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REVIEW

How application of agricultural waste can enhance soil health in soils acidified by tea cultivation: a review

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Abstract

Tea is one of the world's most consumed beverages and an important crop of many developing countries. Intensive tea cultivation has negative impacts on soil health properties and the environment. While soil acidification in tea plantations is a known severe issue, there is a lack of literature analysis of the ways in which soil acidification affects soil health, tea productivity and the environment, and suitable methods to control this issue. Here, we review the mechanisms of tea soil acidification and consequences, the potential of common agricultural wastes for ameliorating soil acidity and enhancing soil health and crop productivity, as well as reducing environmental pollution under tea cultivation. We show that intensive application of mineral nitrogen is the main cause of soil acidification in tea plantations, while tea plants also play a part in accelerating tea soil acidity. Agricultural waste and byproducts have a great potential to correct soil acidity, and to enhance soil health, tea productivity and quality. These soil amendments also have drawbacks such as metal and pathogen pollution, and supplementary costs.

Keywords Agricultural waste · Soil acidification · Biochar · Organic manure · Soil health · Tea plantations

Introduction

Soil acidification has been a major threat to soil health and environmental sustainability in various agricultural systems and regions (Dai et al. 2017; Li et al. 2016; Yan et al. 2020), and occurs in many tea growing countries, such as China (Lin et al. 2019; Ni et al. 2018; Zou et al. 2014), India (Bandyopadhyay et al. 2014), Japan (Oh et al. 2006), Sri Lanka, Rwanda (Mupenzi et al. 2011) and Vietnam (Huu Chien et al. 2019). In China, the leading global tea producer and exporter, greater soil acidification occurred in tea plantations compared to other cash and cereal cropping systems, with 46% of tea plantations nationwide reporting soil pH below 4.5 (Yan et al. 2020). The reduction in the soil pH in tea plantations will have impacts of soil characteristics by changing soil chemical processes, resulting in soil nutrient losses and imbalance, and increasing occurrence of Al and Mn toxicity (Alekseeva et al. 2011; Ni et al. 2018; Yan et al. 2018). In addition, soil acidification significantly degrades the diversity and functionality of soil organisms (Goswami et al. 2017; Li et al. 2017). While soil acidification occurs naturally in tea plantations and increases with increasing tea plant age and plant density, intensive application of mineral

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nitrogen (N) is the main cause of the issue (Li et al. 2016; Yan et al. 2018).

The use of agricultural organic waste products to ameliorate soil acidification has been recognized in agriculture systems worldwide (Cai et al. 2015; Cornelissen et al. 2018; Dai et al. 2017). By definition, agricultural wastes or agriculture by-products are the unwanted residues generated from agriculture activities, such as crop residues, animal manure, forest waste, vegetable matter and weeds (Dai et al. 2018; Ramírez-García et al. 2019). Animal wastes, green manures and products derived from these wastes such as biochars and compost are generally alkaline in nature and have high pH buffering capacity which can neutralize soil acidification (Cai et al. 2021; Rayne and Aula 2020). Also, the presence of basic cations such as Mg^{2+} and Ca^{2+}, and organic anions in these materials contribute to increased soil pH (Cai et al. 2021; Tang et al. 2013). In addition to increasing soil pH, agricultural wastes have long been known to enhance soil health, including soil physical, chemical and biological properties (Bhatt et al. 2019; Cai et al. 2021; Rayne and Aula 2020). Globally, an estimated of 1 billion tons of agricultural wastes per year is generated, which China, USA and India being the largest agricultural waste-producing nations worldwide (Fig. 1) (Clauser et al. 2021; Obi et al. 2016), and this figure has been projected to increase rapidly because of the growing demand of agricultural products (Dai et al. 2018; Wei et al. 2020). Thus, the utilization of agricultural wastes as soil amendments could be a win–win strategy, which can benefit not only soil health but also reduce the pressure of using fossil fuels, mitigate serious environmental problems and human health threats (Bijarchiyan et al. 2020; Mpatani et al. 2021).

Studies on the utilization of agricultural wastes and its components to alleviate soil acidification caused by tea cultivation have been well reported in China, but poorly implemented in other parts of the world. Among these soil amendments, biochar application is considered as the most effective way to counter low soil pH, resulting in subsequent benefits to soil health and tea productivity (Wang et al. 2018; Wang et al. 2014; Yan et al. 2021). Several studies have also reported the positive impacts of organic manures on acidification of tea soil (Lin et al. 2019; Qiu et al. 2014), while the benefit of plant residues varied significantly. Recent reviews have highlighted the potential of biochar in mitigating soil acidification (Dai et al. 2017) and the effects of organic manure on soil health (Bhatt et al. 2019; Rayne and Aula 2020). However, to the best of our knowledge, there has not been any reviews published that specifically focus on the mechanisms and consequences of acidification in tea plantation soils, the advantages and drawbacks of using agricultural wastes and other relevant options in alleviating soil acidification as a result of long-term tea cultivation. This review provides a comprehensive overview of mechanisms and consequence of soil acidification by tea cultivation, the utilization of agricultural wastes and its products on mitigating soil acidification and enhancing soil health properties under tea plantations.

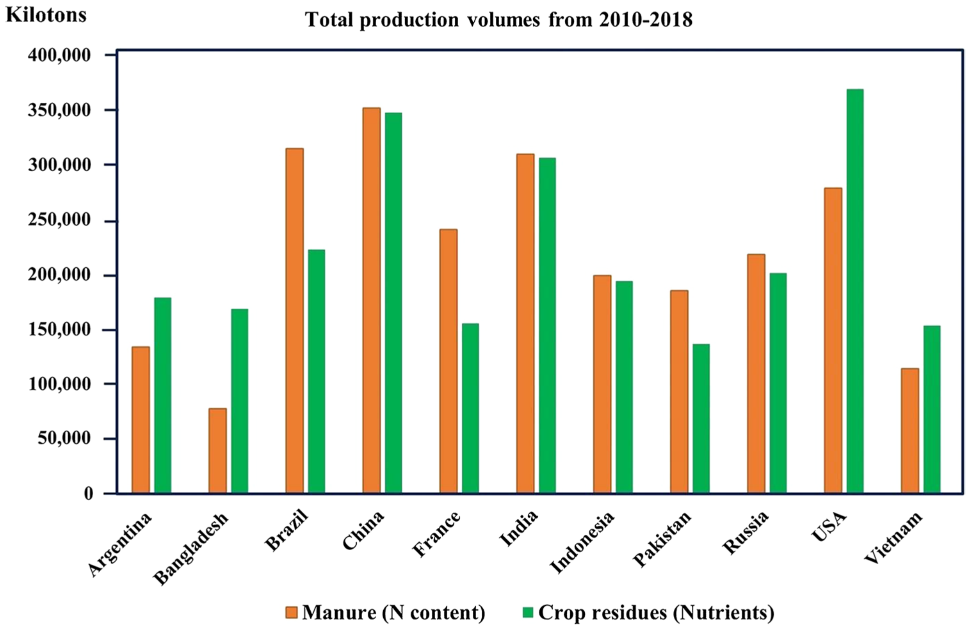

Fig. 1 Total production volumes of manures and crop residues in the world's largest agricultural waste generating countries from 2010 to 2018. Manures and crop residues were measured by kilotons of N content and nutrients, respectively. Of these countries, China, India, Vietnam, Indonesia and Argentina have been also the top global tea producers in the same period. Data were based on FAO (2021)

Soil acidification by tea cultivation and its consequences

Ocean and soil acidification

Ocean and soil acidification have been widely reported as the most critical issues, affecting the sustainability of numerous ecosystems and regions around the world (Ochedi et al. 2021; Yan et al. 2020). Ocean acidity has increased by ~ 25% since 1860s, and the soil pH values of 50% of total arable land worldwide are below 5.5 (Dai et al. 2017; Hall et al. 2020). Ocean acidification appears due to rising atmospheric carbon dioxide (CO_2) concentrations and absorption by seawater, which subsequently leads to a fall of pH and carbonate ion concentrations in surface seawater (Agostini et al. 2018; Sharma and Dhir 2021). Ocean takes up around 25% of global anthropogenic CO_2, making it the largest atmospheric CO_2 absorbent on Earth (Hauck and Völker 2015). Among the CO_2 emission sources, agriculture directly contributes around 14% of the total amount globally, and this proportion is likely to be exceeded in the future (Ayyildiz and Erdal 2021). Intensive agriculture and land use practices have been also the main causes of global soil acidification, particularly inappropriate use of ammonium-based fertilizers (Cai et al. 2015; Dai et al. 2017). Additionally, soil nutrient leaching, product removal, acidic parent materials, acid deposition and host plants are all likely to be significant factors resulting in soil pH reduction (Tang et al. 2013; Yan et al. 2020).

Soil acidification in tea plantations

Tea plant

Tea (*Camellia synesis* Kotze) is one of the oldest and most popular beverages in the world and is an important crop being cultivated in around 50 countries (Gebrewold 2018). Global tea production in 2019 was more than 9.2 million tons, valued at approximately $US55.3 billion (Fig. 2) (Allied Market Research 2020; Food and Agriculture Organization (FAO) 2021).

Tea plants are native to the Asia continent, but they can adapt to a wide range of soil and climatic conditions (Rana et al. 2021; Yan et al. 2018; Yao et al. 2012). This perennial crop requires acidic soils for optimum growth and productivity, with the optimal soil pH for tea plants being between 4.5 and 6, and the plant themselves are capable of acidifying soil (Fig. 3) (Gebrewold 2018; Li et al. 2016). Being a woody perennial, tea plants can retain their productivity for decades and thus have long-term interactions with soil organisms and

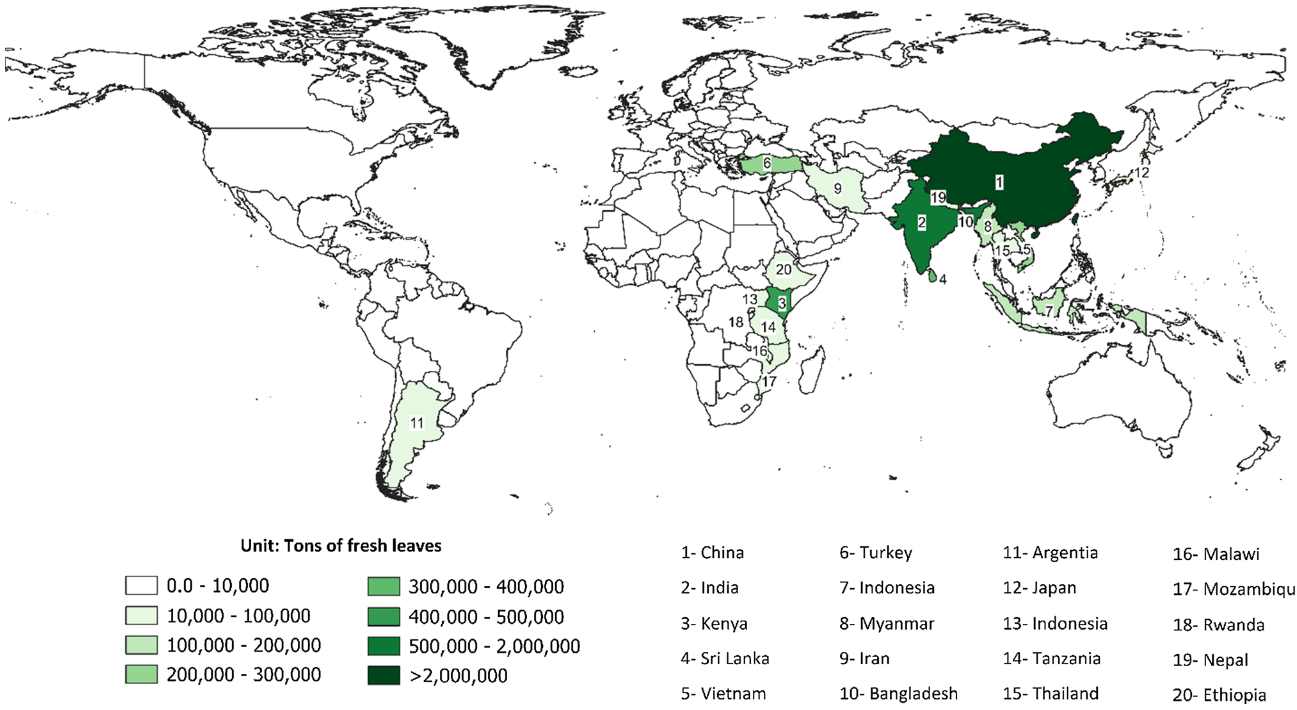

Fig. 2 Map of the 20 world's largest tea-producing nations in 2019. China was the largest tea producer worldwide in 2019, followed by India, Kenya, Sri Lanka and Vietnam. Most of the global tea producers are in Asia and Africa continents. The top 20 global tea-producing countries contributed to around 70% of total global tea production volume in the same year. Data was retrieved from FAO (2021)

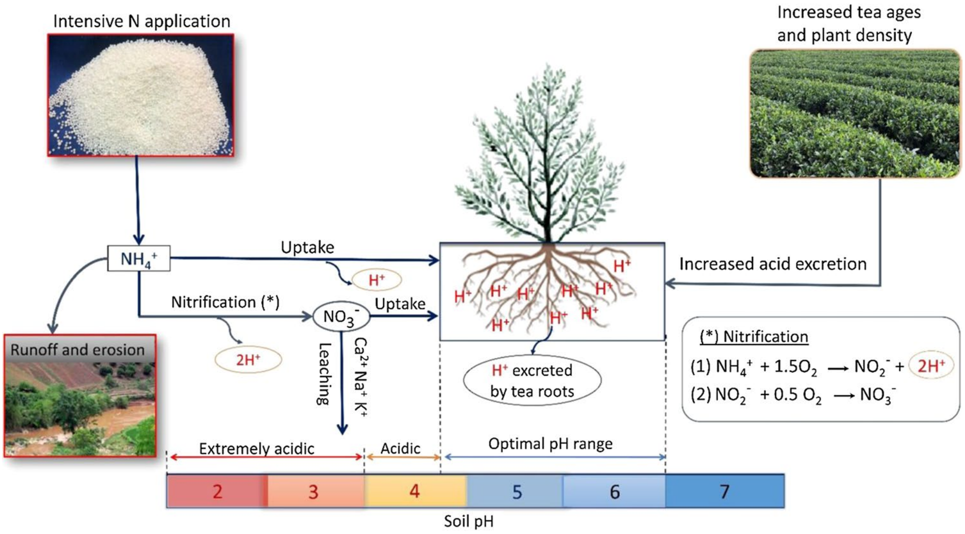

Fig. 3 Main causes of soil acidification by tea cultivation. Heavy addition of N fertilizers is the main reason causing soil acidification, and the accumulation of organic and carbonic acids released by tea roots also play a part in acidifying tea plantation soils

physicochemical processes, affecting soil health and plant productivity (Arafat et al. 2020; Yan et al. 2020).

Soil acidification by tea cultivation practices

Soil acidification in tea plantations results predominantly from inappropriate management practices, particularly the intensive overuse of mineral N (Li et al. 2016; Yan et al. 2018). Tea growers apply N to ensure high tea productivity and as a replacement for soil nutrient loss. In Japan, tea fields are amended with more than 1000 kg/ha of N fertilizers per annum (Abe et al. 2015; Zou et al. 2014) and a majority of tea farmers in China apply a large amount of nitrogen to ensure high tea yield and maintain soil fertility (Yan et al. 2018). A recent study has shown that nitrogen fertilizer application rate can even reach 1200 kg/ha in Chinese tea plantations (Wu et al. 2016). Soil pH significantly reduces when N fertilizers such as ammonium nitrate and urea is applied above 50 kg/ha/year, and increased N addition will accelerate soil acidification (Tian and Niu 2015). Moreover, heavy N application results in greater decrease in the subsoil pH compared with that of the topsoil (Ni et al. 2018). When fertilizers are applied at 2700 kg/ha, only 18.3% of applied nitrogen were absorbed by tea plants, and of that, about 52% of nitrogen were stored in the soil, and 30% were lost through runoff, polluting surrounding watercourses and soils (Chen and Lin 2016; Xie et al. 2021).

The main mechanisms of soil acidification resulting from inappropriate management practices in tea cultivation are shown in Fig. 3. When NH_4^+-N fertilizer is applied, tea plants directly take up the nutrient and tea roots subsequently excrete an equivalent proton into the rhizosphere, causing the concentration of hydrogen ions to increase. NH_4^+ nitrification leads to a net production of 2 mol H^+ for each mol of NH_4^+ applied, contributing to the decrease in the soil pH (Hui et al. 2010; Li et al. 2016; Yan et al. 2020). Cai et al. (2015) estimated that an application rate of 300 kg/ha/year of N fertilizers could produce 21.4 kmol H^+/ha/year by the nitrification processes. N fertilizer application in the long term also promoted the accumulation of exchangeable Al^{3+} including hydrolysis, which further generated H^+ and aggravated the acidification of tea plantation soils (Zhang et al. 2020). Finally, increasing tea plant age and planting density also result in an increase of organic and carbonic acids induced by tea roots into the rhizosphere, which facilitate soil acidification (Hui et al. 2010). Tea plantation soil is not acidified at planting densities of 5000 plants/ ha (Li et al. 2016).

Soil acidification by tea plants

Acidification of soils may naturally occur in soils cultivated with tea–even without any imposed N proton additions, and this issue becomes more challenging with increasing tea plantations (Arafat et al. 2017; Han et al. 2007; Li et al. 2016). In tea plantations, soil pH in the topsoil naturally decreased by 0.071 units per annum, and the values following 13, 34 and 54 years of tea cultivation were 1.1, 1.62 and 2.07 units, respectively (Hui et al. 2010; Ni et al. 2018). The acidification rate observed in the cultivated soil layers (0-10 cm) could reach 4.40 kmol H^+/ha/year during the 0–13 years of tea cultivation period (Hui et al. 2010). Organic acids secreted by tea roots such as malic acid, citric acid and oxalic acid are the main proton source for soil acidification in the tea tree–soil systems (Fig. 3) (Yan et al. 2018). Tea roots also excrete carbonic acids and polyphenols which can aggravate soil acidification, and affect soil nutrient release and subsequent element uptake (Ni et al. 2018; Wang et al. 2013). Additionally, the accumulation of chemical compounds such as epigallocatechin gallate, epigallocatechin, epicatechin gallate, catechin and epicatechin, found in the tea residues also negatively affect soil pH and soil health properties (Arafat et al. 2020). Thus, in summary, intensive application of N fertilizers is the main cause of soil acidity under tea plantations, and the accumulation of acid excreted by tea plants promotes the acidification.

Consequences of acidification in tea plantation soils

Soil chemical parameters

Soil acidification negatively affects chemical processes and properties of tea plantation soils (Fig. 4). One of the most serious challenges of soil acidification under tea cultivation can be the reduction and imbalance of nutrient base cations, including Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} (Alekseeva et al. 2011; Ni et al. 2018; Zhang et al. 2020). Under heavy N application, released protons (H^{+}) may replace the soil exchange base cations, which may have leached with the NO_3^{-} as accompanied cations due to the charge balance in soil solutions (Cusack et al. 2016; Ni et al. 2018). Moreover, a significant increase of Al^{3+} and Mn^{2+} has been widely recorded in acidic tea plantation soils, which could lead to Al and Mn toxicity (Alekseeva et al. 2011; Hui et al. 2010). Under acidic soil conditions, mineral Al solubilizes into trivalent Al^{3+}, which is highly toxic to animals, plants and microorganisms (Zioła-Frankowska and Frankowski 2018). Gruba and Mulder (2015) indicated that the concentration of exchangeable Al maximizes in soils with a $pH_{H2O} \approx 4.2$. Similarly, with decreasing soil pH, the amount of exchangeable Mn^{2+} increases in the soil solution (Millaleo et al. 2010). High concentration of Al^{3+} can inhibit the expansion, elongation and division of root cells, reducing water and nutrient uptake by the root systems (Wang et al. 2015). Similarly, high levels of Mn^{2+} in soil is one of the main factors causing nutrient imbalances, especially with divalent cations such as Mg^{2+}, Zn^{2+} and Ca^{2+} (Venkatesan et al. 2010). Soil acidification can also promote the dissolution of minerals and movement of Fe in the profile, resulting in reduction in the ferrimagnetic mineral content (Alekseeva et al. 2011). Increased Al and Mn toxicity have been considered as the most serious consequences of soil acidification by tea cultivation regarding soil chemical property.

Soil biological parameters

Soil pH is a crucial factor affecting soil organisms (Li et al. 2018; Neina 2019). Mulder et al. (2005) indicated that soil acidification has a close inverse relationship with bacterial, fungal, nematode and arthropod abundance. Long-term soil acidification is responsible for reduction of soil microorganisms, which are regulating the reduction in soil pH by both ecological and evolutionary mechanisms because of the environmental changes (Zhang et al. 2015). In tea plantations, a low soil pH ($pH < 4$) could lead to a loss of up to 70% of important soil biota (Han et al. 2007). Likewise, soil fauna communities were significantly higher in the soil with pH 7.0 (21 classes) compared to acidic soil with pH 2.5 (11 classes) and pH 3.5 (14 classes). In this study, in terms of total individuals, the figures were 3710 (pH 7.0), 759 (pH 3.5) and 645 (pH 2.5) (Wei et al. 2017). Severe soil acidification also leads to significant decreases in soil enzymatic activities, microbial activities and microbial biomass (Li et al. 2017; Zhang et al. 2015). Arafat et al. (2019) found a close association between the decline of some beneficial fungus such as *Mortierella elongatula* and *Mortierella alpina* and a low soil pH caused by long-term tea monoculture. Soil acidification also enhances the environment for growth of some soilborne pathogen diseases. For instance, when soil pH reduced from 5.07 to below 3.5 as a result

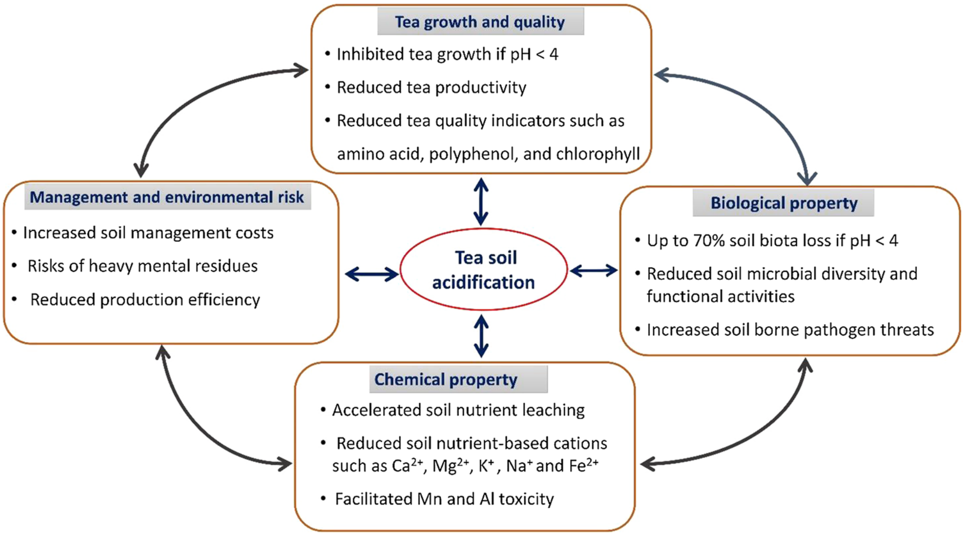

Fig. 4 A summary of the main consequences of soil acidification caused by tea cultivation on aspects of soil chemical and biological properties, tea growth and quality, soil management cost and the environmental risks

of 35 years of continuous tea monoculture, the abundance of some pathogenic bacterial species including *Fusarium oxysporum*, *Fusarium solani* and *Microidium phyllanthi,* which are responsible for diseases in tea plants such as root rot and die back, was significantly increased (Arafat et al. 2019). Investigating the relationship between soil acidity and bacterial wilt disease, Li et al. (2017) found that the proportion of soil affected by bacterial wilt much higher when the soil pH lower than 5.5 and significantly less as the soil pH increases. Likewise, the highest population of *Xiphinema chambersi* was found in soil with a pH 4.5, and the figure decreased when soil pH increased from 4.5 to 6.4 (Chen et al. 2012). Thus, soil acidification by tea cultivation could not only impact soil beneficial microbial diversity, but also promote the development of some potentially pathogenic microbes (Fig. 4).

Tea productivity and quality

Although tea plants prefer acidic soil for optimal growth and productivity, severe soil acidity negatively effects plant performance and quality (Fig. 4). When the soil pH is lower than 4.0, tea plant growth is inhibited, affecting both the quality and quantity of tea production (Li et al. 2016; Yan et al. 2020). Heavy N addition also significantly decreases the polyphenol/free amino acid ratio and affects other tea quality indicators by altering the relative content of chemical constituents (Qiao et al. 2018). High concentrations of Mn^{2+} negatively affect tea quality indicators such as amino acid composition and reduce the chlorophyll and carotenoid content of tea leaves (Venkatesan et al. 2010). Free Al^{3+} at a concentration of more than 1 mM retards tea growth, while the concentration of 10 mM leads to defoliation of tea plants (Fung et al. 2008).

Management cost and environmental risks

Despite the limited study on the management and other associated costs of soil acidification in the tea farming industry, research conducted on negative impacts of soil acidification on other agricultural sectors has highlighted the issues this causes. For instance, the annual loss of agricultural production due to soil acidification in New South Wales, Australia, was around \$387 million (Li 2020). Likewise, soil acidification resulted in an estimated economic value decrease of \$US214,000 per hectare (ha) in the forest industry in America (Caputo et al. 2016). Lime has been considered as the most effective ameliorant to control acidic soils, but it is still too costly for farmers in many countries, due mainly to its transportation costs (Cai et al. 2015; Tang et al. 2013). In tea plantation soils, acidification also occurs at the subsoil layers (100-120 cm); thus, deep incorporation of lime and other alternatives could be very expensive or even impractical due to the costs of suitable machinery (Li et al. 2016; Tang et al. 2013). Tea soil acidification can also promote the accumulation of chemical elements such as arsenic (As), mercury (Hg), lead (Pb), chromium (Cr), cadmium (Cd) and nickel (Ni) in the soil and tea leaves, increasing the human health and environmental risks of heavy metals (Bayraklı and Dengiz 2020; Zhang et al. 2020). It has been reported that more than 75% of soil Cd, Hg, Pb and Zn under acidic tea plantations exceeded uncultivated background concentrations, possibly due to the acidic environment promoted weathering pedogenic process releasing heavy metals (Tao et al. 2021).

Agricultural wastes for correcting tea soil acidification and enhancing soil health

Agricultural wastes for soil acidification and soil health

Agricultural wastes such as organic manures have been considered as a significant resource for agriculture for over hundred years (Rayne and Aula 2020), and since the downsides of agrochemical intensification on human beings and the ecosystem have become the global issue, the potential role of these alternate materials is being scrutinized increasingly closely (Chen et al. 2018; De Corato 2020). Most of agricultural wastes are widely available, cheap, biodegradable and rich in organic matter and nutrient and thus can be recycled as fertilizers or soil amendments (Kaur 2020; Onwosi et al. 2017; Saliu and Oladoja 2021). The nutrient compositions of agricultural wastes and products derived from these resources vary greatly and depend on multiple factors, such as their original sources, animal diets, waste storage and management, as well as production procedures (Amoah-Antwi et al. 2020; Dai et al. 2017; Rayne and Aula 2020). Common agricultural by-product and their components applied to agricultural soils as fertilizers and amendments are illustrated in Fig. 5.

There are various types of agricultural organic wastes applied to croplands, but they can be divided into two different groups based on their origins and common uses (Fig. 5). Organic manures include animal wastes from livestock and poultry industries, and green manures are mainly leguminous and forage crops (Maitra et al. 2018; Rayne and Aula 2020). Globally, animal waste has been predominantly attributed to manures from livestock and, in 2018, contributed around 35 million tons of N applied to croplands globally, compared to more than 13 million tons from poultry (FAO 2021). Organic manures can be applied to soils or used as main materials for compost production, the natural biological processes of decomposing organic wastes involving numerous microbial species (Azim et al. 2018; Bhatt et al. 2019; Sánchez et al. 2015). Compared to manures and

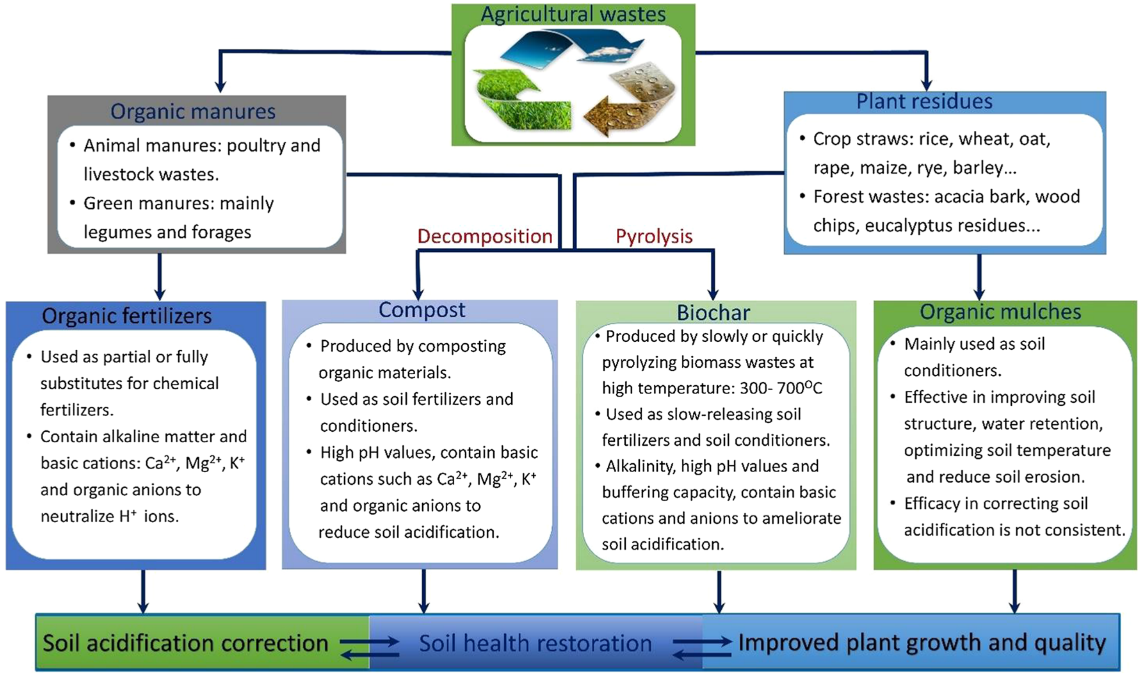

Fig. 5 Common types of agricultural wastes and products using these wastes as main feedstocks, their production and use to mitigate soil acidification and improve soil health, crop growth and quality

compost, plant straws and other organic biomass such as wood chips and tree pruning residues are not often applied directly to soils as fertilizers, but can also be incorporated as mulches, mainly for enhancing soil structure and water retention (Amoah-Antwi et al. 2020; Siedt et al. 2020). Alternatively, using agricultural by-products to produce biochar has been also an increasingly accepted way of recycling wastes. Biochar could be best described as a "soil conditioner," a carbon-rich product produced by thermochemical decomposition of organic matter under low oxygen environment and high temperature, normally from 300 to 700 °C (Peng et al. 2018; Verheijen et al. 2010). Feedstocks for biochar production consist of various biomass types, including municipal wastes and agro-industrial residues, and the feedstock types are important factors affecting biochar properties (Amoah-Antwi et al. 2020; Gunarathne et al. 2019; Guo et al. 2020). Details of elemental properties of some common agricultural wastes, compost and biochar are summarized in Table 1.

The various agricultural wastes have differing effects on alleviating soil acidification. Organic compost and biochar produced from organic manures and plant residues are naturally alkaline and have a higher pH value compared to that in the acid soils, so the addition of these organic amendments can increase soil pH to some extent (Cornelissen et al. 2018; Shi et al. 2019). Additionally, organic manure and its components naturally contain some basic cations such as Mg^{2+}, Ca^{2+}, Na^{2+} and K^+, which can form carbonates or oxides and then subsequently react with the H^+ in the acidic soils and lead to the acid neutralization (Dai et al. 2017; Rayne and Aula 2020). In contrast, some studies showed that the decomposition of some mulching materials such as woody chips, crop straw and pine bark could generate organic and carbonic acids, which facilitate soil acidity (Arafat et al. 2020; Zhao et al. 2018). Nevertheless, numerous studies have reported the neutral to positive effects of mulching practices on soil acidification (Cu and Thu 2014b; Ni et al. 2016; Sadek et al. 2019; Vijay 2014).

With regard to soil physical aspects, plant residues, organic fertilizers and biochar applications can benefit the soil hydrothermal environment, soil structure and water holding capacity (Kader et al. 2017; Siedt et al. 2020; Wang et al. 2020). In terms of soil chemical properties, adding organic fertilizers and biochar significantly improves soil organic matter, soil macronutrients and micronutrients, and reduces Al and Mn toxicity risks and nutrient leaching (Ding et al. 2020; Gong et al. 2020; Patra et al. 2021; Siedt et al. 2020; Zhongqi et al. 2016). Recently, a number of studies have reported the positive impacts of agricultural residue practices on soil organism abundance and functional diversity, such as the applications of organic mulches (Xiang et al. 2021; Zhang et al. 2020b), biochar and compost (Amoah-Antwi et al. 2020; Liu et al. 2021) and organic manures (Rayne and Aula 2020; Su et al. 2021). Despite the preference in using synthetic fertilizers, agricultural wastes and products derived from these resources are being used intensively as soil amendments and fertilizers, to partially or

Table 1 Nutrient composition of some main types of agricultural wastes and its based products used as soil amendments in tea cultivation and croplands

Type of waste	Nutrient composition									Reference
1. Animal manure	N	P	K	Na	Fe	Cu	Mn	Zn	Total C	
Horse	20.7	7.6	41.4	7.58	729	22	110	167	43.3	Moreno-Caselles et al. (2002), Chong et al. (2019)
Cow	18.6	7.89	17.6	5.38	3527	20	111	79	43.88	Mendonça Costa et al. (2015), Moreno-Caselles et al. (2002)
Calf	17.5	9.6	35.1	24.6	2839	40	225	233	–	Moreno-Caselles et al. (2002)
Pig	21.7	14.4	8.9	2.34	1559	170	328	427	–	Moreno-Caselles et al. (2002)
Sheep	18.7	5.67	34.3	6.94	3786	21	137	159	41.84	Mendonça Costa et al. (2015), Moreno-Caselles et al. (2002)
Goat	22.2	8.1	59.2	16.9	1729	31	170	202	–	Moreno-Caselles et al. (2002)
Rabbit	17.9	9.2	18.2	5.07	2623	61	225	453	–	Moreno-Caselles et al. (2002)
Chicken	31.4	13.2	24.7	4.85	154	40	237	304	34	Moreno-Caselles et al. (2002), Ravindran and Mnkeni (2016)
Turkey	39.7	10.9	24.5	3.97	172	45	327	336	39.7	Moreno-Caselles et al. (2002), Calbrix et al. (2007)
Ostrich	16.5	7.7	10.7	4.64	1303	56	257	200	–	Moreno-Caselles et al. (2002)
Earthworm	17.3	11.9	7.8	2.34	6503	78	335	348	–	Moreno-Caselles et al. (2002)
Note: N, P, K (g/kg, dry weight); Na, Fe, Cu, Mn, Zn (mg/kg, dry matter); total C (%, dry weight)										
2. Plant residues	N	P	K	C	Ca	Mg	pH	C:N ratio	Ash content	
Wheat straw	55	9	42	43.9	22.61	2.88	5.1	124.4	23.2	Jalali and Ranjbar (2009) Torma et al. (2018) Wang et al. (2009)
Potatoes	59	6	61	–	–	–	6.1	22.0	20.4	
Maize straw	39	3	19	42.14	6.40	4.60	–	–	48.8	
Oat straw	55	8	58	36.35	–	–	–	54.25		Torma et al. (2018), Zhao et al. (2018)
Rye	45	8	24	–	–	–	–	–	–	Torma et al. (2018)
Barley	43	7	40	–	–	–	–	–	7.14	Torma et al. (2018), Plazonić et al. (2016)
Triticale	54	8	28	–	–	–	–	–	5.27	
Pea straw	112	14	74	43.56	17.32	6.51	–	–	61.6	Torma et al. (2018), Wang et al. (2009)
Soybean straw	132	14	72	44.06	18.24	17.86		44.06	72.0	
Sugar beet	20	2	13	–	–	–	–	–	–	Torma et al. (2018)
Mustard	91	21	127	–	–	–	–	–	–	
Sunflower	108	15	218	–			5.3	81.4	10.4	Jalali and Ranjbar (2009), Torma et al. (2018)
Rape	107	15	218	–	–	–	5.1	65.5	5.4	
Rice straw	0.5- 0.8^a	0.07- 0.12^a	1.16–1.66^a	41.25	7.03	3.96	–	–	33.6	Ayinla et al. (2016), Chivenge et al. (2020)
Note: N content, P, K (kg/ ha); OM, C (%); Ca, Mg (cmol $_{(+)}$/kg); ash content: (%; dry weight); ^{a} (%)										
Tea and wood residues	N	P	K	Dry matter	C	Ca	Mg	C:N ratio	Ash content	
Tea pruned foliage	252	30	72	7.2	2.9	–	–	11	–	Kamau (2008)
Tea pruned twigs	85	10	21	3.6	1.4	–	–	17	–	
Primary wood	101	28	2	4.2	1.8	–	–	42	–	
Secondary wood	44	13	13	4.2	1.8	–	–	40	–	

Table 1 (continued)

Type of waste	Nutrient composition									Reference
1. Animal manure	N	P	K	Na	Fe	Cu	Mn	Zn	Total C	
Acacia bark	133.4	2.6	8.4	8.9	–	76.5	1.2	–	2.1	Taflick et al. (2015), Van Bich et al. (2018)
Eucalyptus biomass	307.5	28.8	249.3	–	–	–	455.7	131.7	15.4	Reina et al. (2016), Resquin et al. (2020)
Note: N, P, K, Ca, Mg (kg/ ha, dry weight); C (t/ ha)										
3. Biochar	N	P	K	Ca	Mg	Total C	pH	C:N ratio	Ash content	
Rice straw biochar at 400 °C	19.8	2.0	24	8.8	5.7	56	8.7	–	39	Naeem et al. (2017)
Wheat straw biochar at 400 °C	19.4	3.8	33	10.3	9.6	62	7.8	–	36	
Pine woodchip biochar at 500 °C	0.7	< 0.001	2.1	10.1	2.7	244.5^c	8.7	366	–	Brantley et al. (2015)
Rice biochar at 500 °C	0.92^a	3.23^a	2.48^a	875.2	578.9	46.4	11.0	–	34.6	Yan et al. (2021)
Bamboo biochar at 750–800 °C	0.58^a	1.85^a	1.01^a	560.3	320.6	77.3	11.3	–	5.8	
Peanut biochar at *300 °C*	2.6^a	–	22.0^b	47.4^b	45.6^b	55.1	9.2	21.5	228.4^b	Wang et al. (2014)
Vermicompost	8.7	< 0.1	1.3	26.3	–	181^c	8.09	20.9	8.09	Adhikary (2012)
Note: Total N, P, K Ca, Mg (g/kg); total C (%); ash content (%); ^{a} (%), ^{b} (cmol $_{(+)}$/kg), ^{c} (g/kg)										
4. Compost	N	P	K	Ca	OC	pH	C:N ratio	OM	Moisture	
Chicken manure compost	13.19	12.5	20.00	–	325.3	7.92	26.06	72.56	29.9	Li et al. (2021)
Pig manure compost	29.82	15.13	8.16	–	–	8.37	–	73.01	78.89	Li et al. (2012)
Buffalo manure compost	1.3	–	–	–	–	7.3	14	–	–	Doan et al. (2014), Ngo et al. (2011)
Cow manure compost	21.3	10.4	21.7	23.7	–	9.6	–	56.96	29.1	Gil et al. (2008)
Note: N, P, K, Ca (g/kg); OC, OM and moisture (%)										

fully substitute for chemical fertilizers (Amoah-Antwi et al. 2020; Lin et al. 2019; Shaji et al. 2021). However, since the nutrient compositions and efficacy of agricultural wastes and its products varied significantly (Table 1), they cannot be applied in a homogenous manner (Dai et al. 2017; Rayne and Aula 2020). Therefore, having a good understanding of characters of agricultural wastes and its components would be important to increase their application efficiency and reduce the pollutant risks to ecosystems (Amoah-Antwi et al. 2020; Ayilara et al. 2020; Cai et al. 2021).

Organic fertilizer and organic tea management practices

Applying animal manure to tea plantation soils could be an effective solution not only for ameliorating soil acidification, improve soil health of tea plantations but also as a waste management tool. Manures from various animals such as sheep, pig, cow and chicken used as organic fertilizers or compost for tea gardens significantly increased pH of acid soils, compared to their chemical nutrient counterparts (Cai et al. 2015; Gu et al. 2019; Ji et al. 2018; Lin et al. 2019; Qiu et al. 2014). For example, Gu et al. (2019) indicated that long-term applications of animal manure resulted in a significant increase in the soil pH (5.36), compared to that in non-fertilizer (4.71) and chemical fertilizer practices (4.31). Likewise, application of pig manure over 18 years increased soil pH by 1.1 units (Cai et al. 2015). Additionally, the replacement of chemical fertilizer by organic fertilizer in organic and agroecological tea cultivation has also had positive impacts on soil pH and other soil health indicators (Li et al. 2014; Viet San et al. 2021; Yan et al. 2020). Analyzing more than 2000 tea soil samples collected from conventional and organic tea plantations, Yan et al. (2020) concluded that conventional tea cultivation which employ heavy application of synthetic fertilizers caused severe soil acidification, while organic tea management approach did not result in significant soil acidification. Similarly, our recent study showed that agroecological tea management practices with chicken and buffalo manures as main nutrient supplies significantly improved soil pH compared to conventional tea cultivation which employs intensive chemical NPK (unpublished data). As outlined above, the mitigation of acidification of tea plantation soils by organic substance addition could be by alkaline matter and basic cations from added organic fertilizers, which can neutralize the soil acidity (Ji et al. 2018). Moreover, other chemical processes involving manure supplementation such as organic anion decarboxylation and organic N ammonification may play a part in reducing soil acidity (Xiao et al. 2013; Xu et al. 2006). Organic fertilizer can also support soil buffering action, thus reducing soil acidification (Chen et al. 2009). More examples of positive effects of organic manure and compost usage on soil acidification are indicated in Fig. 6 and Table 2.

Apart from ameliorating soil acidification, recycling organic amendments as the partial or full substitutes for chemical fertilizers can bring about a range of benefits for other aspects of tea plantation soil health and the environment. Organic fertilizer applications consistently improved soil OM, soil OC, soil exchangeable cations such as Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}, and nutrient availability, while reducing risks of Al toxicity, heavy metal accumulation, greenhouse gas emissions and nutrient runoff such as N and P (Table 2) (Cai et al. 2015; He et al. 2019; Ji et al. 2018; Lin et al. 2019; Qiu et al. 2014). Sustainable effects of adopting organic soil amendments in tea plantation soils on biological soil health have been also clearly indicated. Organic materials such as sheep, cow, chicken manures or compost significantly improved soil fauna communities, soil microbial diversity and functional structures (Gui et al. 2021; Li et al. 2014; Lin et al. 2019; Zhang et al. 2020a). Organic fertilizers are naturally rich in nutrients contain more organic matter compared

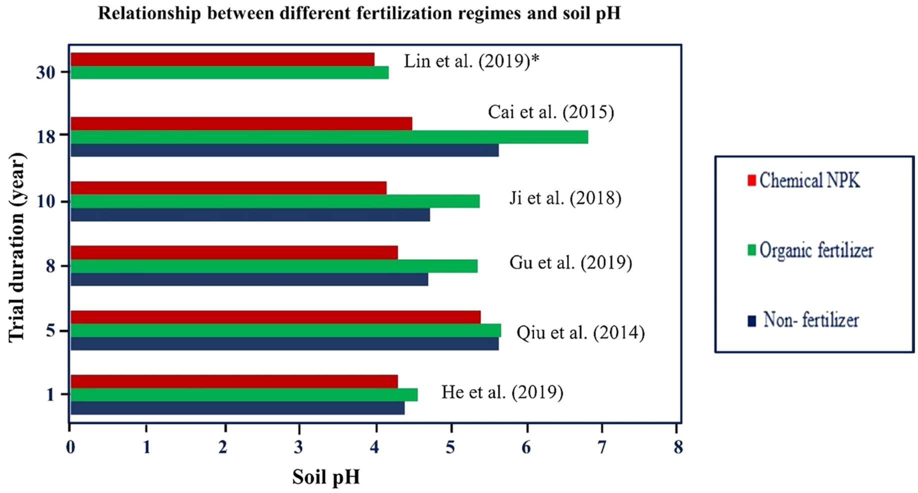

Fig. 6 Effects of different fertilizer type applications on soil pH under tea cultivation. Organic fertilization consistently resulted in grater soil pH in comparison with chemical fertilizer and non-fertilizer practices. Heavy uses of synthetic fertilizers also led to highest reduction in the soil pH, compared to other fertilization approaches. Adapted from Lin et al. (2019), Cai et al. (2015), Ji et al. (2018) Gu et al. (2019), Qiu et al. (2014), He et al. (2019). (*) the data for non-fertilizer management practice not available

Table 2 Summary of current studies of Organic fertilizers, biochar, plant residues and other relevant options on mitigating soil acidification and improving soil health, tea plant growth and reducing environment risks

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Sheep manure + rape cake	Red soil China	Field experiment Trial time: 30 years	Organic fertilizers resulted in an increase by 0.2 units (4.2 vs 4.0) compared to chemical fertilizers	Significant increased soil bacterial abundance, total K, while deceased the contents of Cd, As and Pb in rhizosphere and tea leaves Reduced soil total N (0.23 g/kg); total P (1.24 g/kg)	Lin et al. (2019)
Pig manure	Red soil (Ferralic Cambisol) China	Field experiment Trial time: 18 years	Increased by 1.1 units after 18 years of pig manure application	Pig manure application reduced exchangeable Al^{3+} and significantly increased soil exchangeable Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}	Cai et al. (2015)
Cow manure + Pig manure	Haplic Acrisol Chia	Field experiment Manure: 1.000- 2.000 kg/ha Trial time: 1 year	Soil pH value with chicken and pig manure practices were 5.36 and 5.09, respectively, compared to 4.71 of non-fertilization and 4.31 of mineral compound (NPK) application	Organic fertilizer application increased soil microbial diversity by 8.59–33.14% and resulted in an improvement of potential ecosystem function compared with synthesized fertilizer Increased total P but decreased total N	Gu et al. (2019)
Pig manure	Red soil China	Field experiment Substitution of 25%, 50%, 75% and 100% N by organic manure Trial time: 10 years	0.66 unit increased by application of 100% N substitute compared to the non-fertilizer plots 1.23 units higher compared to the pH value of synthetic fertilizer use	Significantly increased soil OC, total N, $NH4^{+}$-N contents, available P and K Soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN), soil bacterial diversity and community structure were improved significantly	Ji et al. (2018)
Cattle manure	Planosols (Clay loam) China	Field experiment Manure + biochar, 20.000 kg/ha Trial time: 2 years	Organic fertilizer and biochar application resulted in greater soil pH compared to chemical fertilizer	Cattle manure and biochar applications reduced NO emission Adding cattle manure as a partial substitute for biochar reduced NO emission and sorely biochar application reduced N_2O emission by 14%	Han et al. (2021)

Table 2 (continued)

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Chicken manure	China	Field experiment 11.400 kg/ha Trial time: 5 years	Chicken manure application resulted in the highest soil pH (5.67), compared to non-fertilization (5.64) and mineral compound (NPK) (5.40)	Significantly increased soil OM, total N and P; available N, P and K Organic manure uses promoted bacterial diversity, while that was reduced by chemical fertilizer application	Qiu et al. (2014)
Rapeseed cake	Yellow brown China	Field experiment 1.904, 3.928, 6.207 kg/ha Trial time: 1 year	Rape seed cake (6.207 kg/ha) decreased soil pH by 0.19 units while with chemical fertilizer was 0.33 units	Soil OM, available P and K increased by 31.4%, 26.2% and 21.7%, respectively Increased restoration of NH_4-N, NO3-N, total P and K contents in soil while reduced the substances in runoff water	Xie et al. (2019)
Cow manure	Brown loamy China	Field experiment 20 tons/ha Trial time: 6 months	Data not provided	Significantly increased the relative abundance of *Proteobacteria* and *Bacteroidetes* species and enhanced the diversity of bacterial communities	Zhang et al. (2020a)
Rapeseed cake	Acid yellow brown China	Field experiment 1.708, 4.270, 6.831 and 8.539 kg/ha/year 8 months	Significantly increased soil pH by 2.19 – 4.29% compared to chemical compound treatments	Increased total OM and preserved soil C and N pools of the tea plantations Reduced the nitrogen inputs (NH_4-N and NO_3-N) in the tea plantation runoff	Xie et al. (2021)
Pig, chicken and cattle manure compost	Alfisol China	Field trial Trial time: 1 year	Soil pH for pig, chicken and cattle manure compost uses were 4.56, 4.48 and 4.57, respectively, compared to 4.44 of non-fertilizer and 4.31 of chemical fertilizer practices	Increased soil OC, total N while reducing N_2O and NO emissions Organic fertilizer has no influence on tea yield, but that was increased by chicken manure and biochar combined application	He et al. (2019)
Organic management (Chinese Pennisetum, rape cake and farmyard manure)	Ferralsol China	Field trial Chinese Pennisetum: 4.000 kg/ha; rape cake: 3.000 kg/ha; farmyard: 2.000 kg/ha/year Trial time: 6 years	Organic tea management with organic fertilizer uses resulted in greater soil pH compared to conventional tea management; but lower compared to natural tea plantations	Increased soil OM, soil N and C/N ratio Enhanced species diversity, species richness and trophic diversity of nematodes in the soil	Li et al. (2014)

Table 2 (continued)

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Organic management (rape cake, compost and commercial organic fertilizers)	Ultisols China	Field experiment 4.500- 9.000 kg/ha/year Trial time: around 10 years	Soil pH has an inconsistent correlation with tea management methods	Increased soil microbial C by 164.4% and soil microbial N by 482.9% on average Total OC, N and available P increased significantly in organically managed tea plantation soils, but Ca and Mg availability decreased in comparison with conventional management	Gui et al. (2021)
Agroecological management (chicken and cow manure as main nutrient supplies)	Ferralic Acrisols Vietnam	Field experiment 6.000- 8.000 kg/ha/year Trial time: 5–10 years	Increased soil pH by 0.35 units on average, compared to conventional tea plantations	Significantly improved soil OM, colonization and intensity of arbuscular mycorrhizal fungi (AMF) Reduced soil total N	Unpublished data
Organic management (cow and pig manure, commercial organic fertilizer)	Red soil China	Field experiment Management duration: 14 years	Soil pH increased by 0.91 units compared to conventional tea plantations and 0.06 units compared with the tea plantations employed a combined application of organic and chemical fertilizers (non-polluted management practices)	Increased total OC, available P, NH_4-N and NO_3-N but total P and N were lower than that in the non-polluted tea management) Improved soil microbial diversity, increased the abundances of beneficial soil microbes and altered the interaction network structure compared with conventional and pollution-free management practices	Tan et al. (2019)
Organic management	Bangladesh	Field research	Soil pH of organically managed tea plantation was 5.1, compared to 4.2 of conventionally managed tea plantation	Increased total OM and nutrient availability (K, Ca, Mg, P, Zn and S) Significantly increased tea yield and economic efficiency	Sultana et al. (2014)
Organic management (Sheep manure)	Laterites China	Field research 6.000 kg/ha/year, dry matter Management time: 3 years	Soil pH was significantly lower compared to that in longan orchard, both in the surface (5.05 vs 5.32) and 10-20 cm depth (5.04 vs 5.24) No significant difference compared to conventional tea management plantations	Organic tea management increased soil P availability, enhance soil microbial communities (bacteria, fungi, actinomycetes and AMF) compared to conventional tea management Conversion of longan to tea plantation significantly reduced soil fertility	Wu et al. (2020)

Table 2 (continued)

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Rice straw biochar	Oxisols China	Laboratory incubation 1%, 2% and 5% of the dry soil weight (w/w) Trial time: 21 days	Soil pH was 4.4; 4.2 and 3.9 for 5%, 2% and 1% of biochar applications, respectively) Soil pH significantly increased by biochar application, but that was lower compared to lime (CaO) application	Nitrification would be detrimental to the N uptake of tea, while NO3-N produced from nitrification could be lost by leaching, runoff and denitrification Tea soil pH should be maintained at higher value than the optimum pH for nitrification (~5.1)	Wang et al. (2018)
Rice husk biochar at 550 °C	China	Laboratory incubation 0.5%, 1%, 2% (w/w) 60 days	Application of biochar at 2 and 4% significantly increased soil pH (3.52 and 3.63, respectively)	The incorporation of fast pyrolysis rice husk biochar led to a significant increase in the soil total C, N, extractable Ca, Na, Mg and K contents, while available Al and Pb were reduced	Wang et al. (2014)
Rice, wheat and peanut residue biochar at 300 °C	Ultisol China	Laboratory incubation 1%, 2% (w/w) Trial time: 65 days	Soil pH increased in all biochar application treatments, and the highest soil pH value was observed in peanut biochar, followed by wheat and rice residue biochar	Significantly increased soil exchangeable cations but reducing soil exchangeable Al and acidity Increasing biochar application rate has no further effect on soil pH Reduced acidity produced from N cycle	Wang et al. (2014)
Rice straw biochar at 550 °C; Bamboo straw biochar at 750-800^0C	Loamy clay China	Glasshouse trial 2% and 5% (w/w) Trial time: 1 year	pH increased by 0.9 units by bamboo biochar application, 1 unit (from 4.30 to 5.30) by rice biochar use at the rate of 5% Increasing biochar additional rate resulted in greater soil pH increase	Increased plant nutrients (P, K and Mg concentrations), while reducing Mn and Cu concentrations Significantly improved tea growth characters compared to conventional tea management without biochar Rice and bamboo biochar has no significantly different effect on tea growth and tea soil nutrients	Yan et al. (2021)

Table 2 (continued)

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Tea pruning residue biochar at 500–600 °C	Red–yellow Japan	Laboratory incubation 4% (w/w) Trial time: 90 days	Biochar amendment significantly increased soil pH at the surface (0–5 cm, 0.23 units) and 5- 10 cm soil layer (0.73 units)	Tea pruning residue use as mulch significantly increased soil total N, C and also N_2O and CO_2 emissions Converting tea pruning residue to biochar amendment and its incorporation significantly mitigate N_2O emission by up to 74.2%, but increased CO_2 emission	Oo et al. (2018)
Bamboo residue biochar at 500 ^{0}C	Inceptisols	Glasshouse trial 3% and 6% (w/w) Trial time: 180 days	Soil pH increased by 0.31 units with application rate of 3%, 0.75 units with incorporation rate at 6%	Reduced $NH4^+$-N leaching by up to 91.9%; $NO3^-$-N by a maximum of 66.9% and total N by up to 72.8% Enhanced soil nutrient retention (N by up to 23.9%) Improved soil microbial biomass and enzyme activity	Chen et al. (2021)
Wheat straw biochar at 450 °C	Plinthosols China	Laboratory incubation 4% (w/w) Trial time: 35 days	Soil pH increased 1.09 units compared to non-fertilizer practices, but lower compared to the combined application of biochar and N fertilizer (5.2 vs 5.4)	Biochar amendment increased the abundance of ammonia oxidizing bacteria and Nitrous oxide reductase genes Increased soil C/N ratio and decreased N_2O emission in acidic soil Biochar could increase N_2O emission in alkaline soils	Ji et al. (2020a)
Legume and non-legume biomass at 500 °C	Utisols China	Laboratory incubation 1% (w/w) Trial time: 30 days	Soil pH immediately increased by around 0.4 units after biochar addition, then remained stably Legume biochar has greater impact on increasing soil pH compared to that of non-legume biochar	Increased soil dissolved OC but reduced inorganic N Suppressed N_2O emission by around 40% Significantly altered fungal community structure, relative abundance of Ascomycota community, but has no significant effect on bacterial community	Zheng et al. (2019)

Table 2 (continued)

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Wheat straw biochar at 450 ^{0}C	Plinthosols China	Field experiment 20.000 kg/ha Trial time: 2 years	Significantly increased soil pH by 0.2 units	Biochar application decreased N_2O and NO emissions from acidic tea soils Denitrification was mainly responsible for producing N_2O in acidic soil Nitrification and denitrification processes were both facilitated by biochar addition	Ji et al. (2020b)
Wheat straw biochar at 450 °C	Alfisol China	Field experiment 7.500 kg/ha Trial time: 1 year	Increased soil pH by 0.68 units compared to conventional chemical N and by 0.55 units compared with non-fertilizer treatment	Biochar applications reduced N_2O and NO emission factor by 1.82 and 1.38, respectively, compared to chemical N use Biochar combined with manure chicken applied to tea soils could mitigate N gas emissions and increase tea productivity	He et al. (2019)
Mushroom residue biochar at 500 ^{0}C	Ultisols China	Field experiment 1.350 kg/ha and 2.390 kg/ha Trial time: 1 year	Biochar application at a rate of 1.350 kg/ha increased soil pH by 0.1 units after one year, while the figure for the higher rate (2.390 kg/ha, biochar + based chemical fertilizer) was 0.27 units	Biochar application enhanced plant beneficial fungal genera such as *Chloridium, Clavulina, Amylocorticium, Rhodosporidiobolus* and bacterial genera such as, *Mizugakiibacter, Rhodanobacter* and *Pedobacter* Increased tea yield and yield components, tea quality indicators such as amino acids and water extract contents	Yang et al. (2021)
Rice straw	- China	Field experiment 7 cm thick Trial time: 8 months	Increased soil pH by 0.13 units compared to non-mulching practice	Reduced soil temperature variation and having a significant cooling effect in the deep soil layer Significantly improved soil water retention while reducing soil compactness Significantly increased soil OM, available N, P, K and total N	Xianchen et al. (2020)

Table 2 (continued)

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Plant residue ash (canola, wheat rice, corn, soybean peanut…)	Alfisol China	Laboratory incubation 20 g ash/ 350 g soil Trial time: 60 days	Plant residue ash significantly increased soil pH (by 0.3 units on average) Leguminous residues had more significant effects in raising soil pH than the non-legumes	Reduced soil Al exchangeable concentrations	Wang et al. (2009)
Fern (*Gleichenia linearis)*	Acrisols Vietnam	Field experiment 0, 15, 25, 35 and 45 tons/ha (fresh weight) Trial time: 3 years	Application rate of 15 and 25 tons/ ha significantly increased soil pH at the 3 years of experiment, while the rates of 35 and 45 tons/ha had inconsistent effect on soil pH	Significantly increased soil basic cations (Ca^{2+} and Mg $^{2+}$) while reducing soil Al^{3+} Improved soil moisture, soil bulk density and humus substances and enhanced soil microbial activities Application rate at 25tons/ha of fern is recommended	Cu and Thu (2014a)
Tea pruned residues	Acrisols Vietnam	Field experiment 30 tons/ha Trial time: 3 years	Tea residue mulches significantly increased soil pH (by 0.3 units after 1 year; 1.1 units after 3 years) compared to no mulching practice	Increased soil moisture, soil OM content and reduced soil bulk density Significantly increased total number of soil bacteria, fungi and actinomyces The influences of tea pruned residues on soil properties reduced rapidly after 3 application years	Cu and Thu (2014b)
Peanut hull	Brown soil China	Field experiment 10 cm thick	Soil pH slightly increased (0.04 units) compared to non-mulch treatments	Significantly increased soil moisture contents, OM, total N and K, available N but reduced total P, available P and K Increased fungal community diversity in 0–20 cm soils and that of bacterial communities in 20–40 cm soils	Zhang et al. (2020b)
Intercropping with *Vulpia myuros*	China	Field experiment 7 cm thick Trial time: 8 months	Increased soil pH by 0.06 units compared to tea monoculture	Significantly increased soil OM, soil available N, P, K and total N, and soil enzyme activity Optimized topsoil temperature, increased soil water holding capacity while reducing soil compactness	Xianchen et al. (2020)

Table 2 (continued)

Material/practice	Soil type Location	Experiment type. Application rate/time	Soil pH effect	Other positive and/or negative impacts on soil, tea plants and the environment	Reference
Intercropping with aromatic plants (*Cassia tora, Medicago sativa, Leonurus artemisia,* and *Mentha haplocalyx*)	Acidic histosols China	Greenhouse trial Trial time: 2 years	Data not provided	Decreased the population of tea green leafhoppers while increasing the natural enemies of tea pests such as spiders, lacewings and parasitoids	Zhang et al. (2017)
Intercropping with fruit trees (loquat, waxberry and citrus)	Yellow soil China	Field experiment Trial time: 30 years	Soil pH at three soil depths (0–10, 10–20 and 20-30 cm) significantly increased by intercropping practices, compared to that in mono tea plantations	Increased soil OM, available P and K while reducing heavy metal (Cr, Cd, As, Hg and Pb) Improved tea quality indicators such as amino acid and catechin	Wen et al. (2019)
Agroforestry (tea–Gingko tree (*Ginkgo biloba* L))	China	Field experiment Growing distance: 10 × 10 m and 6 × 6 m Trial time: 11 years	Increased soil pH at all observed soil depths (by 0.65 units at 0-10 cm layer, 0.15 at 10- 20 cm layer and 0.35 at 20–30 cm layer)	Significantly increased soil OC, OM and total N contents, soil microbial biomass and enzyme activity Enhanced soil productivity and sustainability	Tian et al. (2013)

to chemical compound; thus, the replacement of organic amendments provides more organic matter in the soils (Wu et al. 2020; Xie et al. 2019). Richer soil organic contents will attract soil fauna and facilitate the activities of soil microbial communities in converting soil nutrients, which ultimately increase soil nutrient of tea plantation soils (Fan et al. 2017; Xie et al. 2019, 2021). These positive changes, in turn, will result in increasing soil organism diversity and community structure (Gu et al. 2019; Wu et al. 2020).

There do exist some concerns for recycling animal manures and organic compost which need further consideration. Firstly, organic fertilizer such as rapeseed cake had inconsistent effect on soil pH (Xie et al. 2019, 2021). This discrepancy may result from the dissimilarity of chemical composition of the product and other conditions such as soil type, application rate and management practices (Gu et al. 2019; Wu et al. 2020). Secondly, it has been reported that organic manure cannot ameliorate deep soil acidification in tea plantations (Li et al. 2016). In this case, biochar or a combined utilization of manure and biochar may be an effective solution to not only mitigate soil acidification but also enhance soil health and tea productivity (Dai et al. 2017; He et al. 2019). Thirdly, long-term application of animal manure and compost to manage acidic tea soils and restore soil health could led to the risks of heavy metal accumulation and manure-borne pathogen contamination (Cai et al. 2021; Li et al. 2020). For heavy metal contamination, Ji et al. (2018) indicated that 10-year application of pig manure did not result in increase of most heavy metals, and Lin et al. (2019) found that sheep manure and rape cake application reduced levels of Cd, Pb and As in soils as well as in tea leaves. To date, however, the relationship between animal manure, compost and pathogenic diseases of tea plants has been poorly understood. Thus, an integrated approach including appropriate application rates, reducing chemical inputs and concentrations of heavy metals in animal feed could be all necessary to minimize the environmental risks from using these organic materials as soil amendments and increase their efficacy (Cai et al. 2021; Ji et al. 2018).

Biochar amendment

Among the ameliorants of soil acidification, biochars could be one of the most effective options as it can also improve soil quality, plant productivity and contribute to a reduction in greenhouse gas emissions (Akhil et al. 2021; Siedt et al. 2020; Zhang et al. 2018). In tea farming, biochars produced from plant residue such as rice, wheat straw and bamboo residues have been commonly incorporated as soil amendment (Chen et al. 2021; Ji et al. 2020b; Wang et al. 2018). Depending on biochar types and application rates, soil condition, tea management practices and the application duration, the liming effect of biochars varied significantly

(Wang et al. 2014; Yan et al. 2021). As shown in Fig. 7, applying biochars at rates of from 1 to 5% of soil dry weight can significantly increase soil pH from 0.2 to more than 1 units within a few months (Ji et al. 2020a; Oo et al. 2018; Wang et al. 2018; Zheng et al. 2019). Studies conducted in tea plantations also demonstrated the positive outcomes of biochar utilization for correcting soil acidification caused by tea cultivation (Table 2) (He et al. 2019; Ji et al. 2020b; Yang et al. 2021).

Biochar ameliorates soil acidification by its natural alkalinity, high pH value and pH buffering capacity. Biochar generally has an alkaline pH value; thus, soil amended with this product can become less acidic (Table 1). For instance, a meta-analysis by Dai et al. (2017) indicated that biochar applications significantly increased soil pH by up to 2 units, and in most cases, the pH of biochars is greater than 7.0, which is at least 1.5 units higher than the pH in acid soils. Moreover, mineral constituents of biochar including basic cations such as Ca, Mg, K, Na and alkaline oxides that originated from feedstocks can mitigate soil exchangeable acidity (mainly H^+ and Al^{3+}) in the soil and ultimately increase soil pH (Dai et al. 2017; Patra et al. 2021; Yuan et al. 2011). In addition, soil pH buffering capacity is an important factor contributing to biochar amelioration of soil. Shi et al. (2019) illustrated that rice straw and peanut straw biochar application increased pH buffering capacity by 22% and 32%, respectively. It has been verified that the increase in CEC of the soil by biochar incorporation, driven by protonation–deprotonation processes, was the main mechanism of increasing soil pH buffering capacity (Shi et al. 2017; Xu et al. 2012). Biochar application also suppressed soil nitrification by limiting the availability of NH_3 or NH_4^+ for oxidation because of the surface adsorption or increased emissions of NH_3 due to enhanced soil pH (Wang et al. 2018; Yang et al. 2015). This in turn generally reduces the proton (H^+) released into soil and ultimately increase soil pH (Shi et al. 2019).

Biochar addition also enhanced soil quality indicators, tea growth and productivity, as well as reduced the environmental risks from pollution by heavy metals and greenhouse gases such as CO_2, N_2O and NO (Chen et al. 2021; Ji et al. 2020a; Yan et al. 2021). Consistently, biochar incorporation in soil improved soil OC, soil nutrient availability including Ca, Na, Mg, P and K contents, soil total N and C (Yan et al. 2018; Wang et al. 2014; Zheng et al. 2019). While the impact of biochar on soil fauna has been poorly investigated, this carbon-rich material has significant effects on enhancing soil microbial diversity and community structure (Table 2) (Ji et al. 2020a; Yang et al. 2021; Zheng et al. 2019). Biochar itself is a source of nutrients, including microminerals, trace elements, ash and so on. So its application also supplies essential agronomic benefits to farmers (Rawat et al. 2019). More importantly, biochar can absorb fertilizers and slowly release these into the soil, which helps to not only retain the nutrient availability in the soil but also reduce fertilizer leaching and drainage, which then contribute to environmental pollution (Rawat et al. 2019). Since soil pH and nutrient status has a close correlation with soil microorganism, the changes in soil chemical and physical properties as a result of biochar application could be the key driven factor for the alteration of soil biological properties (Cheng et al. 2019; Yang et al. 2021).

Several downsides of biochar incorporation need to be considered to improve its effectiveness and reduce the detrimental effects on the environment. Biochar has been considered as the most expensive soil management solution, particularly for large-scale use in agriculture (Siedt et al. 2020). Since the application rate of biochar normally ranges from 10 to 150 tons/ha and controlling strongly acid soils may require large quantity of biochar, which leads to an increased costs for energy inputs, feedstocks, transportation and incorporation (Dai et al. 2017). Furthermore, most studies on biochar application for managing soil acidification in tea farming to date have been conducted in controlled

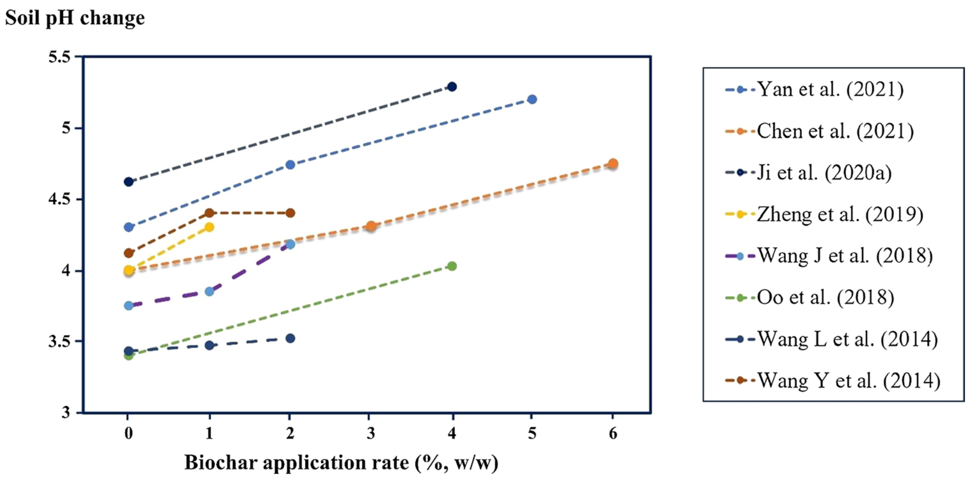

Fig. 7 Effects of biochar application rate on pH of tea plantation soils. Data collated from recent publications: Chen et al. (2021), Ji et al. (2020a), Oo et al. (2018), Wang et al. (2018), Wang et al. (2014), Wang et al. (2014), and Zheng et al. (2019)

conditions in China, suggesting that further research either in long-term field conditions or in other tea-producing areas would be needed. Overall, biochars indicate a great potential in ameliorating soil acidification and improving tea plantation soil health; however, more comprehensive and reliable evidence should be provided to validate these advantages.

Plant residues for organic mulching practices

Organic mulching practices employing plant residues and other agricultural wastes have received limited attention to date. Some studies conducted on tea fields indicated that mulching materials such as Fern (*Gleichenia linearis*) and tea pruning materials can alleviate soil acidity (Cu and Thu 2014a; b). Other materials such as crop straws and legume residues also had positive effects on increasing pH of tea plantation soils, in either field or laboratory trial conditions (Table 2) (Wang et al. 2009; Xianchen et al. 2020). In contrast, there have been a number of investigations revealing the negative impacts of organic mulching on soil pH from other cropping systems. Otero-Jiménez et al. (2021) found that rice straw mulch and rice straw burning significantly reduced soil pH by 0.55 and 0.19 units, respectively, and the application of wheat straw mulching reduced soil pH by 0.11 units (Mehmood et al. 2014). Finally, some studies have demonstrated that plant residues have no significant effects on soil pH (Iqbal et al. 2020; Ni et al. 2016). Positive effects of crop residues in increasing soil pH could be mainly due to the decarboxylation of organic anions, which can neutralize soil exchangeable H^+ and Al^{3+}, and also reduce the toxicity of Al species to plant roots (Dai et al. 2017). Declines in soil pH following application plant residue mulches could be attributed to the release of H^+ from nitrification of NH_4^+, which is produced during the mineralization of organic N in the residues (Dai et al. 2017). Decomposition of crop residues may also produce some organic and carbonic acids, potentially causing soil acidity (Arafat et al. 2020).

The potential of crop residue mulching in enhancing other soil health indicators has been widely recognized. Plant residues improve soil moisture content, soil structure and regulate soil temperature, support soil microbial activities and improve soil nutrient availability, as well as suppress weeds and reduce soil erosion, all of which contribute to enhance soil health and crop productivity (Chatterjee et al. 2017; Kader et al. 2017; Ngosong et al. 2019). These benefits have also been demonstrated in tea cultivation systems. Covering the surface of tea plantation soils with rice straw and tea pruning residues significantly reduced soil temperature variation, soil compactness and soil bulk density, while increasing soil water retention and soil moisture (Cu and Thu 2014b; Xianchen et al. 2020). Organic mulches can also enhance soil nutrient availability (Ca^{2+} and Mg^{2+}, available N, P, K) soil OM content but reduce soil Al^+ concentration (Cu and Thu 2014a; Wang et al. 2009; Xianchen et al. 2020). Enrichment of soil microbial diversity and community structure as a result of mulching material addition have been reported in these studies (Cu and Thu 2014a; b) (Table 2). Organic mulch cover creates favorable moisture and thermoregimes in soils by controlling surface evaporation rates and alter soil temperatures, by reducing temperature in the summer and raising it in the winter (Kader et al. 2017). Under appropriate soil microclimatic conditions, plant litter can decompose and add nutrients to soils. Plant residues and other organic mulch materials generally contain higher level of nutrients compared with inorganic mulch materials, but the influence of organic mulching application on soil nutrients has been also determined by other factors such as soil characteristics, climatic conditions (Iqbal et al. 2020; Kader et al. 2017). In addition, soil physicochemical conditions including soil moisture, soil temperature and soil nutrients play a crucial part in governing soil organisms (Kader et al. 2017; Onwuka and Mang 2018; Tan et al. 2018). For example, Brockett et al. (2012) concluded that soil moisture is the major factor affecting the community structure of soil microbes as well as enzyme activities. Examples of plant residue mulching and the summary of beneficial impacts of organic mulching, organic fertilizer and biochar applications in tea plantation soils are shown in Fig. 8.

However, some of mulching materials such as crop straws generally decompose quickly and thus need to be frequently incorporated for long-term use. This may require extra labor and investments, preventing farmers from adopting them in the long run (Amoah-Antwi et al. 2020; Dai et al. 2017). Extensive use of plant residues such as tea pruned litters to mulch tea soils could also lead to a decrease in the soil pH and the accumulation of active allelochemicals, which can cause soil sickness and tea growth deterioration (Arafat et al. 2020). Too much organic mulch could also result in other issues such as excess moisture and nitrogen, pests and anaerobic conditions, damaging the plant root and negatively affecting its growth and productivity (Iqbal et al. 2020; Kader et al. 2017). Overall, organic mulching employing plant residues is an effective soil management tool to improve soil physicochemical properties, but its role in controlling tea soil acidity needs further investigations.

Intercropping and agroforestry

Tea plants intercropped with loquat, waxberry and citrus significantly improve soil pH, organic matter, N, P and K availability, tea quality indicators, and reduces soil heavy metal concentrations compared with monoculture tea gardens, regardless of sampling seasons (Wen et al. 2019). Similarly, Xianchen et al. (2020) found that interplanting of *Vulpia myuros* at the density of 22.5 kg/seeds/ha in tea plantations significantly increased soil nutrients (OM,

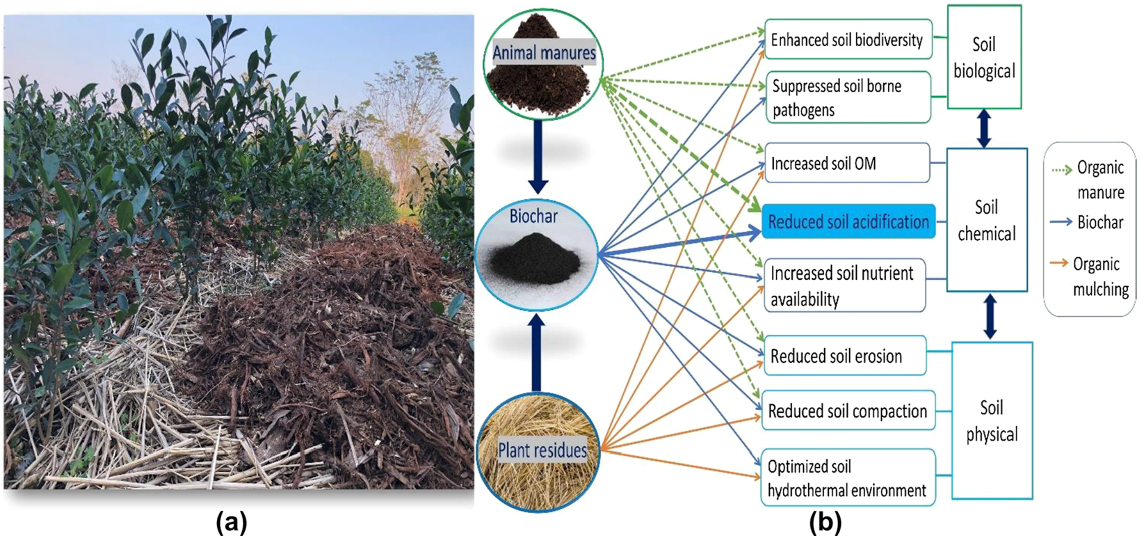

Fig. 8 Application of plant residues (rice straw, Acacia bark and woodchips) and organic manure (poultry manures) in tea plantations (**a**) and beneficial effects of some soil amendments derived from agricultural wastes on soil properties of tea plantations (**b**). Photograph was taken in Thai Nguyen province, Northern Vietnam, by the author

available N, P, K), soil water holding capacity while reducing soil temperature fluctuations and soil compactness at all observed soil depths (0–10 and 10-20 cm). In terms of soil organism, intercropping adoption in tea cultivation enriched soil enzyme activity and regulated tea pests (Xianchen et al. 2020; Zhang et al. 2017) (Table 2). In addition, tea–Ginkgo tree (*Ginkgo biloba* L.) agroforestry significantly increased soil pH (5.86 vs 5.21), soil organic carbon (17.92 vs 16.38 and total N (1.91 vs 1.79) compared with single tea plantations (Tian et al. 2013). The increase in the soil pH in the Ginkgo–tea agroforestry is likely due to the alkaline matter formed during the decomposition of Ginkgo tree residues which neutralizes soil acidity (Tian et al. 2013). Intercropping and agroforestry might increase overall ecosystem productivity and nutrient retention by increasing species diversity, increase soil organic matter by plant residues and attribute to the decomposition of fine roots in the deep mineral layers and surface leaves of trees (Brooker et al. 2015; Cong et al. 2015; Dollinger and Jose 2018). Among these impacts, organic matter enrichment could play a key role, containing basic cations and contributing to increasing the supply of important nutrients (Cardinael et al. 2020; Dollinger and Jose 2018).

Conclusion

Soil acidification is becoming an increasingly severe problem in many tea growing countries, resulting in serious impacts on soil chemical properties, tea productivity and quality and the environment. To date, however, how low pH affects tea soil biological and physical properties as well as its management cost have been poorly explored. Agriculture wastes and products have demonstrated a great potential to mitigate soil acidification by tea cultivation and improve tea soil health. Being naturally alkaline with high pH value and buffering capacity, these materials could supply alkaline matter and essential elements to neutralize soil acidity and alter soil properties, positively influencing soil nutrient availability, enrich soil organisms and ultimately improve tea yield and quality indicators. While promising, their expanded uses would need further understanding to improve their application efficacy while reducing any potential negative consequences on the environment. In addition, the risks of introduction of heavy metal and pathogens from animal manures, compost and biochar applications have been widely reported (Alegbeleye and Sant'Ana 2020; Dai et al. 2017), but how they could affect soil and tea plants have not been clearly understood. Moreover, most of reports on effective impacts of biochar for correcting soil acidification have been the outcomes of laboratory or glasshouse studies; thus, the results need to be validated in field conditions (Dai et al. 2017). Finally, the majority of studies on utilizing agricultural wastes in tea cultivation to date have been implemented in China, with specific but limited soil characteristics, climate conditions and tea management practices. It has been clearly indicated that differences in such conditions could significantly affect the effectiveness of these soil acidification ameliorants (Gu et al. 2019; Siedt et al. 2020; Wu et al. 2020). This research gap highlights the need and opportunities for further investigations in other systems to provide comprehensive knowledge and reliability in recycling these soil amendments.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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