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Review article

Impact of straw returning on soil ecology and crop yield: A review

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ABSTRACT

Several studies have demonstrated the effect of straw return on enhancing soil ecology, promoting sustainable agricultural practices, and cumulative effects on plant yield. Recent studies have focused on straw return methods and their impact on soil nutrient cycling and the overall physicochemical composition of the soil. Despite the substantial progress and successes, several research gaps in these studies require further investigations to harness the full potential of straw return. This review provides a thorough examination of straw diversity and decomposition mechanisms, the effects of straw on soil microorganisms, the interactions between cellulolytic nitrogen-fixing microbes and lignocellulose biomass, as well as nutrient mineralization, organic matter content, and their influence on plant growth and yield. This review also examined the effects of straw return on plant pathogens and its allelopathic impact on plant growth, highlighting research gaps to encourage further studies that could fully realize the potential benefits of straw return in agricultural fields for optimal plant growth.

1. Introduction

Straws are valuable agricultural by-products of dried stalks of plants such as rice, wheat, maize, oat, barley, and cotton [1,2]. Approximately 2.5 billion tons of straw are produced annually globally [3]. Straw has traditionally been used as fuel for domestic cooking, fodder for livestock, thatching, livestock bedding, and basket weaving [4]. However, the amount of straw produced each year exceeds these uses. Therefore, straw recycling back into the soil will sustainably enhance soil properties and optimal plant growth.

The importance of straw return to the soil regarding food productivity and beneficial environmental impact has been the subject of a multidisciplinary investigation by soil scientists, agronomists, and ecologists [5–7]. Straw return plays a significant role in enriching soil organic matter, promoting microbial population and diversity, and enhancing nutrient availability [8,9] and is intimately linked with the global nitrogen and carbon cycles, agricultural productivity, and the promotion of green development [10]. Recent studies examining the effect of straw recycling on greenhouse gas (GHG) emissions have shown that wheat straw reduced net GHG emissions by 33.1 %, while maize straw reduced GHGs by 12.1 %, due to high carbon sequestration. Optimal fertilizer use with 100% straw recycling significantly reduced GHG emissions in wheat and maize, while 60% straw recycling was more effective for rice despite increased fertilizer emissions [10]. However, on-field straw combustion emits fine particulate matter, nitrogen oxides (NO_x), methane, carbon dioxide, and ammonia, which lower air quality and pose significant hazards to humans and animals [11–13].

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Soil structure, carbon, nitrogen composition, and microbial population and diversity are essential for facilitating soil health in cropping systems, and straw return plays a significant role in influencing these factors [14,15]. A recent study demonstrated that straw return mitigates soil warming, creating an ambient environment for enhanced fungal diversity, bacterial activities, organic matter decomposition, and the presence of functional genes associated with nitrogen fixation, nitrification, denitrification, organic phosphorus (P) and potassium (K) mineralization [16–18]. Straw return helps to maintain soil moisture and efficient air circulation to facilitate optimal plant growth and yield [19–21]. Recycling of straw partially mitigates the harmful effects of straw removal by reducing excess K and enhancing maize yield by 5.2 %, rice yield by 5.0 %, and wheat yield by 7.8 % [10].

Several studies over the last five years have significantly contributed to the importance of straw recycling. This article highlighted the composition and characteristics of straw and its decomposition mechanisms, the effects of straw on the soil microorganisms, the interaction between cellulolytic nitrogen-fixing microbes and lignocellulose biomass, nutrient mineralization, organic matter content, and the consequential implications on plant growth and yield. This study also discussed the impacts of straw return on plant pathogens and the allelopathic effects on plant growth. Research gaps are also identified to encourage further studies to assess the benefits of straw return to the field.

2. Diversity of crop straws, applications, and lignocellulose composition

2.1. Diversity of crop straws

Agronomic crops comprise many highly diverse species, including maize, rice, wheat, cotton, sugarcane, rapeseed, beans, etc. Based on their purpose, these crops are classified as: cereals, oilseeds, sugars, forage crops, pulses, fibers, medicinal plants, roots and tubers, and vegetables or garden crops [22]. Cumulatively, these crops generate billions of tons of straw annually, with decomposition rates largely influenced by intrinsic chemical composition, such as lignocellulose biomass composition, or extrinsic factors, such as biotic and abiotic factors [23,24].

2.2. Lignocellulose composition of straw

Crop straw primarily comprises lignocellulose biomass (cellulose, hemicellulose, and lignin) (Table 1) [25]. Cellulose comprises β-D-glucopyranose units linked by β-(1,4)-glycosidic bonds to form a cellulose chain (CC) [26,27]. CC comprises microfibrils containing 500–1400 D-glucose units arranged together to form cellulose fibrils. The cellulose fibrils formed are then deposited within the amorphous and crystalline regions of the cell wall, thus forming a lignocellulosic complex [28,29]. The recalcitrance of lignocellulosic biomass is attributed to complex cross-linkages within its structure. Hemicellulose comprises 20–35 % of the total straw biomass and comprises xylans, xyloglucans, mannans, and glucomannans. Hemicellulose exhibits a lower degree of polymerization than cellulose, typically ranging between100 and 200 units [30–33]. Xylans contribute to the structural network of the secondary cell wall by forming a ribbon-like structure containing two-fold helical screws linked to microfibrils through hydrogen bonds. This plays a significant role in enhancing the integrity and strength of the secondary cell wall [34]. Xylans contribute to biomass recalcitrance by inhibiting cellulose hydrolysis [35].

Lignin is a three-dimensional biopolymer formed by the oxidative coupling reactions of cinnamyl alcohol derivatives: coniferyl alcohol, *p*-coumaryl alcohol, and sinapyl alcohol. It also consists of cross-linked phenylpropanoid units with β-5-phenylcoumaran, 5–5-biphenyl, β-β-resinol, β-*O*-4-aryl ether, and 4-*O*-5-diaryl ether linkages [27,36–39]. For further information on lignocellulose composition and genetic degradation techniques, see Ninkuu et al. [27].

3. Methods of straw management

Crop residues generated after harvest have several on-field and off-field applications. The crop straw can be burnt on-field, composted, and returned to the soil. Straws can also be cleared from the field for off-field utilization (Fig. 1A). The advantages and disadvantages of different straw applications are discussed below.

3.1. Straw removal or burning

Straw removal management is divided into two categories: energy solutions (bioenergy and bioethanol production) and non-energy solutions (basket and hat weaving, fuel for cooking, mushroom production, and fodders for feeding livestock) [40]. Although straw removal for off-field applications indirectly mitigates GHG effects through bioenergy production and reduces the reliance on synthetic raw materials, it can lead to soil erosion, deteriorate soil physicochemical characteristics, and adversely affect soil microbiota [41,42]

Table 1
Lignocellulose content in straws.

Parameter	Cotton stalk (range)	Rape stalk (range)	Corn (range)	Wheat (range)	Rice (range)
Cellulose	31.54–51.80	30.41–51.96	31.57–48.65	25.03–50.56	36.21–48.88
Hemicellulose	9.49–21.65	8.93–19.53	9.63–26.46	13.80–30.40	9.98–23.70
Lignin	22.09–3.03	12.07–25.47	14.66–30.02	15.13–27.90	11.59–26.70

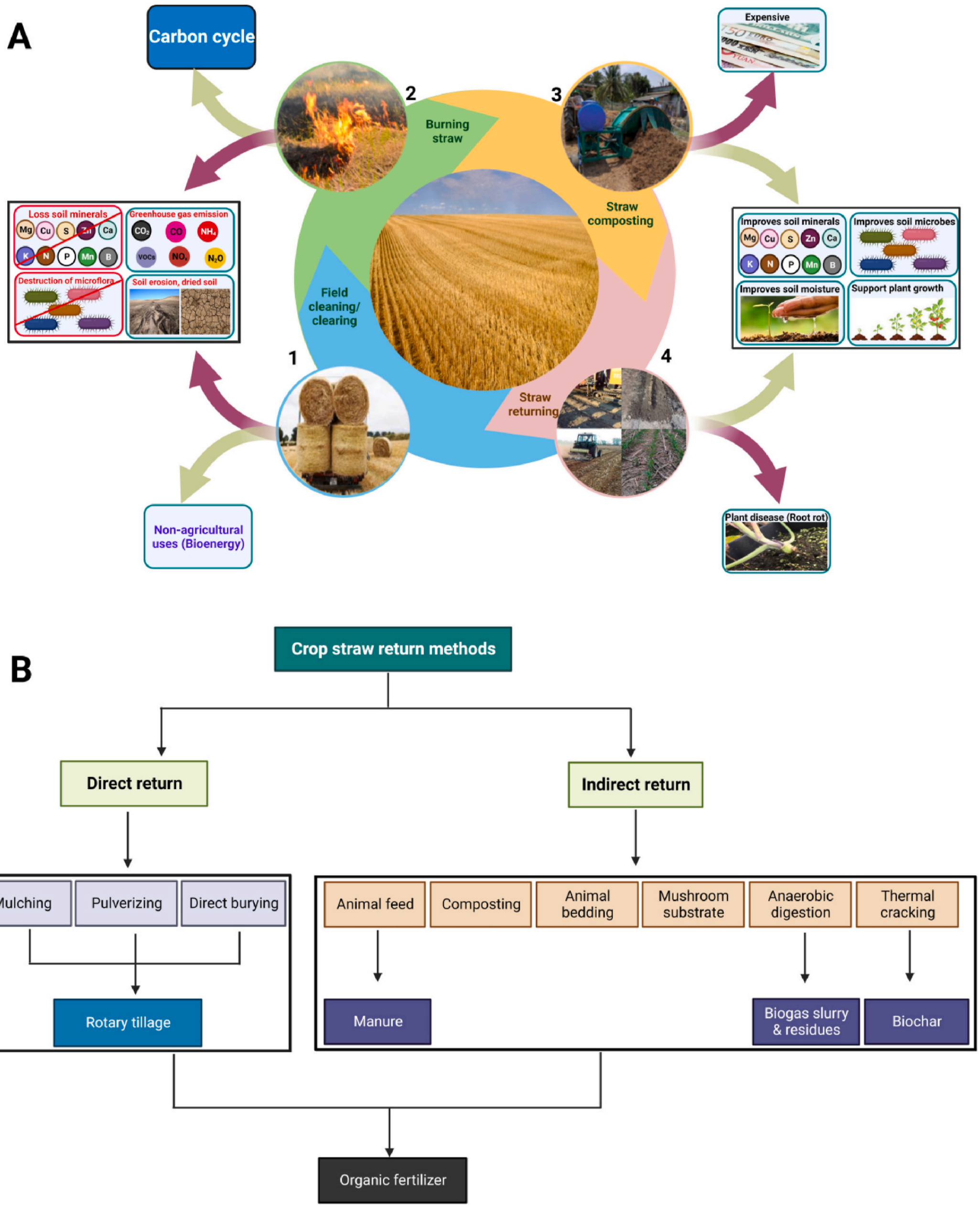

Fig. 1. Advantages and disadvantages of straw treatment and straw return model. **(A)** Straws remaining on the field after harvest is usually subjected to four major treatments: **(1)** clearance/removal for off-field utilization, **(2)** on-field burning, **(3)** straw composting, and **(4)** straw returning. Brown arrows indicate the disadvantages of those specific methods of straw return, while green arrows denote the advantages of those specific methods. **(B)** Straw return is categorized into direct and indirect methods. Direct methods of straw return include mulching, pulverizing, and/or direct burying. Straws applied by these three methods are then incorporated into the soil by rotary tillage. The indirect methods include using straw as animal feed and returning to the soil through manure and rumen remains, compositing before returning, returning straw used as animal bedding, returning straw substrate used for mushroom cultivation, returning biogas residue slurry and residue, and returning biochar produced during thermal cracking of straw. The above method improves the quantity of organic fertilizer in the soil.

(Fig. 1A).

Furthermore, straw burning leads to several adverse effects on soil ecology. Straw burning has been estimated to increase soil temperature by around 42 °C, resulting in the death of several beneficial soil microbes and a significant loss of soil carbon [43–45]. Volatile organic compounds (VOCs) and NO_x released by straw burning combine to form ground-level ozone, which can adversely affect plant metabolism and destroy leaves [46]. At least 60 % of S, 20–25 % of K and P, and over 90 % of nitrogen are lost by straw burning. Moreover, it has been observed that NO_2 and SO_2 produced from straw burning can contribute to enhanced pest growth and disease proliferation [44]. These regulations further strengthened the hypothesis that straw burning and clearance have detrimental effects on soil ecology, plant health, and the overall food chain. In addition, the increased costs of soil maintenance and rejuvenation could lead to higher costs of food production and negatively impact agro-products, ultimately affecting the overall production chain [47]. As a result, several countries and international organizations have enforced punitive laws prohibiting straw burning [48]. For example, the UK statutory regulation No 1366, 1993, strongly prohibits straw or subtle burning, except for disease control, education, or research purposes [47]. Under Article 119 of the 2015 revised Law of Prevention and Control of Atmospheric Pollution of the People's Republic of China, individuals who burn straws, fallen leaves, and other substances that produce soot pollution are subject to a fine ranging from 500 RMB to 2000 RMB. Sometimes, local government officials even lose their jobs as part of the punitive measures imposed in response to the negative impacts of straw burning [49,50].

3.2. Straw returning

Straw returning improves soil ecology and reverses the adverse effects caused by straw burning (Fig. 1A). Although several straw-returning methods have been applied in the field, they can be generally classified into direct and indirect methods. In the indirect method of straw return, the straw is cleared and used off-field as animal feed and bedding materials, a substrate for mushroom production, feed for compost production, etc., and eventually returned to the fields [40,51,52] (Fig. 1A). In the direct methods, straw is buried in the soil or used as mulch. The Chinese Ministry of Agriculture has adopted six methods of straw return based on these direct and indirect approaches [49] (Fig. 1B).

4. Straw decomposition characteristics

Straw decomposition and return to the field are characterized by three phases: a rapid decomposition phase occurring between 0 and 33 days, a slow decomposition phase from 33 to 93 days, and a stagnation phase, which mainly occurs during cold weather (winter) from 93 to 120 days [53]. However, the length of each phase (in days) varies based on several factors, including climatic conditions, straw type, soil type, microbial community, method of return, and pre-treatment techniques. Moreover, the constituents of crop straw, including cellulose, hemicellulose, pectin, proteins, and amino acids, degrade during the rapid decomposition phase due to the active participation of microbes [54–56]. Furthermore, the recalcitrant and persistent compounds such as tannins, lignin, and waxes are broken down during the slow phase of decomposition by a combination of chemical and physical processes, lasting 2–3 years [57]. Tillage treatments directly influence rates of straw return even without the need for additional treatments such as organic fertilizers and biochar. The rate of straw decomposition is increased by ploughing under dry conditions and water retention measures. This enhances the rate of total organic carbon released and increases total K, cellulose, and lignin [58–60].

Some microbial biomarkers exert a more pronounced impact on the decomposition of straw functional groups. Investigating the microbial biomarkers responsible for the decomposition of straw functional groups at different stages of straw decomposition using the RF analytical method indicated that *Aeromonas* was found to be responsible for the changes in O-alkyl carbon, O–CH_3/NCH, O–C–O anomeric carbon, cellulose, and water-soluble pectins (WSP); *Enterobacter* was responsible for the changes in cellulose, O–C–O anomeric carbon, and WSP, exhibiting a significant relative abundance during the early stages of decomposition. Furthermore, the changes in lignocellulose biomass of the decomposing straws were linked to uncharacterized *Ruminococcaceae*, BRC1, and *Prolixibacteraceae* [3]. According to Xia et al. [61], the dominant bacterial communities on returned straw consisted of *Actinobacteria*, *Acidobacteria*, *Chloroflexi*, and *Proteobacteria*, and their diversity, relative abundance, and roles in soil microbiome were significantly altered by short-term returning. However, the combined practice of rotary tillage and returning straw has the most pronounced impact on bacterial diversity. Although further network analysis has revealed that *Mycobacterium* and *Methylibium* could be biomarkers for returning straw, their effects under different tillage practices, soil types, and climatic conditions are relatively unknown [61].

5. Effects of straw return on soil microbial community

The composition of the soil microbial community is pivotal for improving soil fertility, productivity, and sustainability because of their important roles in carbon and nitrogen cycling, aggregate formation, soil aeration, and water retention capacity [62]. A review by Chaudhary et al. also discussed the involvement of soil microbes in degrading pollutants, such as heavy metals [63].

The quantity of straw returning affects the dynamics of microbial abundance and composition in paddy rice fields. Lower amounts of straw ($\leq$50 % straw) returned influenced bacterial community composition, while higher amounts of straw (>50 % straw) affected the abundance of the fungal community relative to the carbon and iron cycles [64]. However, higher rates of straw return provide a conducive environment for the proliferation of pathogenic microbes, which may contribute to plant diseases such as root rot in maize and sharp eyespot and common rot in wheat [65–70].

Studies on microbial community abundance have also demonstrated that fungal and bacterial communities exhibit different patterns during straw decomposition. These communities are unaffected by nitrogen supplementation, while the speed of microbial assembly is observed to increase [71]. Although bacteria constitute 70–90 % of the soil microbial population and are the primary contributors to cellulose decomposition, fungal enzymes are required for straw digestion [72]. Moreover, the lignocellulose biomass in straws is degraded by thermophilic Actinomycetes. The degradation of lignin, cellulose, and hemicellulose in rice, wheat, soybean, and corn is accelerated by Actinomycetes inoculation, resulting in the upregulation of key enzymes such as xylanase, peroxidase, laccase, and manganese peroxidase [73]. Rumen fluid-treated straws buried in the soil accelerate the decomposition rate by more than 45 %, leading to an abundance of microbial communities, enhanced soil nutrients, and increased enzymatic activities [74].

Recent reports have linked microbial traits, straw decomposition, and nutrient cycling to future climate scenarios. Assessing the decomposition of wheat straws under artificial conditions and considering climate projections over the next 80 years indicated accelerated decomposition of straw only in the initial phase [75]. Further, it is postulated that the abundance of saprotrophic fungus increases and contributes to enhanced straw decomposition.

5.1. Interactions between cellulolytic nitrogen-fixing microbes and lignocellulose biomass

The lignocellulolytic microorganisms are ubiquitous microorganisms producing cellulases and nitrogenases. They include fungi, bacteria, and protozoa capable of hydrolyzing straw biomass [76]. Among these microbes, fungal species (*Trichoderma*, *Aspergillus*, and *Penicillium*) are the primary producers of lignocellulose-degrading enzymes.

Recent studies have identified the biomass degradation mechanism of fungus (*Trichoderma reesei*). *T. reesei* is involved in the synergistic activities involving three enzymes (exoglucanases or cellobiohydrolases, endoglucanases, and β-glucosidases). Endoglucanases cleave the internal β-1,4-glucosidic bonds within the cellulose chain to produce short chains with new ends; exoglucanases release cellobiose or glucose molecules by systematically cleaving cellulose chains at both ends, whereas β-glucosidases hydrolyze the possible inhibitory effects of cellobiose [77]. Xia and Lin [78] also observed that a recombinant *T. reesei* (*T. reesei* harboring a laccase gene isolated from *Pycnoporus sanguineus*) effectively degraded rice straw by 51.16 % through the release of xylanase, cellulase, and laccase enzymes under solid-state fermentation. Wang et al. [79] reported that exogenous treatment of straw using fungi enhanced the activities xylanase, CMCase, and LiP enzymes to accelerate straw degradation. Intriguingly, xylanase and peroxidase activity was inhibited by *Phanerochaete chrysosporium* under *T. reesei* presence [79]. However, the coordination between *P. chrysosporium* and *T. reesei* inhibition of enzymatic activities is yet to be unraveled.

While fungi are known for their high cellulolytic activities, bacterial communities are known for their significant roles in straw hydrolysis due to their stability under high temperatures, nitrogen-fixing potentials, and faster growth rates [80–83]. Further, nitrogen-fixing bacteria provide the required nitrogen to the nitrogen-deficient lignocellulose biomass, unlike fungi, making bacteria the preferred cellulolytic microbes for biomass hydrolysis [84]. These bacteria are either facultative anaerobes or strict anaerobes. They are either gram-positive or gram-negative aerobes found within the *Pseudomonas, Teredinibacter, Stenotrophomonas*, *Klebsiella, Paenibacillus*, *Bacillus*, *Pseudoxanthomonas*, and *Rhizobium* genera [85,86]. Global carbon cycling is influenced by the presence of these bacteria in the soil because of their potential to convert cellulose into reducing sugars and free atmospheric nitrogen (N_2) into NH_3 [87]. Lignocellulolytic bacteria can be free-living, for example, *Azotobacter*, *Klebsiella,* and *Pseudomonas,* or symbiotically associated with plants or animals, e.g., the relationship between *Rhizobia* and root nodules of legumes [88]. Table 2 summarizes lignocellulolytic microbes and their roles in straw recycling.

Table 2
Lignocellulolytic microbes and their roles in straw recycling.

Sr. No.	Lignocellulose-degrading microbes	Origin of isolation/ substrate	Enzymes	Activities	References
1	*Clostridium hungatei*	Decomposition of wood in the soil	Cellulases, nitrogenases, and xylanases	Digestion of cellulose or D-glucose and nitrogen fixation	[187]
2	*Paenibacillus polymyxa*	Degradation of corn roots	Cellulases, xylanases, lignin laccases, peroxidases, and nitrogenase	Degradation of lignocellulose biomass	[188]
3	*Lactobacillus plantarum*	Wheat straw	Cellulases	Degradation of lignocellulose biomass	[189]
4	*Pseudomonas fluorescens*	Carbohydrate biomass/ lignin biomass	Cellulases, xylanases, lignin laccases, and peroxidases	Degradation of cellulose and hemicellulose	[190]
5	*Penicillium chrysogenum*	Lignocellulose biomass	Cellulases and hemicellulases	Enhances glucan (37 %) and xylan (106 %) hydrolysis	[191]
6	*Achromobacter xylosoxidans*	Rice and corn bran, sugarcane bagasse, rice straw, and sawdust	β-glucosidases, endoglucanases, and endoxylanases	Higher cellulase activity (512.98 U/gds) on corn bran compared to other straws	[192]
7	*Joostella marina, Pseudomonas putida, Flavobacterium beibuense*	wheat straw	Ligninases	Degradation of lignocellulose under saline conditions	[193]
8	*Bacillus paranthracis, Bacillus paramycoides Bacillus paranthracis, Neobacillus fumarioli*	waste landfill	cellulase	Degradation of lignocellulose biomass	[194]
9	*Aspergillus fumigatus*	Rice straw	Endoglucanase, xylanase, and laccase	Degradation of lignocellulose	[195]
10	*Cellvibrio japonicus*	MOPS minimal media with phosphate and glucose	Mannobiohydrolase, α-galactosidase, and mannosidase	Degradation of galactomannan and hemicellulose	[196]
11	Microbial consortium (*Sphingobacterium paramultivorum* w15, *Coniochaeta* sp. 2T2.1, and *Citrobacter freundii* so4)	wheat straw	*Arabinoxylanase*	Degradation of hemicellulose	[197]

6. Impacts of straw returning on soil nutrients (minerals)

The ultimate goal of straw returning is mineralizing soil nutrients to enhance agricultural production [89,90]. The composition of minerals released by straw decomposition depends on the straw species (Table 3). The nitrogen (Fig. 2) and carbon (Fig. 3) cycles are significantly impacted by straw return. Nitrogen and carbon are crucial minerals, and their assimilatory cycles are intricately linked during the decomposition of crop straws, primarily because of the simultaneous assimilation of these two minerals by decomposing microflora. The carbon assimilation rate depends on the decomposing rates of straw and the amount of carbon assimilated by the decomposing microbes. On the other hand, the assimilation of nitrogen depends on the carbon flow and the C: N ratio of decomposing microflora [91–94]. The amount of minerals returned by straws also depends on the specific method employed for straw returning, for example, mulching or burying. A recent meta-analysis demonstrated that straw burying enhanced soil organic carbon, total soil P, N, and K, while mulching enhanced soil available N, P, and K [95].

Straw returning is identified as one of the major factors affecting soil fertility. It recycles enough organic carbon into the soil [96–99]. However, short-term straw return has a limited impact on the soil organic carbon levels [100,101], whereas extensive studies have shown that long-term straw return improves soil organic carbon, microbial biomass, and crop yield. Further, Xu et al. [102] reported insignificant changes in total organic carbon levels after two years of straw return but enhanced levels of dissolved organic carbon after three years of return in paddy fields [5]. Recently, a 10-year field experiment revealed that straw return at low or high levels significantly increased the concentrations of labile carbon, dissolved organic carbon, and particulate organic carbon in the soil compared to plots with no straw return [103]. Moreover, it was reported that burnt returned straw does not affect total organic carbon but decreases soil pH and significantly reduces the microbial community, indicating straw return is more effective than burning for improving soil organic carbon [101]. Similarly, an 8-year straw retention experiment by Cui et al. [104] revealed that total soil nitrogen, heavy fraction nitrogen, particulate nitrogen, mineral-bound nitrogen, and light fraction nitrogen in soil sequentially increased with time. Straw return impacts denitrification activities by promoting the growth and abundance of bacterial communities. For example, 30-year field experiments demonstrated the dependency of denitrification potential on the abundance and composition of *nirK*- and *nirS*-type bacteria [104]. The rate of straw return combined with chemical fertilizer application has more pronounced effects on the *nirS*-type community than the *nirK*-type.

7. Straw return affects soil physicochemical parameters

Returning straw leads to several effects on the soil physicochemical parameters, such as heavy metal composition, pH, dissolved oxygen concentration, soil temperature, etc. [105]. Different treatments involving rice straws and varying compositions of chemical fertilizers were investigated for their effects on soil physicochemical parameters in a 39-year-old paddy field [106]. The study observed that straw return positively affected soil pH levels, and available P. N + P and N + P + K fertilization without straw led to a significant accumulation of total K. However, the addition of straw resulted in reduced NH_4-N and NO_3-N levels. Straw addition to N + P and N + P + K-fertilized soils (i.e., N + P + S and N + P + K + S) was also significantly enhance silicon (Si), Fe-Mn-Si, and ASi concentrations by 32 % compared to soils without straw treatment, leading to an increase in the rice yield by 15 % [106]. Si plays a significant role in the plant nutrient uptake from the soil and enhances the mechanical strength of the plants [107]. Several studies have also reported that Si alleviates stress caused by heavy metals, salinity, drought, disease, and pests in plants [108–111]. Therefore, straw return enhances Si-mediated plant growth and development. The ditch-buried straw strategy was adopted to investigate the chemical properties of returned straw during the decomposition period using CPMAS 13C NMR spectroscopy and the Bruker AVANCE 400 MHz spectrometer (BrukerBioSpin, Rheinstetten, Germany) [3]. Although the straw (soft tissue) decomposition rate increased with time, cellulose, lignin, hemicellulose, and WSP decomposition was much slower. It was also observed that the proportion of alkyl carbon, aromatic carbon, and aromatic C–O (recalcitrant functional groups) increased with the decomposition rate. However, there was a reduction in the readily decomposable functional groups in straw (O-alkyl carbon and O–C–O anomeric carbon). Moreover, a correlation was observed between the abundance of O-alkyl carbon and O–C–O anomeric carbon functional groups and the bacterial communities during the early stages of decomposition, while the later stages were characterized by recalcitrant and readily degradable groups, including alkyl carbon, aromatic carbon, aromatic C–O, and carbonyl [3], indicating the impact of straw chemistry on microbial turnover.

Heavy metal contamination of agricultural soils has presented serious challenges since the Industrial Revolution. For example, the contamination of mercury (Hg), arsenic (As), copper (Cu), cadmium (Cd), chromium (Cr), zinc (Zn), lead (Pb), and nickel (Ni) poses a serious threat to the physiological functioning of plants as well as the soil microbial community [112–115]. Heavy metals in the food chain also affect humans and animals [114,116,117]. Nonetheless, studies have demonstrated that returning straw can reduce soil

Table 3
Mineral composition of straw.

Parameter	Cotton stalk (range)	Rape stalk (range)	Corn (range)	Wheat (range)	Rice (range)
Carbon (%)	42.50–51.40	37.15–47.50	39.68–47.70	38.07–47.09	37.40–46.12
Nitrogen (%)	0.56–1.69	0.23–1.69	0.15–1.68	0.23–1.04	0.13–1.58
Phosphorus (g/kg)	0.39–3.15	0.15–3.42	0.04–3.65	0.13–1.75	0.30–10.59
Potassium (g/kg)	1.30–20.14	2.94–31.58	3.70–38.41	2.78–47.81	6.26–35.38
Sulfur (%)	0.29–1.21	0.15–1.04	0.15–1.04	0.19–0.90	0.18–0.77
Oxygen (%)	38.49–49.02	15.24–18.30	36.13–49.17	37.52–47.35	33.56–44.53
Hydrogen (%)	4.39–6.86	4.60–6.75	4.31–8.68	4.05–6.58	4.39–8.46

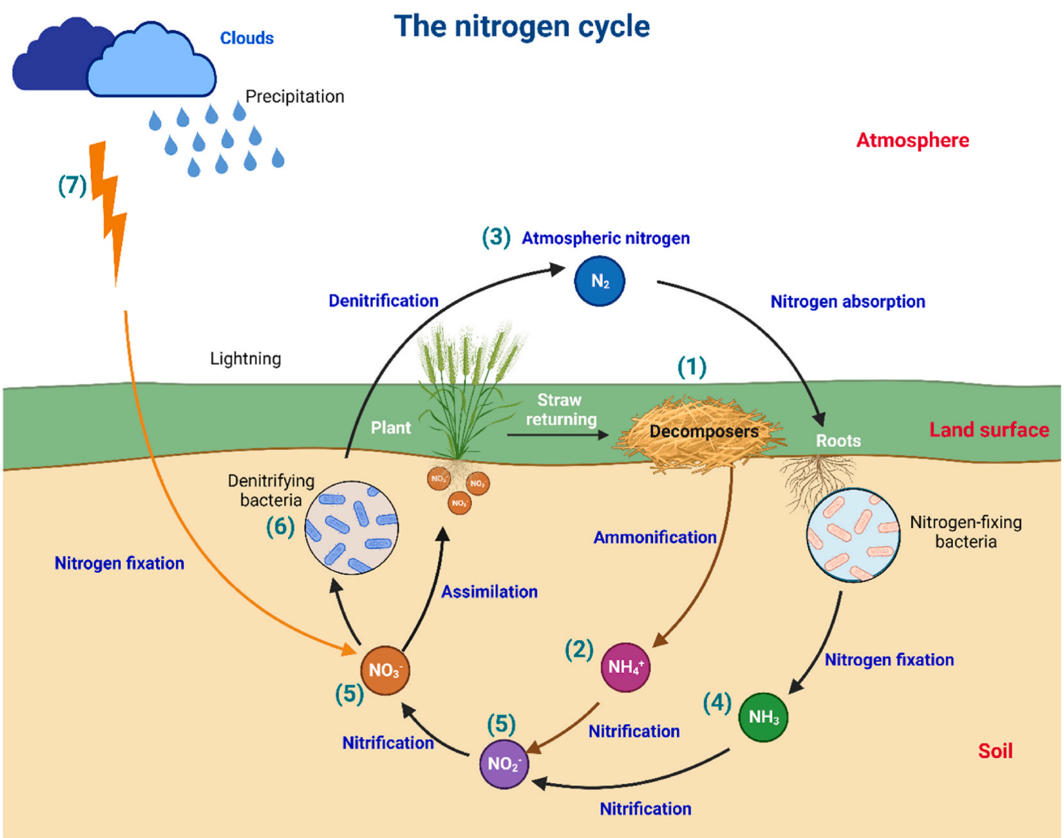

Fig. 2. Straw return affects nitrogen cycling in the soil.
Nitrogen fixation: Returned straw **(1)** releases nitrogen into the soil through the activities of decomposers (bacteria and fungi), and decomposed straw is converted back into ammonium (NH_4^+) (Ammonification) **(2)** Atmospheric nitrogen (N_2) **(3),** existing as an inert gas, is also converted into ammonia (NH_3) **(4)** by nitrogen-fixing bacteria that live in a symbiotic association with root nodules, e.g., *Azotobacter* and *Rhizobium*. Nitrification: Soil bacteria further convert ammonia into nitrate **(5).** Nitrate **(5)** is also formed when ammonia is oxidized by *Nitrosomonas,* which is subsequently converted into nitrates by *Nitrobacter* (Nitrification) as follows: $2NH_3 + 3O_2 \rightarrow 2NO_2^- + 2H^+ + 2H_2O$; $2NO_2^- + O_2 \rightarrow 2NO_3^-$. Assimilation: Primary producers (plants) take up soluble nitrogen through their roots, available as ammonia, nitrite ions, nitrate ions, or ammonium ions for protein formation. Denitrifying bacteria **(6)** convert soil nitrates back into atmospheric nitrogen, and lightning **(7)** plays a role in nitrogen fixation in the soil.

heavy metal concentrations by positively impacting the microbial community and promoting plant growth. Rice and wheat straw returned significantly reduced soil Cd by 12 % and 19 % and Pb by 4 % and 28 %, respectively. The mechanism underlying these reduction was attributed to increased organic carbon content, which enhanced microbial activity and promoted the binding of more metals with microorganisms [118]. Moreover, the return of bamboo biochar, rice, and wheat straw reduced Cd in maize shoots by 59.9 %, 69.5 %, and 66.9 %, respectively [118]. Further studies involving the combined application of Chinese milk vetch, rice straw, and chemical fertilizer consisting of 180 kg ha^{-1} N, 45 kg ha^{-1} P_2O_5, and 120 kg ha^{-1} K_2O reduced Cd concentration by 52 % (without lime supplementation) and 65 % (with lime supplementation) in the early rice growth period and 23 % (without lime supplementation) and 43 % (with lime supplementation) in the late rice growth period [119]. Although lime is reported to enhance Ca and Cd competition for absorption sites, consequently inhibiting the available Cd concentration [120,121], the intricate mechanism by which the combination of straw and lime reduces Cd remains unclear. In contrast, the pot experiments conducted by Liu et al. [122] reported that only straw returning or incorporating straw with microbial inoculant or biochar enhanced the Cd content in rapeseed, while the combination of straw and biochar or straw incorporated with decomposing microbial inoculant led to lower organic As content in rice. Therefore, further studies are required to elucidate the physicochemical interactions induced by the straw return to the soil, especially its impacts on heavy metal concentrations.

Soil pH measures the alkalinity or acidity of the soil on a scale of 0–7–14, where 7 represents a neutral indicator, <7 indicates acidic soil, and >7 denotes alkaline soil. The optimal pH of most plants ranges between 5.5 and 7.5 [123,124], indicating that alkaline soil limits plant growth and development by inhibiting root water uptake. Alkalinity also leads to Zn and P deficiencies, inhibiting plant growth [125,126]. Hanlin et al. [127] reported that the combined application of straw and fertilizer supplementation reduced soil pH but enhanced organic carbon and ammonium content, thus providing a conducive ecological environment for plant growth.

Cation exchange significantly affects soil fertility by promoting the availability of Mg, Ca, and K. Tavakkoli et al. [128]

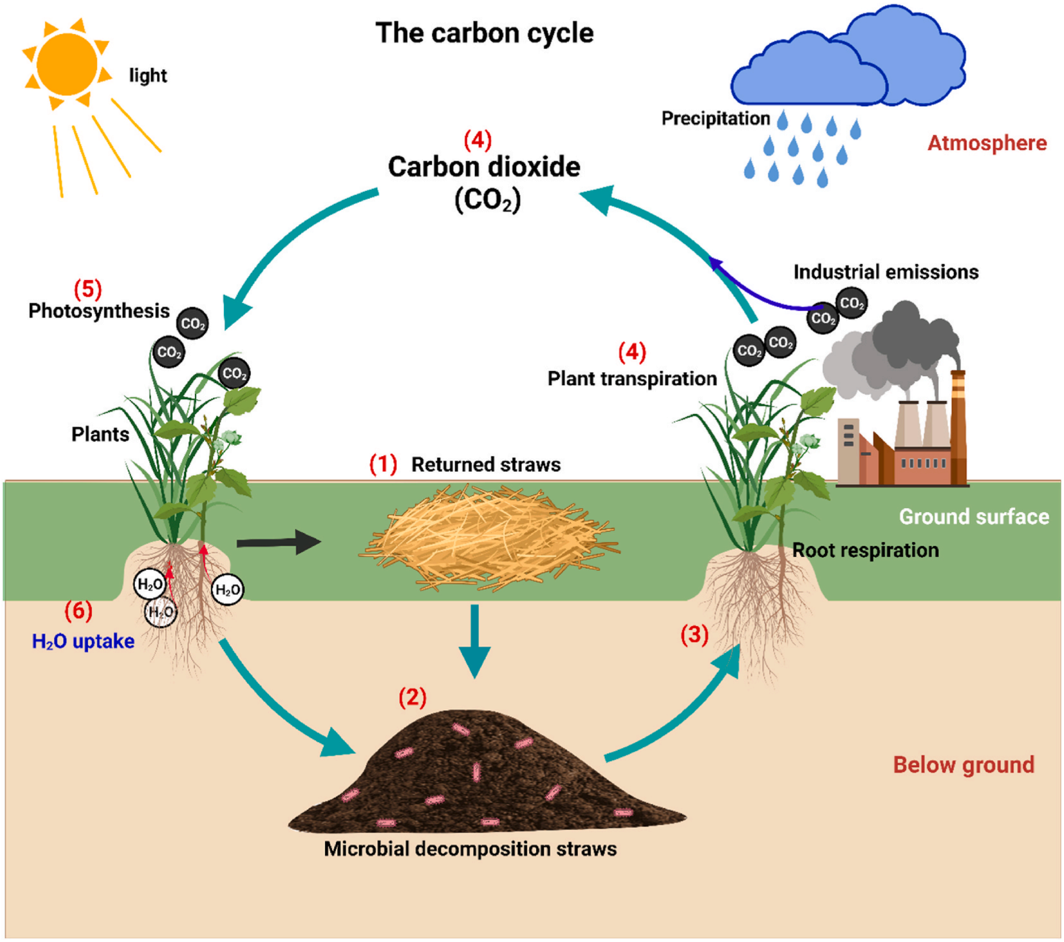

Fig. 3. Straw return affects carbon cycling in the soil. Straw from harvested crops **(1)** is returned to the soil and decomposed by microbial agents **(2).** The released carbon is absorbed by plant roots **(3)** and converted into atmospheric CO_2 by transpiration **(4).** In addition, the CO_2 released by industries or automobiles also increases atmospheric CO_2 content **(4).** CO_2 from these sources is absorbed by plants (carbon sinks) **(5)** and combined with water absorbed by the roots **(6)** in the presence of light to produce food (photosynthesis) for plant growth. After harvesting, the plants are eventually returned to the soil, completing the natural cycle.

demonstrated that high Na^+ content interferes with Ca^{2+} and K^+ acquisition and affects the effective regulation of stomatal activity, thereby inhibiting photosynthesis and growth. Under saline conditions, straw return to soil has been demonstrated to affect the soil ionic concentrations. A study investigated the effects of straw return on soil chemistry at five rates, namely, 0 %, 40 %, 60 %, 80 %, and 100 %, in combination with the application of chemical fertilizer composed of urea (150 kg ha^{-1} N); calcium superphosphate (50 kg ha^{-1} P_2O_5); potassium chloride (75 kg ha^{-1} K_2O); and zinc sulfate heptahydrate (20 kg ha^{-1} $ZnSO_4$) in saline soil [129]. In that study, the ionic concentration of the soil revealed that Na^+ and Ca^{2+} were the dominant cations, followed by Mg^{2+} and K^+. Except for K^+, which increased with an increasing amount of straw return, Na^+, Ca^{2+}, and Mg^{2+} concentrations demonstrated a downward trend with an increasing amount of straw return [130]. This may be attributed to the ionic form of K^+ that promotes its release, while other ions tend to decrease. The higher straw return also leads to a gradual decline in soil anionic (HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-) concentrations and is negatively correlated with soil pH [129]. The increasing volume of straw return also results in a downward trend in soluble salt reduction, indicating that straw could effectively mitigate soil salinity. Moreover, the electrical conductivity of soil (at 25–30 cm depth) was reported to reduce after straw return [129,131].

8. Effects of straw return on soil texture, temperature, and water retention

Straw return improves soil aggregation and soluble organic carbon [132]. Crop straw carbon is initially converted into labile organic carbon by microbial mineralization, then into humus carbon molecules through the process of humification [6,133]. In a controlled experiment to assess humus return, Li and Zhang [134] incubated a mixture of rice and corn straw with soil and chemical fertilizer at 40 °C under moderate moisture conditions and observed a 3 % increase in soil organic matter content and organic carbon content of three-fold. A wheat/maize rotation system with straw application and nitrogen fertilization effectively prevented nitrogen leaching, improved soil nitrogen content, and enhanced yield [135].

Returning straw improves soil moisture, porosity, water infiltration, and aggregate stability [136–141]. For example, maize straw mulch without tillage increased soil nitrogen content, improved root-soil interactions and nutrient assimilation, and enhanced crop yield [142]. It has also been shown to reduce the evaporation rate and soil surface runoff, improving soil moisture content, water infiltration, and saturated hydraulic conductivity [72]. In addition, applying straw reduced the topsoil temperature (0–5 cm depth) and increase moisture content [138]. The soil bulk density (dry bulk density), which measures the ratio of the weight of dry soil (M_{solids}) to total soil volume (V_{soil}), is a significant indicator of changes in the soil structure [143]. Returning straw has been demonstrated to decrease soil bulk density. For example, returning maize straw (4500 kg ha^{-1}) reduced bulk soil density by 10 % at 0–20 cm soil depth and 9 % at 20–40 cm depth [144]. Moreover, soil properties such as texture and pH influence carbon sequestration. A meta-analysis, suggesting an increase in soil organic carbon in loam soil (15%–21 %) compared to clay soil (12 %) under straw return conditiona can be attributed to the low oxygen concentration in clay soil resulting in lower carbon transfer efficiency to soil organic carbon [6,18,145].

9. Effects of straw returning on seedling growth and crop yield

The effects of different residue cleaning methods (corrugated disc, profiling residue cleaner, and rotary blade) was investigated on straw returning and their subsequent influence on maize germination. The corrugated disc method significantly improved maize emergence by 92–95 %, withstraw return rates of 52–68 % [146]. In cotton (*Gossypium hirsutum*), returned straw and biochar significantly improved growth and increased cottonseed yield for four consecutive years. Straw-biochar incorporation enhanced cottonseed yield by 24 % compared to other methods, such as microbial pre-inoculant straw incorporation (16.1 %), straw incorporation without treatment (14.3 %), and straw mulching (8.2 %) [147]. Straw-biochar incorporation was further found to enhance soil available N, P, and K, resulting in increased transport and efficiency in root uptake of N, P, and K, as well as their effective

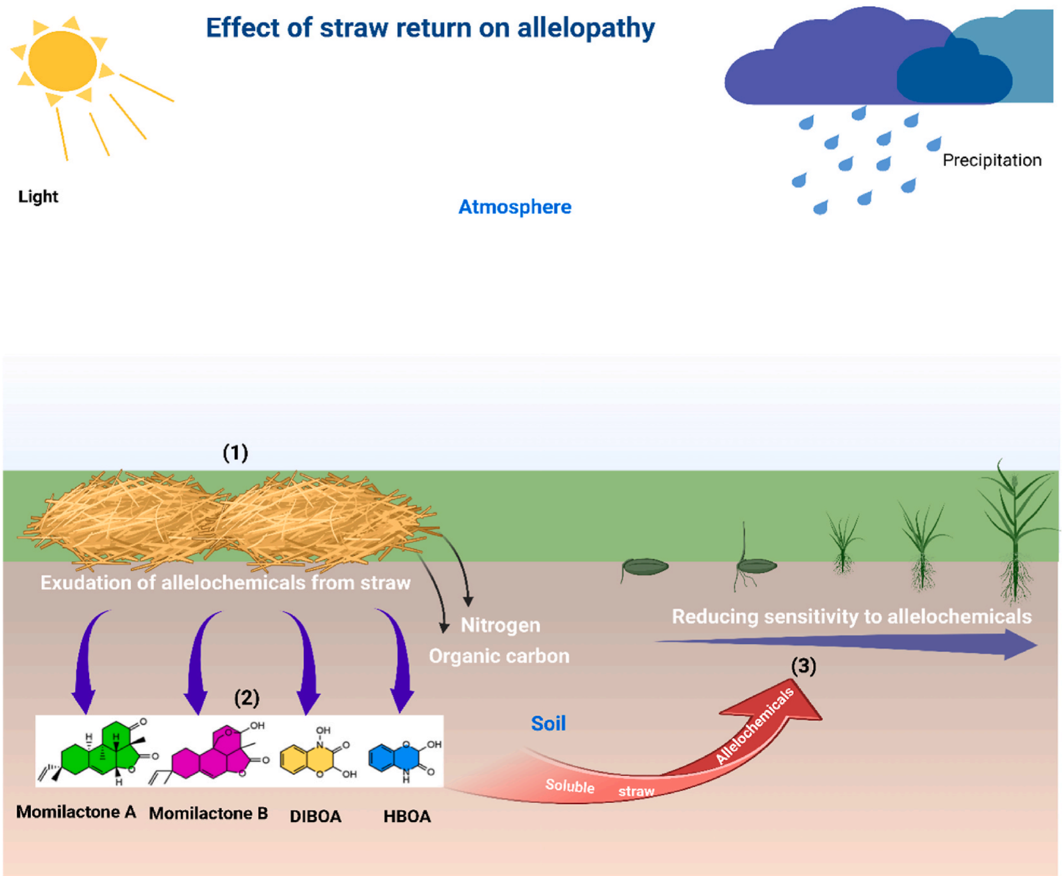

Fig. 4. Effects of returned straws on allelopathy. Returned straws **(1)** produce a multitude of allelochemicals **(2)** depending on the species of the return straws. Some examples of allelochemicals released include momilactones A and B, DIBOA (2,4-dihydroxy-1,4-benzoxazine-3-one), and HBOA (2-hydroxy-1,4-benzoxazine-3-one), and their presence in the soil inhibits seed germination as well as root and shoot growth. **(3)** The sensitivity of the allelochemicals to plants depends on the distance of their release. The closer the plants are to the source of return straw, the higher the allelopathic effect.

partitioning to bolls and vegetative branches for efficient photosynthesis [147]. Elsewhere, a 2-year investigation in a paddy rice field demonstrated that the application of 7 t ha^{-1} straw +40 t ha^{-1} biochar significantly enhanced ammonium content by 30.19 % and nitrate content by 42.72 %, compared to the application of 7 t ha^{-1} straw +20 t ha^{-1} biochar. However, applying 7 t ha^{-1} straw +20 t, ha^{-1} biochar increased the biomass of rice stem and ear, thereby enhancing yield [148]. Moreover, no-tillage combined with straw mulching helped maintain efficient soil temperature and moisture levels throughout wheat's growth and yield stages. Conversely, applying NPK combined with cattle manure in rice production significantly increased grain yield by 11.6 % and 4.3 % in the LYP9 cultivar and by 10.5 % and 7.6 % in the YY12 cultivar, compared to fields treated with NPK and straw [149]. Additionally, NPK + cattle manure treatment significantly enhanced soil mineral content (P, Cu, Fe, Ca, and Zn) compared to NPK + straw treatment. The K content increased with the increase in the amount of straw returned. Wang, Hu [150] found that the practice of returning straw led to a reduction in K application by 10 %, with a proportional increase in grain yield by 3.5 %.

10. Effects of straw returning on allelopathic interactions

Agronomic weeds have been estimated to cause approximately $95 billion worth of crop losses annually worldwide. Weeds compete with crops for soil nutrients and act as transient hosts for pest and disease proliferation. For example, *Echinochloa crus-galli* can deplete approximately 80 % of soil nitrogen and also act as a suitable host for the spread of mosaic virus infections [151–155]. Some plant species produce allelopathic chemicals that inhibit the growth of neighboring plants. A few examples of these growth/germination-inhibiting compounds are momilactones and benzoxazinoids. While monilactones are robust metabolites in rice, benzoxazinoids are mainly isolated from wheat, rye, and maize [152,156,157]. Decomposed straws exhibits significant chemical diversity. Qi et al. [66] identified several allelochemicals among other metabolites in decomposed straws, namely, 9.21 % *p*-hydroxybenzoic acid, 6.94 % dibutyl phthalate, 5.06 % 3-phenyl-2-acrylic, and 2.26 % 4-hydroxy-3,5-dimethoxybenzoic acid. The remaining metabolites included 1.73 % hexanoic acid, 1.06 % 8-octadecenoic acid, 1.04 % 3-(4-hydroxy-3-methoxy-phenyl)-2-propenoic acid, 0.94 % 4-hydroxy-3-methoxy-benzoic acid, and 0.94 % salicylic acid.

Straw return could increase the concentrations of soil allelochemicals, which in turn can inhibit the growth of weeds (Fig. 4). Allelochemicals are involved in autotoxicity and directly interfere with plants, posing challenges to crop growth when the straw is applied [158]. Therefore, a well-designed crop rotation system is required when practicing straw return. Studies have focused on investigating the allelopathic activities of crops, specifically maize, wheat, rice, etc., when their straws were returned to fields. The findings from these studies are summarized below.

A combination of high carbon and nitrogen ratios in straw with lignocellulosic biomass are natural barriers to biological straw degradation. This practice adversely affects root penetration and imposes allelopathic effects on seeds and seedlings [159,160]. A rice-rapeseed plot rotation system was used to assess the impact of returned rice straw on rapeseed. In that study, soil containing decomposed rice straw had enhanced levels of phenolic compounds, resulting in reduced chlorophyll content of rapeseed up to 57 %. Although the returned straw increased total soil nitrogen content, it adversely exerted allelopathic effects on the crops [161]. Phytoextracts derived from rice roots, shoots, and husks were found to inhibit the growth of *Echinochloa crus-galli* seedlings, a highly destructive weed in rice plantations [155,162,163].

11. Effects of returned straws on plant diseases and pests

Returned crop residues can serve as a primary source of pathogen inoculum, potentially increasing the risk of residue- or stubble-borne diseases, ultimately affecting crop yield [164]. Plants' most frequent soil-borne infections include *Fusarium* wilt, take-all, damping off, root rot, etc. Among these, root rot infection of host plants occurs throughout the crop's lifespan and reduces root nodulation [165]. Pathogenic microbial communities contributing to root rot are mostly soil-borne and exist as sclerotia or mycelium that have direct contact with plant roots, such as *Phytophthora* spp., *Fusarium* spp., *Pythium* spp., and *Rhizoctonia* spp [166–168]. The colonization of soil by pathogens poses multiple threats to plants, including inhibiting their ability to water and nutrients uptake. Further, higher rates of straw return create a conducive environment for the proliferation of pathogenic microbes [65–70]. However, the return of sugarcane straw has been reported to reduce pathogen abundance from 16 % to 7.6 % [169]. Interestingly, the specific pathogen antagonizing factor was not reported. The practice of wheat straw return has been found to stimulate lignin accumulation, which provides a defense against *Fusarium oxysporum f.sp.* in watermelon fields [170]. The management of soil-borne pathogens has

Table 4
Effects of straw return on crop diseases.

Straw type/method return	Pathogens/Crop disease	Incidence	Reference
All or half straws return	Rice sheath blight and rice false smut diseases	Increased	[198]
Wheat and barley residues	Reduce spore viability of *Cochliobolus sativus*	Reduced sporulation	[199]
Sugarcane straw return	Abundance of the pathogens	Increased	[169]
Decomposed maize straw at 0.03, 0.06, and 0.12 g mL^{-1}	*Rhizoctonia cerealis*/sharp eyespot, take-all, and common rot	Increased	[66]
Decomposed maize straw at 0.00, 0.03, 0.06, and 0.12 g mL^{-1}	*Bipolaris sorokiniana*/sharp eyespot, take-all, and common rot	Increased	[66]
Decomposed maize straw at 0.00, 0.03, 0.06, and 0.12 g mL^{-1}	*Gaeumannomyces graminis*/sharp eyespot, take-all, and common rot	Inhibited	[66]

also proven to be problematic. In addition to using resistant cultivars or chemical treatments, soil solarization has also been employed to control soil-borne pathogens. However, the broad-spectrum control of these pathogens often leads to unintended killing of non-targeted or beneficial microbes, highlighting the need for efficient straw management and utilization to fully exploit the benefits of these pathogen control methods. Table 4 presents the various crop diseases resulting from straw return. Integrating these studies with the significant effects of C, N, K, P, etc., returned straw could enhance our understanding of developing proper procedures for straw treatment and avoiding recycling diseases in the field.

Straw return increases biological control activities [171,172] by promoting the proliferation of natural enemies, such as predators and parasitoids, to control pest populations. Providing organic matter via straw return balances pest populations through natural predation and serves as a cover to inhibit pest movement. For instance, returned straw reduced the feeding efficiency of cabbage stem flea beetle (*Psylliodes chrysocephala*) in oilseed rape fields. In potato fields, straw mulch reduced Colorado potato beetle (*Leptinotarsa decemlineata*) and aphid populations [173–176]. The squash bug population was also reduced, with straw mulch covering [177].

Straw returning increases the habitat for pest incidents, creating a favorable environment such as shelter, food, and breeding grounds for some pests. The decaying organic matter from the returned straw also attracts pests, including stem borers, cutworms, and some soil-dwelling insects. These pests may thrive in the residual plant material, leading to higher populations [177]. In contrast, straw returning can promote disease vectoring by enhancing populations of pests acting as transient vectors for plant diseases. For instance, pests that survive the winter in crop residues can transmit fungal or bacterial diseases to new crops [178]. Straw returning can enhance aphid population, which serves as a vector for viral disease (Barley Yellow Dwarf Virus) transmission in cereal crops [179]. Thrip is a transient host for Tomato Spotted Wilt Virus infection. Therefore, increase in thrip population due to decomposing plant debris, such as straws, exposes plants to Tomato Spotted Wilt Virus infection [180]. Additionally, The Cotton Leaf Curl Virus persists within its whitefly host, and decomposing straw supports whitefly populations, increasing their capacity to transmit the virus to plants. Straw returning also increases leafhopper populations, intensifying the transmission of Rice Tungro Virus in rice paddies [181].

While straw returning offers significant benefits for soil health and nutrient cycling, it must be carefully managed to prevent the risk of increased pest proliferation. Implementing integrated pest management practices, such as timely incorporation of straw, crop rotation, and biological control agents, can help optimize the advantages of straw returning while effectively managing pest populations.

12. Perspective and conclusions

The cost of soil maintenance keeps rising due to poor agricultural techniques largely attributed to straw clearance- or burning-induced nutrient depletion and erosion. Farmers tend to rely heavily on chemical fertilizers to enhance plant yield in response to the global population growth and food supply. This has also become a significant challenge due to the increasing costs of fertilizers. The global fertilizer requirement is estimated to rise from 193.28 billion US dollars (USD) in 2022 to approximately 241.87 billion by 2030 [182,183]. However, excessive chemical fertilizers endanger soil microbiomes with cascading adverse effects on the trophic feeding levels, ultimately contributing to biodiversity loss [184]. To mitigate these consequences, straw generated from the field must be utilized innovatively for soil amendments. Although straw returning promotes ecosystem sustainability by reducing carbon emissions from straw burning and enriching soil nutrients, moisture, texture, and mineral composition, some key questions have still not been appropriately addressed in the existing literature in this field.

Crop straw contains several thousands of secondary metabolites that have the potential to either influence or impact the rhizosphere microbiome (rhizobiome). For example, allelochemicals are root exudates that can inhibit microbial growth and exhibit allelopathic effects on plants, as discussed in this review. However, no study has evaluated the effects of allelochemicals and other secondary metabolites produced during straw return and decomposition on the soil and root rhizosphere. Although studies have investigated the root-soil microbiome interactions in some crops [185,186], these interactions may lead to different impacts on the soil ecology in the presence of returned straw. Therefore, further studies elucidating these interactions can provide a better understanding towards unlocking the full potential of straw return. Furthermore, the allelopathic effects of straw types on the growth of seedlings should be systematically studied and modeled with respect to physiological factors such as salinity and drought to design an effective crop rotation system for soils with straw return, especially in short-term scenarios.

Improper straw-returning methods could aggravate the incidence of pests in the fields, especially when straws are directly returned without pre-treatment. Dormant pathogens and their eggs may rapidly proliferate under favorable conditions provided for straw decomposition. Although other studies have highlighted the inhibition of pathogenic populations by straw returning, the intricate mechanism underlying this inhibition has not been investigated. Therefore, further studies identifying antagonizing pathogens can help unlock new horizons for agricultural practices using straw return by developing bio-control agents for straw pre-treatment. Furthermore, the safety of straw return could be improved if the microbial communities in the soil are characterized to distinguish decomposers from pathogenic microbes for targeted control.

The lignocellulose composition of straws varies with the crop species (Table 1). Therefore, developing an integrated straw decomposition model that applies to all straw types is difficult. Although several modeling studies reported crop-straw-specific formulations for effective decomposition, integrating these methods into a universal method is cumbersome due to the varying physicochemical properties of the soil. Furthermore, soil treatment using biochar, manure, nitrogen fertilizers, etc., has been demonstrated to enhance straw decomposition and nutrient mineralization. However, the underlying chemistry that explains these ecological findings is currently lacking.

In conclusion, while straw returning offers significant ecological benefits, such as improving soil health and reducing carbon emissions, several challenges remain unaddressed. The complexity of straw's interaction with soil microbiomes, the potential for increased pest incidence, and the variability in lignocellulose composition across different straw types all necessitate further research. Developing a deeper understanding of these interactions and refining straw management practices are essential for optimizing the use of straw as a sustainable agricultural resource. Addressing these gaps will fully harness straw's potential to enhance soil quality and promote sustainable farming.

CRediT authorship contribution statement

Vincent Ninkuu: Writing – original draft. **Zhixin Liu:** Writing – review & editing, Funding acquisition, Data curation. **Aizhi Qin:** Writing – review & editing. **Yajie Xie:** Writing – review & editing, Visualization. **Xiao Song:** Writing – review & editing, Validation. **Xuwu Sun:** Writing – review & editing, Supervision.

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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References

[1] S. Chaturvedi, et al., Chapter 15 - stalk fibers (rice, wheat, barley, etc.) composites and applications, in: S. Mavinkere Rangappa, et al. (Eds.), Plant Fibers, Their Composites, and Applications, Woodhead Publishing, 2022, pp. 347–362, https://doi.org/10.1016/B978-0-12-824528-6.00009-6.
[2] R.K. Srivastava, et al., Biorefineries development from agricultural by-products: value addition and circular bioeconomy, Sustainable Chemistry and Pharmacy 32 (2023) 100970, https://doi.org/10.1016/j.scp.2023.100970.
[3] Y. Bao, et al., Straw chemistry links the assembly of bacterial communities to decomposition in paddy soils, Soil Biol. Biochem. 148 (2020) 107866, https://doi.org/10.1016/j.soilbio.2020.107866.
[4] M.A. Iqbal, et al., Underutilized grasses production: new evolving perspectives. Grasses and Grassland: New Perspectives, 2022, p. 53.
[5] J. Wang, et al., Crop yield and soil organic matter after long-term straw return to soil in China, Nutrient Cycl. Agroecosyst. 102 (3) (2015) 371–381, https://doi.org/10.1016/j.scitotenv.2017.12.096.
[6] L. Xia, et al., Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems, Global Change Biol. 24 (12) (2018) 5919–5932, https://doi.org/10.1111/gcb.14466.
[7] M. Berhane, et al., Effects of long-term straw return on soil organic carbon storage and sequestration rate in North China upland crops: a meta-analysis, Global Change Biol. 26 (4) (2020) 2686–2701, https://doi.org/10.1111/gcb.15018.
[8] Y. Guan, et al., Effects of continuous straw returning on soil functional microorganisms and microbial communities, J. Microbiol. 61 (1) (2023) 49–62, https://doi.org/10.1007/s12275-022-00004-6.
[9] B.-J. Lin, et al., Management-induced changes in soil organic carbon and related crop yield dynamics in China's cropland, Global Change Biol. 29 (13) (2023) 3575–3590, https://doi.org/10.1111/gcb.16703.
[10] D. Li, et al., Bio-straw resource recycling systems: agricultural productivity and green development, Resour. Conserv. Recycl. 190 (2023) 106844, https://doi.org/10.1016/j.resconrec.2022.106844.
[11] G. He, T. Liu, M. Zhou, Straw burning, PM2.5, and death: evidence from China, J. Dev. Econ. 145 (2020) 102468, https://doi.org/10.1016/j.jdeveco.2020.102468.
[12] P. Bhattacharyya, et al., Turn the wheel from waste to wealth: economic and environmental gain of sustainable rice straw management practices over field burning in reference to India, Sci. Total Environ. 775 (2021) 145896, https://doi.org/10.1016/j.scitotenv.2021.145896.
[13] G.K. Porichha, et al., Crop residue management in India: stubble burning vs. other utilizations including bioenergy, Energies 14 (2021), https://doi.org/10.3390/en14144281.
[14] Z. Bai, et al., Effects of agricultural management practices on soil quality: a review of long-term experiments for Europe and China, Agric. Ecosyst. Environ. 265 (2018) 1–7, https://doi.org/10.1016/j.agee.2018.05.028.
[15] X. Chen, et al., Soil microbial communities under wheat and maize straw incorporation are closely associated with soil organic carbon fractions and chemical structure, Appl. Soil Ecol. 182 (2023) 104724, https://doi.org/10.1016/j.apsoil.2022.104724.
[16] G. Wu, et al., Straw return counteracts the negative effects of warming on microbial community and soil multifunctionality, Agric. Ecosyst. Environ. 352 (2023) 108508, https://doi.org/10.1016/j.agee.2023.108508.
[17] S. Wang, et al., The effect of corn straw return on corn production in Northeast China: an integrated regional evaluation with meta-analysis and system dynamics, Resour. Conserv. Recycl. 167 (2021) 105402, https://doi.org/10.1016/j.resconrec.2021.105402.
[18] M.U. Islam, et al., Does straw return increase crop yield in the wheat-maize cropping system in China? A meta-analysis, Field Crops Res. 279 (2022) 108447, https://doi.org/10.1016/j.fcr.2022.108447.
[19] H. Yin, et al., Balancing straw returning and chemical fertilizers in China: role of straw nutrient resources, Renew. Sustain. Energy Rev. 81 (2018) 2695–2702, https://doi.org/10.1016/j.rser.2017.06.076.
[20] W. Fan, et al., Short-term effects of different straw returning methods on the soil physicochemical properties and quality index in dryland farming in NE China, Sustainability 12 (2020), https://doi.org/10.3390/su12072631, 10.3390/su12072631.
[21] M. Zhuang, et al., Potential environmental benefits of substituting nitrogen and phosphorus fertilizer with useable crop straw in China during 2000–2017, J. Clean. Prod. 267 (2020) 122125, https://doi.org/10.1016/j.jclepro.2020.122125.
[22] S. Naz, et al., Agronomic crops: types and uses, in: M. Hasanuzzaman (Ed.), Agronomic Crops: Volume 1: Production Technologies, Springer Singapore, Singapore, 2019, pp. 1–18, https://doi.org/10.1007/978-981-32-9151-5_1.
[23] Y. Cheng, et al., Enhanced cornstalk decomposition by a psychrotrophic bacterial consortium comprising cellulose, hemicellulose, and lignin degraders with biochar as a carrier for carbon neutrality, Bioresour. Technol. 344 (2022) 126259, https://doi.org/10.1016/j.biortech.2021.126259.

[24] J.M. Talbot, K.K. Treseder, Interactions among lignin, cellulose, and nitrogen drive litter chemistry–decay relationships, Ecology 93 (2) (2012) 345–354, https://doi.org/10.1890/11-0843.1.
[25] X. Wang, et al., The composition characteristics of different crop straw types and their multivariate analysis and comparison, Waste Manag. 110 (2020) 87–97, https://doi.org/10.1016/j.wasman.2020.05.018.
[26] J.N. Putro, et al., Pre-treatment and conversion of lignocellulose biomass into valuable chemicals, RSC Adv. 6 (52) (2016) 46834–46852, https://doi.org/10.1039/C6RA09851G.
[27] V. Ninkuu, et al., Mitigating biomass recalcitrance for plant-based bioenergy production, Mod. Agric. 1 (2) (2023) 122–141, https://doi.org/10.1002/moda.21.
[28] Y.-H.P. Zhang, L.R. Lynd, Toward an aggregated understanding of enzymatic hydrolysis of cellulose: noncomplexed cellulase systems, Biotechnol. Bioeng. 88 (7) (2004) 797–824, https://doi.org/10.1002/bit.20282.
[29] M. Wojtusik, et al., Enzymatic hydrolysis of several pretreated lignocellulosic biomasses: fractal kinetic modeling, Bioresour. Technol. 318 (2020) 124050, https://doi.org/10.1016/j.biortech.2020.124050.
[30] A.K. Chandel, et al., The path forward for lignocellulose biorefineries: bottlenecks, solutions, and perspective on commercialization, Bioresour. Technol. 264 (2018) 370–381, https://doi.org/10.1016/j.biortech.2018.06.004.
[31] P. McKendry, Energy production from biomass (part 1): overview of biomass, Bioresour. Technol. 83 (1) (2002) 37–46, https://doi.org/10.1016/S0960-8524(01)00118-3.
[32] M. Thatiane Rodrigues, et al., Plant cell wall composition and enzymatic deconstruction, AIMS Bioengineering 5 (1) (2018) 63–77, https://doi.org/10.3934/bioeng.2018.1.63.
[33] A. Ebringerová, Z. Hromádková, T. Heinze, Hemicellulose, in: T. Heinze (Ed.), Polysaccharides I: Structure, Characterization and Use, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 1–67, https://doi.org/10.1007/b136816.
[34] T.J. Simmons, et al., Folding of xylan onto cellulose fibrils in plant cell walls revealed by solid-state NMR, Nat. Commun. 7 (2016) 13902, https://doi.org/10.1038/ncomms13902.
[35] M.J. Selig, et al., The impact of cell wall acetylation on corn stover hydrolysis by cellulolytic and xylanolytic enzymes, Cellulose 16 (2009) 711–722, https://doi.org/10.1155/2023/8899956.
[36] Z.-H. Liu, et al., Defining lignin nanoparticle properties through tailored lignin reactivity by sequential organosolv fragmentation approach (SOFA), Green Chem. 21 (2) (2019) 245–260, https://doi.org/10.1039/C8GC03290D.
[37] M. Kosa, A.J. Ragauskas, Lignin to lipid bioconversion by oleaginous Rhodococci, Green Chem. 15 (8) (2013) 2070–2074, https://doi.org/10.1039/C3GC40434J.
[38] N. Mahmood, et al., Depolymerization of lignins and their applications for the preparation of polyols and rigid polyurethane foams: a review, Renew. Sustain. Energy Rev. 60 (2016) 317–329, https://doi.org/10.1016/j.rser.2016.01.037.
[39] V. Ninkuu, et al., Lignin and its pathway-associated phytoalexins modulate plant defense against fungi, Journal of Fungi 9 (2023), https://doi.org/10.3390/jof9010052.
[40] L. Singh, B.S. Brar, A review on rice straw management strategies, Nat. Environ. Pollut. Technol. 20 (4) (2021) 1485–1493, https://doi.org/10.46488/NEPT.2021.v20i04.010.
[41] S. Sarkar, et al., Management of crop residues for improving input use efficiency and agricultural sustainability, Sustainability 12 (2020), https://doi.org/10.3390/su12239808, 10.3390/su12239808.
[42] D. Abalos, et al., A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues, Sci. Total Environ. 828 (2022) 154388, https://doi.org/10.1016/j.scitotenv.2022.154388.
[43] N. Jain, A. Bhatia, H. Pathak, Emission of air pollutants from crop residue burning in India, Aerosol Air Qual. Res. 14 (1) (2014) 422–430, https://doi.org/10.4209/aaqr.2013.01.0031.
[44] M. Lin, T. Begho, Crop residue burning in South Asia: a review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses, J. Environ. Manag. 314 (2022) 115104, https://doi.org/10.1016/j.jenvman.2022.115104.
[45] S. Singh P, G. Singh, G.P.S. Sodhi, Energy and carbon footprints of wheat establishment following different rice residue management strategies vis-à-vis conventional tillage coupled with rice residue burning in north-western India, Energy 200 (2020) 117554, https://doi.org/10.1016/j.energy.2020.117554.
[46] R. Sharma, et al., Inferring air pollution from air quality index by different geographical areas: case study in India, Air Quality, Atmosphere & Health 12 (11) (2019) 1347–1357, https://doi.org/10.1016/j.scp.2023.100970.
[47] A.P. Cracknell, M.R. Saradjian, Monitoring of straw burning in the UK using AVHRR data—summer 1995, Int. J. Rem. Sens. 17 (12) (1996) 2463–2466, https://doi.org/10.1080/01431169608948784.
[48] C.C. Launio, et al., Economic analysis of rice straw management alternatives and understanding farmers' choices, in: D. James, H.A. Francisco (Eds.), Cost-Benefit Studies of Natural Resource Management in Southeast Asia, Springer Singapore, Singapore, 2015, pp. 93–111, https://doi.org/10.1007/978-981-287-393-4_5.
[49] H. Li, et al., Current status and environment impact of direct straw return in China's cropland – a review, Ecotoxicol. Environ. Saf. 159 (2018) 293–300, https://doi.org/10.1016/j.ecoenv.2018.05.014.
[50] W. Zheng, B. Luo, Understanding pollution behavior among farmers: exploring the influence of social networks and political identity on reducing straw burning in China, Energy Res. Social Sci. 90 (2022) 102553, https://doi.org/10.1016/j.erss.2022.102553.
[51] N. Kamaliah, et al., Evaluating the experimental cultivation of edible mushroom, Volvariella volvacea underneath tree canopy in tropical agroforestry systems, Agrofor. Syst. 96 (1) (2022) 35–47, https://doi.org/10.1007/s10457-021-00685-9.
[52] Y. Li, et al., Addition of cellulose-degrading bacterial agents promoting keystone fungal-mediated cellulose degradation during aerobic composting: construction the complex co-degradation system, Bioresour. Technol. 381 (2023) 129132, https://doi.org/10.1016/j.biortech.2023.129132.
[53] K. Wang, et al., Seasonal temporal characteristics of in situ straw decomposition in different types and returning methods, J. Soil Sci. Plant Nutr. 22 (4) (2022) 4228–4240, https://doi.org/10.1007/s42729-022-01021-5.
[54] G. Janusz, et al., Lignin degradation: microorganisms, enzymes involved, genomes analysis and evolution, FEMS (Fed. Eur. Microbiol. Soc.) Microbiol. Rev. 41 (6) (2017) 941–962, https://doi.org/10.1093/femsre/fux049.
[55] J. Changsheng, Y. Jianhong, X. Deti, Decay of organic materials in newly-weathered purple rock fragments and its adjustment, Xinan Nongye Daxue Xuebao (China), J. Southwest Agricultural University (2001). https://api.semanticscholar.org/CorpusID:131387031. Accessed 2025.01.03.
[56] Y. Jiang, Z. Yu, Y. Ma, The effect of stubble return on agro-ecological system and crop growth, Chinese Journal of Soil Science 32 (5) (2001) 209–213.
[57] Z. Dai, *Study on Nutrient Release Characteristics of Crop Residue and Effect of Crop Residue Returning on Crop Yield and Soil Fertility.* PhD, Huazhong Agricultural University, 2009 (in Chinese).
[58] Y. Wang, et al., Nutrient recycling, wheat straw decomposition, and the potential effect of straw shear strength on soil mechanical properties, Agronomy 10 (2020), https://doi.org/10.3390/agronomy10020314, 10.3390/agronomy10020314.
[59] R. Bu, et al., Tillage and straw-returning practices effect on soil dissolved organic matter, aggregate fraction and bacteria community under a rice-rice-rapeseed rotation system, Agric. Ecosyst. Environ. 287 (2020) 106681, https://doi.org/10.1016/j.agee.2019.106681.
[60] Q. Rong, et al., An enhanced export coefficient based optimization model for supporting agricultural nonpoint source pollution mitigation under uncertainty, Sci. Total Environ. 580 (2017) 1351–1362, https://doi.org/10.1016/j.scitotenv.2016.12.099.
[61] X. Xia, et al., Effects of tillage managements and maize straw returning on soil microbiome using 16S rDNA sequencing, J. Integr. Plant Biol. 61 (6) (2019) 765–777, https://doi.org/10.1016/j.still.2023.105652.
[62] L.B. Martínez-García, et al., Organic management and cover crop species steer soil microbial community structure and functionality along with soil organic matter properties, Agric. Ecosyst. Environ. 263 (2018) 7–17, https://doi.org/10.1016/j.agee.2018.04.018.

[63] P. Chaudhary, et al., Application of synthetic consortia for improvement of soil fertility, pollution remediation, and agricultural productivity: a review, Agronomy 13 (2023), https://doi.org/10.3390/agronomy13030643.
[64] E. Wang, et al., Effects of short-term rice straw return on the soil microbial community, Agriculture 11 (2021), https://doi.org/10.3390/agriculture11060561.
[65] J. Tingxiang, The present research situation and control countermeasure of root rots in wheat, Sci. Agric. Sin. (1995), https://doi.org/10.3969/j.issn.1008-7303.2014.03.05.
[66] Y. W. Zhen Qi, H. Li, Allelopathy of decomposed maize straw products on three soil-born diseases of wheat and the analysis by GC-MS, J. Integr. Agric. 14 (1) (2015) 88–97, https://doi.org/10.1016/S2095-3119(14)60795-4.
[67] X. Zhang, Y. Cao, K. Cao, Management of wheat soil-borne diseases under the conservative farming system, Journal of Northwest A&F University (Natural Science Edition) 33 (2005) 47–48.
[68] W. Zhen, et al., Influence of maize straw amendment on soil-borne diseases of winter wheat, Front. Agric. China 3 (2009) 7–12, https://doi.org/10.1007/s11703-009-0003-4.
[69] B. Govaerts, et al., Infiltration, soil moisture, root rot, and nematode populations after 12 years of different tillage, residue, and crop rotation managements, Soil Tillage Res. 94 (1) (2007) 209–219, https://doi.org/10.1016/j.still.2006.07.013.
[70] Y. Su, et al., Long-term decomposed straw return positively affects the soil microbial community, J. Appl. Microbiol. 128 (1) (2020) 138–150, https://doi.org/10.1111/jam.14435.
[71] Y. Zhong, et al., Microbial community assembly and metabolic function during wheat straw decomposition under different nitrogen fertilization treatments, Biol. Fertil. Soils 56 (5) (2020) 697–710, https://doi.org/10.1007/s00374-020-01438-z.
[72] Z. Jin, et al., Effect of straw returning on soil organic carbon in rice–wheat rotation system: a review, Food Energy Secur. 9 (2) (2020) e200, https://doi.org/10.1002/fes3.200.
[73] Y. Wei, et al., Improved lignocellulose-degrading performance during straw composting from diverse sources with actinomycetes inoculation by regulating the key enzyme activities, Bioresour. Technol. 271 (2019) 66–74, https://doi.org/10.1016/j.biortech.2018.09.081.
[74] K. Song, et al., Effects of rumen microorganisms on straw returning to soil at different depths, Eur. J. Soil Biol. 114 (2023) 103454, https://doi.org/10.1016/j.ejsobi.2022.103454.
[75] S.F.M. Wahdan, et al., Future climate conditions accelerate wheat straw decomposition alongside altered microbial community composition, assembly patterns, and interaction networks, ISME J. 17 (2) (2023) 238–251, https://doi.org/10.1038/s41396-022-01336-2.
[76] M. Sohail, et al., Cellulase production from Aspergillus Niger MS82: effect of temperature and pH, N. Biotech. 25 (6) (2009) 437–441, https://doi.org/10.1016/j.nbt.2009.02.002.
[77] I.S. Druzhinina, C.P. Kubicek, Genetic engineering of Trichoderma reesei cellulases and their production, Microb. Biotechnol. 10 (6) (2017) 1485–1499, https://doi.org/10.1111/1751-7915.12726.
[78] Y. Xia, X. Lin, Efficient biodegradation of straw and persistent organic pollutants by a novel strategy using recombinant Trichoderma reesei, Bioresources and Bioprocessing 9 (1) (2022) 91, https://doi.org/10.1186/s40643-022-00581-9.
[79] L. Wang, et al., Exogenous microbial antagonism affects the bioaugmentation of humus formation under different inoculation using Trichoderma reesei and Phanerochaete chrysosporium, Bioresour. Technol. 373 (2023) 128717, https://doi.org/10.1016/j.biortech.2023.128717.
[80] N. Bansal, et al., Production of cellulases from Aspergillus Niger NS-2 in solid state fermentation on agricultural and kitchen waste residues, Waste Manag. 32 (7) (2012) 1341–1346, https://doi.org/10.1016/j.wasman.2012.03.006.
[81] D.B. Wilson, Microbial diversity of cellulose hydrolysis, Curr. Opin. Microbiol. 14 (3) (2011) 259–263, https://doi.org/10.1016/j.mib.2011.04.004.
[82] S. Jayasekara, R. Ratnayake, Microbial cellulases: an overview and applications, Cellulose 22 (2019) 92.
[83] S. Thapa, et al., Microbial cellulolytic enzymes: diversity and biotechnology with reference to lignocellulosic biomass degradation, Rev. Environ. Sci. Biotechnol. 19 (3) (2020) 621–648, https://doi.org/10.1007/s11157-020-09536-y.
[84] A.L. Benatti, The main players involved in multiple biotechnological processes for biomass valorization, Microorganisms 11 (2023), https://doi.org/10.1016/j.jgeb.2016.12.001. M.D. Polizeli *Lignocellulolytic Biocatalysts*.
[85] H.L. Woo, et al., Enzyme activities of aerobic lignocellulolytic bacteria isolated from wet tropical forest soils, Syst. Appl. Microbiol. 37 (1) (2014) 60–67, https://doi.org/10.1016/j.syapm.2013.10.001.
[86] B.C. Behera, et al., Microbial cellulases - diversity & biotechnology with reference to mangrove environment: a review, J. Genet. Eng. Biotechnol. 15 (1) (2017) 197–210, https://doi.org/10.1016/j.jgeb.2016.12.001.
[87] J.D. Harindintwali, et al., Biotechnological potential of cellulolytic nitrogen-fixing Klebsiella sp. C-3 isolated from paddy soil, Bioresour. Technol. Rep. 13 (2021) 100624, https://doi.org/10.1016/j.biteb.2021.100624.
[88] J.D. Harindintwali, J. Zhou, X. Yu, Lignocellulosic crop residue composting by cellulolytic nitrogen-fixing bacteria: a novel tool for environmental sustainability, Sci. Total Environ. 715 (2020) 136912, https://doi.org/10.1016/j.scitotenv.2020.136912.
[89] W. Ahmed, et al., Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils, J. Soils Sediments 20 (2) (2020) 850–861, https://doi.org/10.1007/s11368-019-02468-3.
[90] M. Hao, et al., Shifts in microbial community and carbon sequestration in farmland soil under long-term conservation tillage and straw returning, Appl. Soil Ecol. 136 (2019) 43–54, https://doi.org/10.1016/j.apsoil.2018.12.016.
[91] B. Mary, et al., Interactions between decomposition of plant residues and nitrogen cycling in soil, Plant Soil 181 (1) (1996) 71–82, https://doi.org/10.1007/BF00011294.
[92] V. Ninkuu, Z. Liu, X. Sun, Genetic regulation of nitrogen use efficiency in Gossypium spp, Plant Cell Environ. 46 (6) (2023) 1749–1773, https://doi.org/10.1111/pce.14586.
[93] O.O. Aluko, Z. Liu, X. Sun, The interplay of carbon and nitrogen distribution: prospects for improved crop yields, Mod. Agric. 1 (2023) 57–75, https://doi.org/10.1002/moda.7.
[94] V. Ninkuu, et al., Regulation of nitrogen metabolism by COE2 under low sulfur stress in Arabidopsis, Plant Sci. 346 (2024) 112137, https://doi.org/10.1016/j.plantsci.2024.112137.
[95] T. Huang, et al., Soil organic carbon, total nitrogen, available nutrients, and yield under different straw returning methods, Soil Tillage Res. 214 (2021) 105171, https://doi.org/10.1016/j.still.2021.105171.
[96] X. Yan, et al., Carbon sequestration efficiency in paddy soil and upland soil under long-term fertilization in southern China, Soil Tillage Res. 130 (2013) 42–51, https://doi.org/10.1016/j.still.2013.01.013.
[97] L. Zhu, et al., Short-term responses of soil organic carbon and carbon pool management index to different annual straw return rates in a rice–wheat cropping system, Catena 135 (2015) 283–289, https://doi.org/10.1016/j.catena.2015.08.008.
[98] K. Tian, et al., Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: a meta-analysis, Agric. Ecosyst. Environ. 204 (2015) 40–50, https://doi.org/10.1016/j.agee.2015.02.008.
[99] S. Li, et al., Effect of straw management on carbon sequestration and grain production in a maize–wheat cropping system in Anthrosol of the Guanzhong Plain, Soil Tillage Res. 157 (2016) 43–51, https://doi.org/10.1016/j.still.2015.11.002.
[100] S. Zhao, et al., Changes in soil microbial community, enzyme activities and organic matter fractions under long-term straw return in north-central China, Agric. Ecosyst. Environ. 216 (2016) 82–88, https://doi.org/10.1016/j.agee.2015.09.028.
[101] W. Huang, et al., Effects of long-term straw return on soil organic carbon fractions and enzyme activities in a double-cropped rice paddy in South China, J. Integr. Agric. 20 (1) (2021) 236–247, https://doi.org/10.1016/S2095-3119(20)63347-0.
[102] M. Xu, et al., Soil organic carbon active fractions as early indicators for total carbon change under straw incorporation, Biol. Fertil. Soils 47 (7) (2011) 745–752, https://doi.org/10.1007/s00374-011-0579-8.
[103] S. Yan, et al., Changes in soil organic carbon fractions and microbial community under rice straw return in Northeast China, Global Ecology and Conservation 22 (2020) e00962, https://doi.org/10.1007/s10705-019-09999-8.

[104] X. Wang, et al., Response of soil denitrification potential and community composition of denitrifying bacterial to different rates of straw return in north-central China, Appl. Soil Ecol. 170 (2022) 104312, https://doi.org/10.1016/j.apsoil.2021.104312.
[105] Z. Li, et al., Neoformed aluminosilicate and phytogenic silica are competitive sinks in the silicon soil–plant cycle, Geoderma 368 (2020) 114308, https://doi.org/10.1016/j.biortech.2018.02.028.
[106] A. Song, et al., Soil bacterial communities interact with silicon fraction transformation and promote rice yield after long-term straw return, Soil Ecology Letters 3 (4) (2021) 395–408, https://doi.org/10.1371/journal.pone.0102681.
[107] D. Xu, et al., Silicon addition improves plant productivity and soil nutrient availability without changing the grass: legume ratio response to N fertilization, Sci. Rep. 10 (1) (2020) 10295, https://doi.org/10.1038/s41598-020-67333-7.
[108] A. Song, et al., The alleviation of zinc toxicity by silicon is related to zinc transport and antioxidative reactions in rice, Plant Soil 344 (1) (2011) 319–333, https://doi.org/10.1007/s11104-011-0749-3.
[109] D. Ning, et al., Effects of slag-based silicon fertilizer on rice growth and Brown-spot resistance, PLoS One 9 (7) (2014) e102681, https://doi.org/10.1371/journal.pone.0102681.
[110] J. Cooke, M.R. Leishman, Consistent alleviation of abiotic stress with silicon addition: a meta-analysis, Funct. Ecol. 30 (8) (2016) 1340–1357, https://doi.org/10.1111/1365-2435.12713.
[111] D. Coskun, et al., The controversies of silicon's role in plant biology, New Phytol. 221 (1) (2019) 67–85, https://doi.org/10.1038/s41396-019-0375-2.
[112] J. Wang, et al., Individual and combined effects of enrofloxacin and cadmium on soil microbial biomass and the ammonia-oxidizing functional gene, Sci. Total Environ. 624 (2018) 900–907, https://doi.org/10.1016/j.scitotenv.2017.12.096.
[113] G. Dziubanek, et al., Cadmium in edible plants from Silesia, Poland, and its implications for health risk in populations, Ecotoxicol. Environ. Saf. 142 (2017) 8–13, https://doi.org/10.1016/j.ecoenv.2017.03.048.
[114] C. Li, et al., A review on heavy metals contamination in soil: effects, sources, and remediation techniques, Soil Sediment Contam.: Int. J. 28 (4) (2019) 380–394, https://doi.org/10.1080/15320383.2019.1592108.
[115] P.K. Singh, D. Shikha, S. Saw, Evaluation of potential toxic heavy metal contamination in soil, fly ash, vegetables and grain crops along with associated ecological and health risk assessment of nearby inhabitants of a thermal power station in Jharkhand (India), Environ. Sci. Pollut. Control Ser. 30 (3) (2023) 7752–7769, https://doi.org/10.1007/s11356-022-22638-0.
[116] C. Wang, et al., Human health risks of polycyclic aromatic hydrocarbons in the urban soils of Nanjing, China, Sci. Total Environ. 612 (2018) 750–757, https://doi.org/10.1016/j.scitotenv.2017.08.269.
[117] N.A. Bhat, et al., Heavy metal contamination in soils and stream water in Tungabhadra basin, Karnataka: environmental and health risk assessment, Int. J. Environ. Sci. Technol. 20 (3) (2023) 3071–3084, https://doi.org/10.1007/s13762-022-04040-y.
[118] P. Xu, et al., The effect of biochar and crop straws on heavy metal bioavailability and plant accumulation in a Cd and Pb polluted soil, Ecotoxicol. Environ. Saf. 132 (2016) 94–100, https://doi.org/10.1016/j.ecoenv.2016.05.03.
[119] C. Fang, et al., Combined utilization of Chinese milk vetch, rice straw, and lime reduces soil available Cd and Cd accumulation in rice grains, Agronomy 13 (2023), https://doi.org/10.3390/agronomy13030910.
[120] Y. Yang, et al., Limestone dosage response of cadmium phytoavailability minimization in rice: a trade-off relationship between soil pH and amorphous manganese content, J. Hazard Mater. 403 (2021) 123664, https://doi.org/10.1016/j.jhazmat.2020.123664.
[121] G. Huang, et al., Polymer-coated manganese fertilizer and its combination with lime reduces cadmium accumulation in brown rice (Oryza sativa L.), J. Hazard Mater. 415 (2021) 125597, https://doi.org/10.1016/j.jhazmat.2021.125597.
[122] Y. Liu, et al., Variation of Cd and as accumulation in crops under oilseed rape–rice rotation system in response to different contaminated rice straw-return methods, Plant Soil (2023).
[123] J. Buates, T. Imai, Biochar functionalized with layered double hydroxides improve physicochemical properties of growing media, J. Plant Nutr. (2023) 1–16, https://doi.org/10.1080/01904167.2023.2203169.
[124] X. Yang, Q. Zhang, S.J. Ergas, Enhancement of the system and environmental performance of high solids anaerobic digestion of lignocellulosic banana waste by biochar addition, Sustainability 15 (2023), https://doi.org/10.3390/su15086832.
[125] M.A. Ashraf, et al., Effect of exogenous taurine on pea (Pisum sativum L.) plants under salinity and iron deficiency stress, Environ. Res. 223 (2023) 115448, https://doi.org/10.1016/j.envres.2023.115448.
[126] W. Seifu, et al., Characterization and mapping of soil-landscape for site-specific soil management in Ayiba Watershed, Northern highlands of Ethiopia, Applied and Environmental Soil Science 2023 (2023) 8899956, https://doi.org/10.1155/2023/8899956.
[127] Z. Hanlin, et al., Effects of straw returning and fertilization on soil bacterial and fungal community structures and diversities in rice-wheat rotation soil, Chin. J. Eco-Agric. 29 (3) (2021) 531, https://doi.org/10.13930/j.cnki.cjea.200502.
[128] E. Tavakkoli, P. Rengasamy, G.K. McDonald, High concentrations of Na+ and Cl– ions in soil solution have simultaneous detrimental effects on growth of faba bean under salinity stress, J. Exp. Bot. 61 (15) (2010) 4449–4459, https://doi.org/10.1093/jxb/erq251.
[129] C. Ran, et al., Straw return alleviates the negative effects of saline sodic stress on rice by improving soil chemistry and reducing the accumulation of sodium ions in rice leaves, Agric. Ecosyst. Environ. 342 (2023) 108253, https://doi.org/10.1016/j.agee.2022.108253.
[130] C. Yan, et al., Decomposition characteristics of rice straw returned to the soil in northeast China, Nutrient Cycl. Agroecosyst. 114 (3) (2019) 211–224, https://doi.org/10.1007/s10705-019-09999-8.
[131] Y. Zhao, et al., Effects of straw layer and flue gas desulfurization gypsum treatments on soil salinity and sodicity in relation to sunflower yield, Geoderma 352 (2019) 13–21, https://doi.org/10.1016/j.geoderma.2019.06.004.
[132] S. Ma, et al., Effects of straw return mode on soil aggregates and associated carbon in the north China plain, Agronomy 10 (2020), https://doi.org/10.3390/agronomy10010061.
[133] H. Lian, et al., Straw strip return increases soil organic carbon sequestration by optimizing organic and humus carbon in aggregates of mollisols in Northeast China, Agronomy 12 (2022), https://doi.org/10.3390/agronomy12040784.
[134] C. Li, C. Zhang, Effects of straw returning on paddy soil environmental remediation, in: Proceedings of the 2022 12th International Conference on Environment Science and Engineering (ICESE 2022), Springer Nature Singapore, Singapore, 2023, https://doi.org/10.3390/plants12112071.
[135] X. Meng, et al., Straw incorporation helps inhibit nitrogen leaching in maize season to increase yield and efficiency in the Loess Plateau of China, Soil Tillage Res. 211 (2021) 105006, https://doi.org/10.1016/j.still.2021.105006.
[136] X. Zhao, et al., Effects of full straw incorporation on soil fertility and crop yield in rice-wheat rotation for silty clay loamy cropland, Agronomy 9 (2019), https://doi.org/10.3390/agronomy9030133.
[137] G. Brankatschk, M. Finkbeiner, Modeling crop rotation in agricultural LCAs — challenges and potential solutions, Agric. Syst. 138 (2015) 66–76, https://doi.org/10.1016/j.agsy.2015.05.008.
[138] Y. Lou, et al., Straw coverage alleviates seasonal variability of the topsoil microbial biomass and activity, Catena 86 (2) (2011) 117–120, https://doi.org/10.1016/j.catena.2011.03.006.
[139] A.A. Jacobs, et al., Cover crops and no-tillage reduce crop production costs and soil loss, compensating for lack of short-term soil quality improvement in a maize and soybean production system, Soil Tillage Res. 218 (2022) 105310, https://doi.org/10.1016/j.still.2021.105310.
[140] P. Ruisi, et al., Long-term effects of no tillage treatment on soil N availability, N uptake, and 15N-fertilizer recovery of durum wheat differ in relation to crop sequence, Field Crops Res. 189 (2016) 51–58, https://doi.org/10.1016/j.fcr.2016.02.009.
[141] Y. Liao, et al., By increasing infiltration and reducing evaporation, mulching can improve the soil water environment and apple yield of orchards in semiarid areas, Agric. Water Manag. 253 (2021) 106936, https://doi.org/10.1016/j.agwat.2021.106936.
[142] H. Yang, et al., Maize straw mulching with no-tillage increases fertile spike and grain yield of dryland wheat by regulating root-soil interaction and nitrogen nutrition, Soil Tillage Res. 228 (2023) 105652, https://doi.org/10.1016/j.still.2023.105652.

[143] S.S. Abuzahrah, A. Akhdhar, M.N. Baeshen, Studying the impact of physicochemical parameters in marine sediments, J. Pharm. Negat. Results (2023) 539–558, https://doi.org/10.47750/pnr.2023.14.S02.67.
[144] S.S. Abuzahrah, A. Akhdhar, M.N. Baeshen, Studying the impact of physicochemical parameters in marine sediments, J. Pharm. Negat. Results (2023) 539–558, https://doi.org/10.47750/pnr.2023.14.S02.67.
[145] C. Liu, et al., Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis, Global Change Biol. 20 (5) (2014) 1366–1381, https://doi.org/10.1111/gcb.12517.
[146] J. Zhao, et al., Effects of straw returning and residue cleaner on the soil moisture content, soil temperature, and maize emergence rate in China's three major maize producing areas, Sustainability 11 (2019), https://doi.org/10.3390/su11205796.
[147] L. Ma, et al., Growth and yield of cotton as affected by different straw returning modes with an equivalent carbon input, Field Crops Res. 243 (2019) 107616, https://doi.org/10.1016/j.fcr.2019.107616.
[148] H. Li, et al., Response of soil nutrients retention and rice growth to biochar in straw returning paddy fields, Chemosphere 312 (2023) 137244, https://doi.org/10.1016/j.chemosphere.2022.137244.
[149] W. Mi, et al., Higher yield sustainability and soil quality by manure amendment than straw returning under a single-rice cropping system, Field Crops Res. 292 (2023) 108805, https://doi.org/10.1016/j.fcr.2022.108805.
[150] X. Wang, et al., Effects of potassium fertilizer and straw on maize yield, potassium utilization efficiency, and soil potassium balance, Arch. Agron Soil Sci. 69 (5) (2023) 679–692, https://doi.org/10.1080/03650340.2022.2025997.
[151] V. Ninkuu, et al., Biochemistry of terpenes and recent advances in plant protection, Int. J. Mol. Sci. 22 (2021), https://doi.org/10.3390/ijms22115710.
[152] V. Ninkuu, et al., Hrip1 mediates rice cell wall fortification and phytoalexins elicitation to confer immunity against Magnaporthe oryzae, Front. Plant Sci. 13 (2022) 980821, https://doi.org/10.3389/fpls.2022.980821.
[153] M.M.G. Saad, N.A.A. Gouda, S.A.M. Abdelgaleil, Bioherbicidal activity of terpenes and phenylpropenes against Echinochloa crus-galli, Journal of Environmental Science and Health, Part B 54 (12) (2019) 954–963, https://doi.org/10.1080/03601234.2019.1653121.
[154] L. Mahaut, et al., Weeds: against the rules? Trends Plant Sci. 25 (11) (2020) 1107–1116, https://doi.org/10.1016/j.tplants.2020.05.013.
[155] L. Guo, et al., Echinochloa crus-galli genome analysis provides insight into its adaptation and invasiveness as a weed, Nat. Commun. 8 (1) (2017) 1031, https://doi.org/10.1038/s41467-017-01067-5.
[156] M. Sue, M. Fujii, T. Fujimaki, Increased benzoxazinoid (Bx) levels in wheat seedlings via jasmonic acid treatment and etiolation and their effects on Bx genes including Bx6, Biochemistry and Biophysics Reports 27 (2021) 101059, https://doi.org/10.1016/j.bbrep.2021.101059.
[157] V. Ninkuu, et al., Genome-wide identification, phylogenomics, and expression analysis of benzoxazinoids gene family in rice (Oryza sativa), Plant Stress 10 (2023) 100214, https://doi.org/10.1016/j.stress.2023.100214.
[158] S. Adhikary, Efficacy of rice-stubble allelochemicals on vegetative growth parameters of some oil-yielding crops, International Journal of Trend in Scientific Research and Development 3 (2) (2019) 2456–6470, https://doi.org/10.31142/ijtsrd20251.
[159] P. Su, et al., An evaluation of a microbial inoculum in promoting organic C decomposition in a paddy soil following straw incorporation, J. Soils Sediments 16 (6) (2016) 1776–1786, https://doi.org/10.1007/s11368-015-1340-y.
[160] A. Khaliq, et al., Effect of crop residues applied isolated or in combination on the germination and seedling growth of horse purslane (Trianthema portulacastrum), Planta Daninha 29 (2011) 121–128, https://doi.org/10.1590/S0100-83582011000100014.
[161] Y. Chang-Bing, et al., Allelopathic effect of rice straw on rape(*Brassica napus L.*) seedlings, J. Agric. Resour. Econ. 33 (3) (2016) 253–261, https://doi.org/10.13254/j.jare.2015.0208.
[162] J. Ko, et al., Allelopathy of Rice Husk on Barnyardgrass, Journal of Agronomy, 2005.
[163] C.H. Kong, et al., Allelochemicals released by rice roots and residues in soil, Plant Soil 288 (1) (2006) 47–56, https://doi.org/10.1007/s11104-006-9033-3.
[164] A.H.C. van Bruggen, A. Gamliel, M.R. Finckh, Plant disease management in organic farming systems, Pest Manag. Sci. 72 (1) (2016) 30–44, https://doi.org/10.1002/ps.4145.
[165] J. Su, et al., Genetics of resistance to common root rot (spot blotch), Fusarium crown rot, and sharp eyespot in wheat, Front. Genet. 12 (2021) 699342, https://doi.org/10.3389/fgene.2021.699342.
[166] H. Martin, Management of soilborne diseases of beetroot in Australia: a review, Aust. J. Exp. Agric. 43 (11) (2003) 1281–1292, https://doi.org/10.1071/EA02150.
[167] F. Yu, et al., Does straw returning affect the root rot disease of crops in soil? A systematic review and meta-analysis, J. Environ. Manag. 336 (2023) 117673, https://doi.org/10.1016/j.jenvman.2023.117673.
[168] P. Chitrampalam, N. Abraham, B.D. Nelson, A culture-independent PCR-based assay to detect the root rot pathogen Fusarium solani species complex 11 from soybean roots and soil, Plant Dis. 102 (2) (2017) 327–333, https://doi.org/10.1094/PDIS-03-17-0447-RE.
[169] C. Zhang, et al., Straw retention efficiently improves fungal communities and functions in the fallow ecosystem, BMC Microbiol. 21 (1) (2021) 52, https://doi.org/10.1186/s12866-021-02115-3.
[170] L. Tang, et al., Wheat straw increases the defense response and resistance of watermelon monoculture to Fusarium wilt, BMC Plant Biol. 19 (1) (2019) 551, https://doi.org/10.1186/s12870-019-2134-y.
[171] C. Booij, J. Noorlander, J. Theunissen, Intercropping cabbage with clover: effects on ground beetles, Biol. Agric. Hortic. 15 (1–4) (1997) 261–268, https://doi.org/10.1080/01448765.1997.9755201.
[172] J.R. Prasifka, et al., Effects of living mulches on predator abundance and sentinel prey in a corn–soybean–forage rotation, Environ. Entomol. 35 (5) (2006) 1423–1431, https://doi.org/10.1093/ee/35.5.1423.
[173] G. Seimandi-Corda, et al., Companion plants and straw mulch reduce cabbage stem flea beetle damage on oilseed rape, Pest Manag. Sci. 80 (5) (2024) 2333–2341, https://doi.org/10.1002/ps.7641.
[174] K.A. Stoner, et al., Effects of straw mulch, spent mushroom compost, and fumigation on the density of Colorado potato beetles (Coleoptera: chrysomelidae) in potatoes, J. Econ. Entomol. 89 (5) (1996) 1267–1280, https://doi.org/10.1093/jee/89.5.1267.
[175] S.M. Kirchner, et al., Comparison of straw mulch, insecticides, mineral oil, and birch extract for control of transmission of potato virus Y in seed potato crops, Potato Res. 57 (1) (2014) 59–75, https://doi.org/10.1007/s11540-014-9254-4.
[176] H. Saucke, T.F. Döring, Potato virus Y reduction by straw mulch in organic potatoes, Ann. Appl. Biol. 144 (3) (2004) 347–355, https://doi.org/10.1111/j.1744-7348.2004.tb00350.x.
[177] S.K. Poonia, S.E. Topno, A. Kerketta, Integrated pest and disease management in cucumber and muskmelon, A Monthly Peer-Reviewed Magazine for Agriculture and Allied Sciences (2024) 1. https://theagricultureonline.com/wp-content/uploads/2024/03/February-2024-issue.pdf#page=16. Accessed: 2024.08.16.
[178] A. Ratnadass, et al., Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review, Agron. Sustain. Dev. 32 (2012) 273–303, https://doi.org/10.1007/s13593-011-0022-4.
[179] T. Kennedy, et al., A comparison of the occurrence of aphids and barley yellow dwarf virus in minimum-till and conventional-till autumn-sown cereals, J. Agric. Sci. 148 (4) (2010) 407–419, https://doi.org/10.1017/S0021859610000304.
[180] J. Stavisky, et al., Population dynamics of Frankliniella spp. and tomato spotted wilt incidence as influenced by cultural management tactics in tomato, J. Econ. Entomol. 95 (6) (2002) 1216–1221, https://doi.org/10.1603/0022-0493-95.6.1216.
[181] R.T.H. Wee, Biological and cultural control strategies for rice blast, Pyricularia oryzae(Cavara), sheath blight. Rhizoctonia solani(Kuhn), and Tungro Virus in Southeast Asia, Simon Fraser University, 2001.
[182] M. Sutton, N. Raghuram, T. Adhya, The nitrogen fix: from nitrogen cycle pollution to nitrogen circular economy, in: Frontiers Emerging Issues of Environmental Concern, United Nations Environment Programme, Nairobi, 2019. https://wedocs.unep.org/handle/20.500.11822/27543.
[183] Lucía Fernández, Global fertilizer market size in 2020 and 2021, with a forecast for 2030, in Monthly. 2022: statista.com. https://www.statista.com/statistics/1266004/global-fertilizer-market-size/.

[184] J.A. Harvey, et al., Scientists' warning on climate change and insects, Ecol. Monogr. 93 (1) (2023) e1553, https://doi.org/10.1002/ecm.1553.
[185] T.E.A. Cotton, et al., Metabolic regulation of the maize rhizobiome by benzoxazinoids, ISME J. 13 (7) (2019) 1647–1658, https://doi.org/10.1038/s41396-019-0375-2.
[186] L. Philippot, et al., Going back to the roots: the microbial ecology of the rhizosphere, Nat. Rev. Microbiol. 11 (11) (2013) 789–799, https://doi.org/10.1038/nrmicro3109.
[187] A. Poehlein, et al., First insights into the genome sequence of the cellulolytic bacterium Clostridium hungatei DSM 14427, Genome Announc. 5 (20) (2017) e00363, 17.
[188] B. Weselowski, et al., Isolation, identification and characterization of Paenibacillus polymyxa CR1 with potentials for biopesticide, biofertilization, biomass degradation, and biofuel production, BMC Microbiol. 16 (1) (2016) 244, https://doi.org/10.1186/s12866-016-0860-y.
[189] J. Stern, et al., Assembly of synthetic functional cellulosomal structures onto the cell surface of lactobacillus plantarum, a potent member of the gut microbiome, Appl. Environ. Microbiol. 84 (8) (2018) e00282, https://doi.org/10.1128/AEM.00282-18, 18.
[190] T. Ghosh, et al., Cleaning carbohydrate impurities from lignin using Pseudomonas fluorescens, Green Chem. 21 (7) (2019) 1648–1659, https://doi.org/10.1039/C8GC03341B.
[191] Y. Yang, et al., The composition of accessory enzymes of Penicillium chrysogenum P33 revealed by secretome and synergistic effects with commercial cellulase on lignocellulose hydrolysis, Bioresour. Technol. 257 (2018) 54–61, https://doi.org/10.1016/j.biortech.2018.02.028.
[192] E. Hareesh, P. Faisal, S. Benjamin, Optimization of parameters for the production of cellulase from Achromobacter xylosoxidans BSS4 by solid-state fermentation, Electron J Biol 12 (4) (2016). https://www.researchgate.net/publication/309407477.
[193] L. Cortes-Tolalpa, et al., Halotolerant microbial consortia able to degrade highly recalcitrant plant biomass substrate, Appl. Microbiol. Biotechnol. 102 (6) (2018) 2913–2927, https://doi.org/10.1007/s00253-017-8714-6.
[194] O.B. Chukwuma, et al., Isolation and characterization of lignocellulolytic bacteria from municipal solid waste landfill for identification of potential hydrolytic enzyme, Fermentation 9 (2023), https://doi.org/10.3390/fermentation9030298.
[195] D. Wu, et al., Strengthening Fenton-like reactions to improve lignocellulosic degradation performance by increasing lignocellulolytic enzyme core microbes during rice straw composting, Waste Manag. 161 (2023) 72–83, https://doi.org/10.1016/j.biortech.2018.09.081.
[196] J.K. Novak, J.G. Gardner, Galactomannan utilization by Cellvibrio japonicus relies on a single essential α-galactosidase encoded by the aga27A gene, Mol. Microbiol. 119 (3) (2023) 312–325. 10.1111/mmi.15024.
[197] Y. Wang, et al., Functioning of a tripartite lignocellulolytic microbial consortium cultivated under two shaking conditions: a metatranscriptomic study, Biotechnology for Biofuels and Bioproducts 16 (1) (2023) 54, https://doi.org/10.1111/jipb.12802.
[198] A. Shan, et al., Effects of straw return with N fertilizer reduction on crop yield, plant diseases and pests and potential heavy metal risk in a Chinese rice paddy: a field study of 2 consecutive wheat-rice cycles, Environ. Pollut. 288 (2021) 117741, https://doi.org/10.1016/j.envpol.2021.117741.
[199] L.J. Duczek, et al., Survival of leaf spot pathogens on crop residues of wheat and barley in Saskatchewan, J. Indian Dent. Assoc. 21 (2) (1999) 165–173, https://doi.org/10.1080/07060669909501208.