increase in treatment could lead to a higher enzymatic rate, but to a small extent, and some inhibitors may be produced in the process [26]. During high temperature and pressure treatment, attention should also be paid to some inhibitory substances such as organic acids, furanic acids, and aromatic compounds produced [110]. Since water is used as the medium, the treatment process does not require chemical reagents, is friendly to the environment [111], and is widely used for its advantages such as short time and efficient energy use efficiency compared to other treatments [43].

Ammonia fiber expansion (AFEX) uses liquid ammonia to treat the raw material at a relatively low pressure and temperature, and then suddenly releases the pressure raw material burst. The crystalline structure of cellulose is disrupted and some of the lignin or hemicellulose is degraded in a solid-to-solid process that does not involve the involvement of liquids and is a way of not requiring water washing or detoxification [112]. Numerous studies have proven that the enzymatic rate is greatly improved after ammonia fiber swelling treatment [113,114]. Chundawat et al. found that the rate of glucose and xylose release from ammonia swollen pretreated corn stover after enzymatic hydrolysis under high solids conditions was increased by about three times. Ammonia pretreatment also produces fewer inhibited degradation products than dilute acid pretreatment [114]. Ammonia fiber expansion pretreatment improves the enzymatic rate of cellulose and the nitrogen content of the material, which is beneficial to microbial fermentation, and the liquid ammonia can also be recovered and recycled, so the whole process has low energy consumption, which is a more promising pretreatment technology. However, effective ammonia recovery is an issue that must be properly addressed for ammonia blasting treatment. The disadvantage is that it is costly and less effective for some woods with high lignin content [115].

The wet oxidation method refers to the treatment of the material using water and oxygen above 120 °C [21]. The process consists of two reaction: low-temperature hydrolysis reaction and high-temperature oxidation reaction [116]. The treatment process was carried out without any catalyst and the raw material was maintained in high temperature water for a certain period of time. The aim was to increase the enzymatic accessibility of cellulose by dissolving the hemicellulose in lignocellulose through self-hydrolysis. Also to avoid inhibitor generation, the pretreatment pH was controlled between 4 and 7 [117]. Jietal et al. increased the sugar recovery from 5.12% to 42.9% after the pretreatment of wood pulp waste by WO [118]. The most significant advantage of the wet oxidation reaction is that multiple responses can be performed in one step, which is beneficial for later scale-up production [119].

3.4.2. Combined processing between different pretreatments

Examples include steam explosion treatment combined with alkali solution pretreatment [111], mild acid pretreatment combined with biological pretreatment [120], and mild physical and chemical pretreatment combined with biological treatment [121]. These combined pretreatments reduce the crystallinity of cellulose, change the composition of lignocellulose to different degrees, and promote the degradation of lignocellulose. It was found that dilute alkali-catalyzed pretreatment could reduce the lignin content in lignocellulose and increase the enzymatic rate and glucose yield [122], while pretreatment by dilute acid-catalyzed pretreatment could effectively reduce the hemicellulose content in lignocellulose [123]. Chen et al. pretreated rape straw hydrothermally at 180 °C for 45 min and 2% NaOH at 100 °C for 2 h. The saccharification rate was significantly increased by 5.9 times compared to the untreated feedstock [124]. Wang et al. treated with 2% NaOH at 80 °C for 2 h followed by ozone treatment for 25 min at an initial pH of 9, when the highest efficiency of cellulase hydrolysis was 91.73%, and the combined pretreatment led to improved enzymatic hydrolysis, composition and structure and characteristics of corn stover [125]. Binod et al. combined microwave pretreatment with acid-base treatment (1% sodium hydroxide and 1% sulfuric acid), increasing the yield of reducing sugars by 830 mg/g [126]. By combined pretreatment, the lignocellulose degradation rate was substantially improved, but there are still disadvantages, such as environmental and energy unfriendliness.

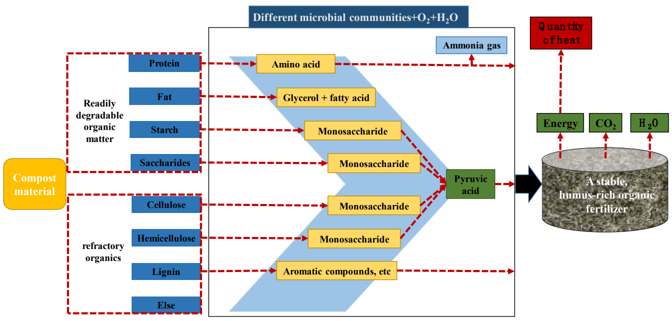

Fig. 5. Aerobic composting reaction process of organic matter.

The combination of biological methods and mechanical treatments is a prevalent treatment method. Firstly, the physical structure of the feedstock is destroyed by mechanical treatment to promote the accessibility of the feedstock to hydrolytic enzymes [127]. Oliver et al. obtained higher enzymatic sugar yields using ultrasonic pretreatment and treatment of wheat hulls with white rot fungi and yellow spore fungi [128]. Biological methods combined with chemical pretreatments are more common than mechanical pretreatments. Ren et al. used a combination of hydrothermal pretreatment and fungi on cereal straws. The combined pretreatment gave higher reducing sugar yields and saccharification efficiencies than the individual treatments [129]. Xie et al. combined white rot fungi with alkali/oxidation (A/O) treatment and increased reducing sugar yields by 1.10–1.29 times [130]. Lignocellulose exists mainly in the form of glycans and oligosaccharides after pretreatment. The pretreatment products can be completely converted into glucose and xylose [110], monosaccharides used by microorganisms, after enzymatic hydrolysis to achieve the degradation of AOW.

4. Factors affecting composting of AOW waste and its regulation

Since composting is a complex and variable process as shown in Fig. 5 [139], where changes in each parameter cause different results, mainly influenced by factors such as pile aeration rate, particle size, temperature, water content, pH, EC and C/N [140]. Poor handling of the above factors can lead to carbon and nitrogen losses, greenhouse gas emissions, pathogenic bacteria contamination and poor compost quality, ultimately leading to poor compost quality or even failure [141]. Therefore, by adjusting composting characteristics, controlling the composting process, applying additives and other treatment methods [142], researchers hope to improve composting efficiency, reduce nutrient dissipation and improve compost product quality.

4.1. Aeration rate

The aeration rate mainly affects the respiration of aerobic microorganisms, which in turn affects the efficiency of composting [143]. If the aeration rate is too low, the oxygen content of the pile will be insufficient, leading to the production of NH_3 and other odorous gases [144]. Han et al. also found that the production of ammonia in the pile is caused by insufficient oxygen content in the pile, and when the oxygen content is increased, it is able to reduce the emission of the above gases to some extent [145]. Although excessive aeration rate can provide sufficient oxygen and accelerate organic matter degradation, it will take away the pollutant gas produced by composting and reduce the carbon and nitrogen fixation capacity of the pile [146]. A paradox in the composting process is that turning the pile leads to ammonia emissions, but not turning leads to localized high temperatures and anaerobic production of the pile, which promotes CH_4 production [147]. Therefore, optimizing the aeration rate and aeration interval during the composting process can have a positive effect on compost nutrient conservation and gas emission reduction [148]. Kamarehie et al. found that increasing the rotation frequency from twice a week to once a week reduced CH_4 and N_2O emissions, but increased NH_3 volatilization [149]. Therefore, adjusting the flip frequency or delaying the flip for different periods will benefit GHG reduction and N conservation.

4.2. Temperature and moisture content

Temperature is an important parameter to judge the maturity of compost [150], which mainly impacts the growth rate and activity of microorganisms in the compost. Then it affects the decomposition rate of lignocellulose and the maturity of compost [8]. The variation in compost temperature can reflect the change in the organic matter metabolism of microorganisms during the warming period, thermophilic period, and decaying period [85]. After inoculating the organic waste with the microbial agent, the temperature of the pile rises rapidly due to the life activity of microorganisms [151], and the thermophilic period of the pile is prolonged to some extent [152]. At pile temperatures below 40 °C, mainly thermophilic microorganisms decompose easily degradable compounds, and N_2O is mainly produced by nitrifying and denitrifying bacteria at this stage. At temperatures above 40 °C, thermophilic microorganisms start to be active, mainly CH_4-producing bacteria [153]. When the temperature is higher than 55 °C, pathogenic bacteria and worm eggs in the pile are basically killed, but when the temperature exceeds 65 °C, the activity of most microorganisms is inhibited, making the composting efficiency of the pile lower [154]. The high temperature of the composting process can kill most of the pathogenic bacteria and eggs, but the high temperature will lead to the loss of C and N volatilization within the pile [125]. Therefore, it is not possible to solve the problems in composting by controlling the temperature of the compost alone.

Compost moisture content affects the amount of oxygen transported by the material pile, and also regulates fermentation temperature, material porosity, and microbial activity [155]. The initial moisture content of the pile should generally be 55%–70% [156], which is most conducive to composting, but the moisture content is generally uncontrolled during the recomposting process. However, the water content during re-composting is generally uncontrolled and when the water content is low, it affects the microbial life activity within the pile, thus reducing the microbial activity on the solid substrate and its biodegradation. When the water content $<$60% NH_3 volatilization is relatively high [157]. As the water content rises, it leads to a reduction in the porosity of the compost, making the pile less permeable and less oxygenated. TN losses increased when moisture $>$65% (or higher), which may be due to N leaching and denitrification [156]. The positive correlation between moisture content and CH_4 emissions, which is also true when controlling for feedstock type, is supported by the results of Pardo et al. [158]. Tamura and Osada found that the higher the water content of the material, the higher the greenhouse gas emissions through experimental studies of composting at different water contents [159]. This may be due to the elevated water content that puts the pile in an anaerobic environment and promotes the production of greenhouse gases.

4.3. pH and EC

The dynamic changes in pH during the degradation of organic waste composting can have an impact not only on the degradation of AOW, but also on the emission of greenhouse gases. Initially, it is reduced by the production of organic acids, and ammonification is inhibited when the pH is low [160]. As the temperature of the pile increases, the decomposition of organic acids contributes to the increase in pH, which promotes the release of ammonia in the process of ammonification and organic nitrogen mineralization [161]. Therefore, pH affects the ratio of NH_4^+ to NH_3 within the pile. Liang et al. confirmed that significant ammonia volatilization occurs at high pH by simulating the mechanism of NH_3 volatilization under composting conditions [162]. Zhao et al., on the other hand, found that lowering the pH of the compost would reduce NH_3 emissions [163]. Similar results were obtained by Gu et al. Lowering the pH of the compost reduced the cumulative NH_3 emissions and TN losses by 47.80% and 44.23%, respectively [164]. Changes in pH variation are difficult to control during the composting process, and it would take a lot of effort to maintain it in a certain range suitable for organic waste composting, which is clearly inappropriate.

4.4. C/N

C/N is one of the most critical factors affecting the quality of compost [165]. Carbon provides the energy required for microbial growth, and nitrogen mainly supplies microbial growth and protein synthesis [166], which impacts the rate of microbial growth and lignocellulosic degradation. Adding microbial agents can promote carbon degradation, reduce the nitrogen loss, and promote the degradation of compost substrate [167]. The optimal carbon-to-nitrogen ratio of the pile is between 20 and 30:1 [168], and relatively low C/N will lead to increased ammoniacal nitrogen and volatile fatty acid accumulation in the compost substrate, thus resulting in reduced CH_4 output [169]. The optimum carbon to nitrogen ratio for the compost pile is between 20 and 30:1 [168], and a relatively low C/N will lead to increased accumulation of NH_3 nitrogen and volatile fatty acids in the substrate of the compost, and excess nitrogen will be dissipated in the form of NH_3 [169]. When the C/N in a pile is high, it will slow down the composting process, mainly because higher lignocellulose content will slow down the microbial biodegradation and biotransformation of organic waste [170], while higher C/N will also limit the formation of humus [171]. When the carbon-to-nitrogen ratio is below 20–25, it proves that the pile has reached maturity and has some safety [172]. Too high or too low C/N is not conducive to composting, therefore, it is not possible to solve the problems in composting by C/N regulation alone.

4.5. Stack exogenous additives

Factors such as aeration rate, temperature, water content, pH, EC, and C/N in composting do not exist in isolation, and the regulation of one factor will often have an impact on the other factors as well. Therefore, researchers have considered adding different types of additives to the composting process to reduce harmful gas emissions, promote compost maturation, and improve compost product quality, such as chemical additives (guano stone, phosphoric acid, etc.) [173,174], physical adsorbents (biochar, zeolite, etc.), and biological additives (earthworms, black gadfly, and microbial preparations, etc.). The addition of exogenous additives to the pile can reduce gas emissions to varying degrees, regulate the C/N, water content and pH of the pile, and improve the quality of the compost produced [175].

Biochar is characterized by large surface area, high adsorption capacity, cation exchange capacity and high pore volume. Adding biochar as an additive to compost not only regulates the moisture and porosity of the compost, but also provides a suitable living environment for microorganisms and significantly improves composting performance [176]. Biochar has strong adsorption properties that can significantly reduce the emission of carbon dioxide, N_2O and NH_3 during the composting process [177]. Li et al. added 10% biochar to the compost pile and showed that the addition of biochar reduced nitrogen losses by 53% and emissions of NH_3 and N_2O by 48% and 31%, respectively, and completed the composting process in 21 days [178]. Manu et al. added 10% biochar to the compost and showed that the addition of biochar reduced, 58% NH_3 and 50 N losses compared to the control group and the compost reached maturity in 15 days [179]. Therefore, the addition of biochar to compost not only reduces gas emissions, but also promotes compost maturation to a certain extent. This may be due to the fact that biochar acts as a biocatalyst in composting, accelerating the decomposition of organic matter and producing high-quality compost in a relatively short period of time [180].

The addition of chemical additives such as $Ca_3(PO_4)_2$, $Al_2(SO_4)_3$, $CaCl_2$, $MgCl_2$, HNO_3 and $FeCl_3$ to the composting process can significantly reduce the greenhouse gas emissions during the composting process [181]. Chemical additives are added to the pile to provide immobilization, reduce gas emissions, and regulate the physicochemical properties of the pile [182]. Xiong et al. added sulfur powder and mature compost to the compost and showed a maximum reduction of 56.3% in NH_3 emissions and a reduction in N_2O emissions (36.9%) by the synergistic effect of the two [183]. Liu et al. added calcium-magnesium phosphorus, biochar, and mushroom substrate to the compost. The addition of calcium-magnesium phosphorus reduced the emission of pollutant gases and increased the nutrient content of the compost, and the addition of biochar promoted the maturation of the compost and reduced the emission of sulfur-containing gases from the pile [177]. Although the addition of chemical additives can reduce compost gas emissions, the price of this chemical additive is often high, and it is unknown whether the addition of chemical additives is accompanied by some salt ions that pose unknown and potential risks to the compost [184].

Microbial inoculation not only promotes the degradation of AOW, but also reduces greenhouse gas emissions from the pile. Microbial additives are usually combined with organisms such as earthworms and black gadflies to compost organic waste, i.e. the microorganisms pretreat the organic waste and then inoculate it with earthworms or black gadflies for re-composting. Microbial decomposition of organic waste generates a lot of heat to make the compost temperature die quickly on, killing most of the grass and worm eggs in the pile as well as pathogens. After the temperature of the pile drops, then inoculate with earthworms or black gadfly for secondary composting and fermentation. Zhang et al. treated pre-composting in combination with vermicomposting and showed that vermicomposting increased CO_2 and decreased CH_4 and N_2O emissions compared to the control [142]. The difference is that Lv et al. performed vermicomposting at different carbon to nitrogen ratios and compared to the control group, vermicomposting promoted the degradation of organic matter, accelerated the mineralization process of nitrogen, and reduced CH_4 production but increased N_2O emissions [185]. In response to the increased release of N_2O, some additives with sorptive effect can be added to the compost to reduce its emission.

5. Potential impact on plant growth

Using composted AOW in agricultural production not only improves soil fertility but also promotes plant growth and improves the resistance of plants to soil-borne diseases etc. [186,187], When it is returned to the field with suitable tillage patterns, it can improve crop yield and nitrogen utilization and potentially positively impact plant growth patterns [188]. Numerous studies have proved that returning composted and matured AOW to the field has many advantages: (1) increasing the activity of soil phosphatase, urease, and convertase, which are closely related to soil fertility [189]. (2) increasing the number of beneficial soil bacteria and inhibiting the survival of pathogenic soil microorganisms [190]. (3) reducing soil bulk, increasing soil permeability, porosity, large particle size micro agglomerates, and water stability [191,192]. (4) Plant growth provides nutrients such as C, N, P, and K [193].

5.1. Effect of microorganisms in compost on plant growth

After inoculation of microbial agents into AOW piles, the relevant degrading microorganisms regulate the activity of the microbial community through a community sensing (QS) system to achieve decomposition and metabolism of organic waste [194]. Compost products are used in agricultural production not only to increase biodiversity in the soil, but also to reduce the abundance of soil pathogens [195], promote plant growth and resist external environmental stresses [196]. Compost products not only improve the growing environment of plants, but the microorganisms in them also have a positive impact on plant growth [197].

Microorganisms generate a lot of heat through metabolism when degrading organic wastes, prompting the pile to warm up rapidly and deactivating pathogenic bacteria and weed seeds in organic wastes, which has a positive effect on the control of soil-borne pathogens in agriculture. The compost products returned to the field have the potential ability to suppress some plant disease bacteria, such as Pythium ultimum and Pythium irregulare, Phytophthora nicotianae, Rhizoctonia solani, Fusarium oxysporum, Pythium sp. Verticillium dahliae, and Pythium sp. etc [198,199]. Paned et al. added tomato straw compost products to the soil and found that the addition of compost products reduced the biomass of Fusarium wilt in the soil, which in turn increased the activity of related enzymes such as β-glucosidase, dehydrogenase, and alkaline phosphatase [200]. Jiao et al. inoculated maize stover compost with aerobic complex strains and found that the inoculation of complex strains not only eliminated toxicity to other plants and soil microorganisms, but also compost products had positive effects on maize yield, soil microbial biomass, field microbial diversity, and enzyme activity [201]. Pei et al. on the relationship between core microorganisms and metabolites during aerobic composting, analyzed the effect of metabolites of microorganisms on plant growth, and concluded that composting can eliminate toxic substances from waste and promote plant growth [202].

Many microorganisms in compost have a specific role in promoting plant growth [202]. For example, Xylella spp. can suppress plant pathogens and a solid environmental tolerance, and even stimulate plant growth [203]. Azotobacter spp. can fix atmospheric nitrogen, synthesize substances that can chelate iron, promote plant growth and enhance plant resistance to pathogens [204]. Bacillus and actinomycetes species in compost products can promote the uptake of soluble phosphorus by crops [205], and spore-producing microorganisms with good downgrading ability to lignocellulose are important for nitrogen fixation and phosphorus mineralization in the soil [206], which in turn promotes plant growth. Antoniou et al. found an increase in plant height, fresh dry weight, plant height, and total leaf surface compared to plants grown in non-composted compost, again demonstrating the role of microorganisms in promoting plant growth and found that the microbial community in compost not only helps plants resist certain diseases, but also improves overall plant health [207].

Microorganisms in compost have an impact on the growth of plants, and likewise, plants have an impact on the activity of microorganisms [208]. De-la-Peña et al. found that plant changes in the growth stage affect the composition of the microbial community. For example, during the flowering stage of the plant, there is an increase in the secretion of defense proteins [209]. Numerous studies have demonstrated that the structure of the inter-root microbial community is influenced to some extent by host genes [210]. Various amino acids, organic acids, polysaccharides, and proteins that microorganisms can use can be secreted in the interroot of plants, and these substances become important drivers of microbial activity [211].

5.2. Improvement of plant growth environment by composting

Intensive agricultural cultivation and environmental degradation have led to a continuous deterioration of the plant growing environment, which has severely affected both plant growth and yield. Compost products used in agricultural production have a positive impact on the improvement of the growing environment of crops, and their physical properties can directly affect root water transport, gas environment, and heat transfer rate during seedling growth, while water transport indirectly affects nutrient availability [212].

Using compost also increases the nutrient content of the soil, reduces the effect of high mineral nitrogen levels on the inter-rooted soil and plant growth [213], and reduces the negative environmental impact of chemical fertilizer use [214]. Qayyum et al. found that the total nitrogen, phosphorus, and potassium were higher in soils amended with organic compost than in the control group (unamended soils) and that crop yields were higher than in the control group [215]. In addition, the composting process of AOW not only produces humic acids, fulvic acids, humin and amino acids, which have a growth-promoting and disease-suppressing effect on plants [216–218]. It is also able to increase the nutrient content of the soil and reduce the impact of high mineral nitrogen levels on the inter-root soil and plant growth [213]. Toumpeli et al. found that the composting of AOW products had a more positive effect on soil physicochemical properties than others. The reduction of N, P, Ca and Mg concentrations and clay dispersion in the soil was highest after the addition of compost [219]. Qayyum et al. found that total N, P, and K in soils amended with organic compost were higher than in the control group (unamended soils) and that crop yields were higher than in the control group [215]. Pei et al. used compost products in an experiment with potted chard, and the plants grown in the compost product treatment group showed an 84.37% increase in fresh weight and 13.69% higher in plant height compared to the control group [220]. Therefore, compost products are used in agricultural cultivation to improve the growth environment of plants, increase the nutrient content of the soil and reduce the negative impact on the environment due to the use of chemical fertilizers.

Although compost is rich in nutrients, most composts do not meet the nutrient requirements of crops. Composted organic waste is usually high in salinity, low in nitrogen, and neutral to alkaline in pH. For some leafy crops meeting their nitrogen requirements is a prerequisite for achieving high yields, and nitrogen plays an essential role in the biosynthesis of some plant secondary metabolites such as polyphenols, ascorbic acid, and antioxidant enzymes such as glutathione [221]. Machado et al. applied organic compost in combination with inorganic nitrogen to supplement the nitrogen deficiency in compost and achieve high crop yields [222]. In agriculture, compost is usually applied in combination with other fertilizers. Zulfiqar et al. studied composting of biochar, compost, and biochar-compost mixtures to investigate the effects on plant growth, photosynthesis, antioxidant systems, and secondary metabolism, mixing biochar-compost positively affected plant growth and physiological biochemistry, significantly increasing plant growth, chlorophyll content, photosynthesis, and activity of antioxidant defense systems while decreasing the accumulation of proline and GB [223].

The effect of compost on plant growth is not only to provide nutrients for growth but also to increase the activity of many soil enzymes, such as catalase and phosphatase enzymes, and to facilitate the conversion of organic nitrogen nutrients in the soil to form more favorable for plant uptake [224]. Numerous reports have also identified many biostimulants in the end products of composting, such as phenols, lipids, ferulic acid, fatty acids, and sterols [225]. The composting of AOW can become a more stable and harmless organic fertilizer, which can eventually be applied in agricultural production and the reuse of biological resources. Due to the diversity of nutrients and physicochemical properties contained in different AOW decomposition products, Zhao et al. proposed a new concept of precise composting strategy (PCS) for this purpose (Fig. 6 [226]). Designed to promote the diversification of compost to meet the different needs of cropping systems for organic matter and nutrients. By matching compost characteristics, cropping system characteristics and application methods to obtain a superior result, the compost product is matched to the soil properties and crops grown to maximize crop yield.

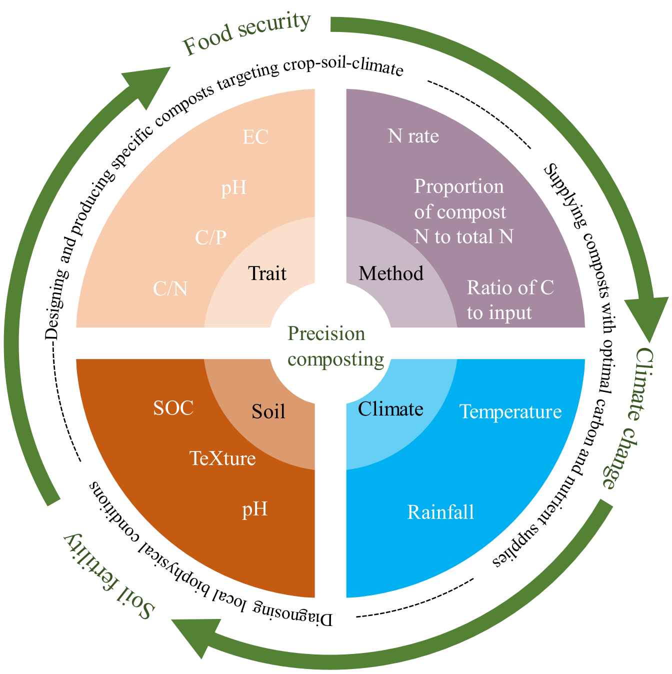

Fig. 6. Potential global benefits of precision composting strategies.

6. Summary and measures for future development

Giving economic value to AOW and making it profitable agriculture is the key to sustainable agricultural development. Composting of AOW for field treatment focuses on promoting compost maturation, reducing greenhouse gas emissions from compost, reducing toxicity of toxic substances, and improving compost product quality. Improper or incomplete treatment will not only lead to the aggravation of pests and diseases, deteriorate the growing environment of plants, affect the growth of the next crop, but also play a suppressive role in plant growth, resulting in crop yield reduction, etc. Therefore, the necessary human intervention in the composting process of AOW is necessary. However, there is no clear standard for composting AOW back to the field that can be applied in practice, resulting in more or less inhibited crop growth. There are various pretreatment and treatment technologies for AOW composting, each with its own advantages and disadvantages, which need to be reasonably selected and adjusted in the production with the actual situation.

Researchers have positively influenced the chemical, physical, biological, and combined pretreatment of AOW prior to composting treatment, as well as the addition of additives during composting. But most composting treatments come at the cost of greater energy consumption and even have some negative effects. Organic agricultural waste comes from nature, so the best way to compost it is to use the power of nature. The biological pretreatment method is a more economical and green treatment method compared to other treatment methods. As far as the current composting methods are concerned, the main problems in composting are greenhouse gas emissions during the composting process, harmful substances within the compost and poor composting products. In view of the above problems, the best, economic and green composting method is to mechanically crush the AOW before composting, adjust the initial moisture content and C/N of the pile to a suitable range, inoculate the compost with microbial agents that efficiently degrade organic waste, and further improve the quality of the compost by inoculating it with carrion animals such as earthworms or black gadflies during the cooling stage of the compost.

In the future, the composting of AOW can be used in a "take from the land and use it" model - the composting and maturing of a crop straw is used again to grow that crop. However, the composting of AOW and the loss of some elements from the previous crop harvest can often result in a deficiency of one or more of the mineral elements needed for crop growth. Nonetheless, the return of agricultural waste to the field requires only a tiny amount of mineral fertilizer to achieve a good crop yield, which can reduce environmental pollution and increase economic benefits. AOW recycling is the key to realizing the green transformation of agriculture, the essence of which is to achieve the goal of minimum input, more output, and better quality in agricultural production. It can not only promote the development of agricultural production but also fertilize the soil, protect the environment, and promote the development of agriculture in the direction of high quality and green, which is a critical path for the future green development of agriculture.

Author contribution statement

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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