Nitrogen

MDPI

Review

Identifying Sustainable Nitrogen Management Practices for Tea Plantations

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Abstract: Tea (*Camellia sinensis* L.) is the most widely consumed beverage in the world. It is mostly grown in the tropics with a heavy dependence on mineral nitrogen (N) fertilisers to maintain high yields while minimising the areas under cultivation. However, N is often applied in excess of crop requirements, resulting in substantial adverse environmental impacts. We conducted a systematic literature review, synthesising the findings from 48 studies to assess the impacts of excessive N application on soil health, and identify sustainable, alternative forms of N management. High N applications lead to soil acidification, N leaching to surface and groundwater, and the emission of greenhouse gases including nitrous oxide (N_2O). We identified a range of alternative N management practices, the use of organic fertilisers, a mixture of organic and inorganic fertilisers, controlled release fertilisers, nitrification inhibitors and soil amendments including biochar. While many practices result in reduced N loading or mitigate some adverse impacts, major trade-offs include lower yields, and in some instances increased N_2O emissions. Practices are also frequently trialled in isolation, meaning there may be a missed opportunity from assessing synergistic effects. Moreover, adoption rates of alternatives are low due to a lack of knowledge amongst farmers, and/or financial barriers. The use of site-specific management practices which incorporate local factors (for example climate, tea variety, irrigation requirements, site slope, and fertiliser type) are therefore recommended to improve sustainable N management practices in the long term.

Keywords: tea; fertiliser; soil amendments; biochar; nitrification inhibitor; application rate; eutrophication; yield; quality; nitrous oxide

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1. Introduction

Tea is the most widely consumed beverage in the world [1] and is made from the dried new leaves of the *Camellia sinensis* (L.) plant, an evergreen shrub [2,3]. Cultivation is generally confined to the tropics, due to the specific climate and soil that is required. In 2019, the global tea production was approximately 6.49 Mt, with 42% being exported with a value of about 15 billion USD [4,5]. In 2019, the largest tea producers globally were China (2.77 Mt), followed by India (1.39 Mt), Kenya (0.46 Mt), and Sri Lanka (0.30 Mt) [4]. There has been significant growth in tea production over the past two decades attributable to the increasing acceptance of tea as a drink of choice, the increasing area of production, better cultivars, advanced technology, and the widespread use of nitrogen (N) fertilisers to increase yield [6]. The size of the tea industry has been predicted to grow at an annual growth rate of about 4% to 5.5% from 2017 to 2024 [7]. The entire tea sector is projected to reach a retail value of about 73 billion USD by 2024 [7]. In order to maintain high levels of production to meet demand there will be an increase in dependence on high N fertiliser inputs. This is likely to have significant adverse environmental consequences resulting in an urgent need to identify and implement alternative practices.

The tea plant grows as an evergreen bush and can attain a maximum height of 15 m in the wild [8]. However, for the ease of cultivation the shrub is kept at a maximum height of

0.6–1.0 m to allow for easier harvesting [9]. Tea is consumed mainly as ‘black’, ‘green’ or ‘oolong’ tea, with the type of tea mainly dependent on the country of origin. For example, Sri Lanka, India, Kenya, and Malawi produce mainly black tea while green tea is mainly produced in Japan and China [1]. Harvesting tea leads to the removal of macronutrients (N, P, and K) thereby making it necessary to replenish these nutrients to the crop [10]. The new shoots that are harvested to produce tea have a high proportion of nutrients, with N being the most abundant [11].

Application rates of N fertilisers in tea are high, with upper estimates reported of up to 544 kg N ha^{-1} $year^{-1}$ [12]. However, depending on the type of applied N, only 25–50% is taken up by the plants, meaning that the majority of the inorganic NPK added to the soil ends up lost through leaching, erosion, volatilisation, or is immobilised in soil organic matter [13]. The excessive dependence on and use of fertilisers negatively impacts the water quality in the regions where tea is grown. High NO_3^- concentrations are found in ponds near tea plantations with excessive leaching leading to the contamination of the underground water [14,15]. In addition to water contamination, excessive use of ammonium fertilisers also has the effect of lowering the soil pH [16]. Regular increases in soil acidity result in a reduction in the uptake efficiency of the new N applied, therefore requiring ever greater N additions, thereby creating a compounding effect. In some locations, high applications of N only increase the yield of the tea when there is adequate irrigation [17]. This becomes an issue in drought-prone tea-growing areas. High application rates of N fertiliser can increase the partitioning of assimilates to the canopy rather than the roots which can reduce drought resistance [18]. The application of synthetic N fertilisers also results in the emissions of N_2O. For example, Akiyama, Yan, and Yagi (2006) found that among the crops grown in agricultural fields in Japan, tea plantations had the highest levels of N_2O emissions [19]. Such findings have been replicated in other major tea growing countries [20]. This is problematic as N_2O is an extremely potent and long-lived greenhouse gas with a global warming potential approximately 300 times more than carbon dioxide (CO_2) for a 100-year time horizon [21].

In this study, we assess the impacts of synthetic N fertilisers in tea plantations and identify alternative sustainable N management strategies that can help to reduce the impact. In this paper, we conduct a systematic literature review to (i) assess the N cycle in context to the tea plantations, assess types of fertiliser inputs and common application rates for each, investigating differences between regions and systems, (ii) quantify N use efficiency rates and the consequences of excess application, including evidence of eutrophication, soil acidification, and greenhouse gas emissions, and (iii) identify and assess sustainable and alternative N management strategies, focusing on organic systems and alternative solutions (e.g., soil amendments to mitigate N_2O) which may already be applied in other plantation systems. On this basis, we identify areas of future research to better support the development and implementation of sustainable N management in tea plantations.

2. Methods

We used a systematic literature review to assess the impacts of synthetic N fertilisers in tea plantations and identify alternative practices. In order to identify and select the relevant papers, we applied the preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach [22]. Applying a set of key search terms, the literature database on Scopus was searched in May–June 2021 to identify papers that were relevant to the study area. The search strings used were a combination of ‘tea’, ‘nitrogen’, ‘fertiliser’, ‘fertilizer’, ‘application rate’, ‘eutrophication’, ‘greenhouse gas emission’, ‘yield’, ‘nitrogen management’, ‘sustainable’ and ‘plantations’, selected as the most appropriate terms for identifying papers as in scope. These search strings were added to the Scopus search tool searching within the article title, abstract, and keywords database categories of original research papers published in peer-reviewed academic journals. A total of 590 papers were found through the initial search (Figure 1).

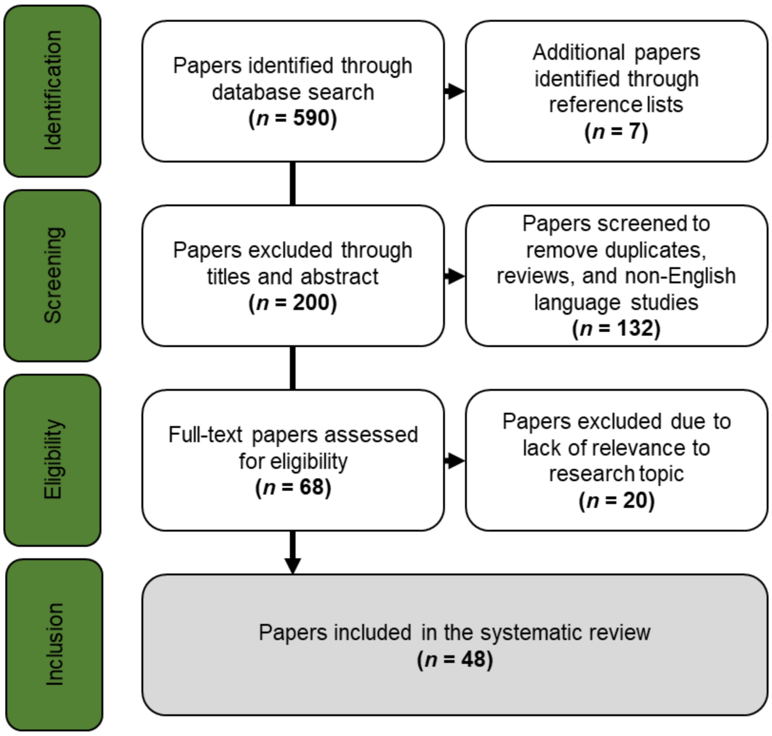

Figure 1. Selection process for the systematic literature review.

Of these, 394 papers were subsequently excluded based on the article title demonstrating that they were outside the scope of the study. A further 13 papers were excluded because they were reviews (book chapters and review articles), non-peer-reviewed conference papers and editorials, or commentary or perspective articles. Papers were subsequently excluded if they were not available either as open access publications, through institutional access, or online repositories (e.g., ResearchGate.net), reducing the number of studies to 144. Only English language studies were included, resulting in 132 papers. These were then shortlisted by reading the abstract and checking if the papers were within scope, reducing the total number of studies to 41. Seven additional relevant papers were found through the reference list of the 41 papers and were also included in the study, resulting in a total of 48 studies. A table of the final 48 papers is listed in the Supplementary Materials (Table S1). The selection criteria used may have excluded some relevant publications from other peer-reviewed literature which are published in non-English language journals and other "grey" literature. It was also noted that there was a large proportion of studies from China (*n* = 31) with comparatively few studies being from other tea growing regions including India (*n* = 2), Sri Lanka (*n* = 1), Kenya (*n* = 4), Japan (*n* = 4), Ethiopia (*n* = 1), Tanzania (*n* = 1), East Africa more widely (*n* = 1), and global trends (*n* = 3). Overall, there was also a lack of socioeconomic studies which looked into the impact of switching N fertilisers and utilising alternative methods and how this would impact the tea gardens and farmers. Such information is important to develop a better understanding of the impacts on the social as well as the economic aspects of tea growing, leading to the creation of more sustainable tea.

Data from each article was recorded including information on geographical distribution, tea variety, and its focus on either the need for nitrogen, the impacts of excessive nitrogen applications, or current or alternative nitrogen management. All units were converted into standard S.I. units with the exception of Xiao et al. (2018) for which insufficient data were available [23]. Overall, our approach allowed us to synthesise and identify the need for N, current practices adopted by tea plantations, their impacts, and consequences for the environment, as well as any practices that can help in mitigation highlighted in the literature. Effects and causes that were known to impact tea plantations but not found in the literature review were also noted and a separate search was conducted to find literature and practices that are used in other plantation types. This data was then used to identify sustainable and alternative N management strategies for tea plantations and identify gaps to inform future research recommendations [24].

This study did not investigate the availability of such approaches to various farming communities (particularly smallholders), instead focusing on synthesizing our understanding of the relevant biogeochemical pathways, and evidence for the benefits (or trade-offs of each technique). Making techniques rapidly available for smallholder farmers (for example through the outreach programs of non-governmental organisations) and making appropriate financial capital available to facilitate this is key to wider adoption, and important in terms of more widely improving the sustainability and adoption of principles of equity in the tea sector [24].

3. Results and Discussion

3.1. The Need for Nitrogen

3.1.1. Nitrogen and Crop Yields

N plays a vital role in plant growth and is one of the most deficient mineral elements in the soil [25]. Like all crops, tea bushes can suffer from N deficiency. The effects of N deficiency in tea include the leaves having a lighter green colour and shorter internodes [8]. In general, a tea plant is deficient when the mature leaf N concentration is below 3%, is mildly deficient between 3% and 3.5%, with an optimum concentration above 3.5% [26]. Harvesting, leaching, gaseous emissions, and immobilisation in the soil microbial communities all reduce available N for plant growth (Figure 2). As a consequence, maintaining yields requires soil N additions through fertiliser applications.

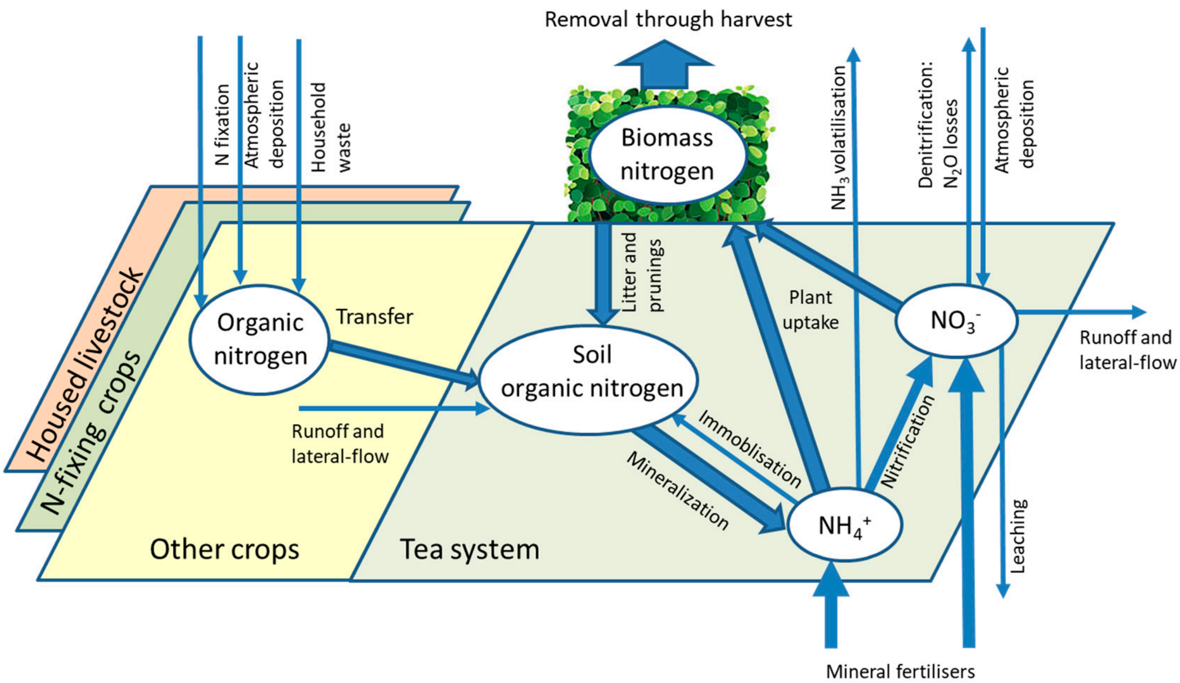

Figure 2. Nitrogen flows in tea plantations, focusing on organic management. Inorganic fertiliser additions could also be used to increase the size of the NO_3^- and NH_4^+ pools.

Five studies explicitly investigated the relationship between N application and yield (Table 1). Venkatesan et al. (2004) in South India found that the increase in the rate of N fertiliser application from no application to 150 kg N ha^{-1} year^{-1} resulted in an increase in the yield of 4.96 kg ha^{-1} year^{-1} per kg of applied N, and an increase of 2.38 kg ha^{-1} year^{-1} and 2.36 kg ha^{-1} year^{-1} per kg of applied N when the application rate was increased to

300 kg N ha^{-1} year^{-1} and 450 kg N ha^{-1} year^{-1}, respectively [27]. Similarly, Stephens and Carr (1991) in Southern Tanzania noted that yield increases with higher NPK fertiliser application rates, but with a critical 'turn-over point' (375 kg N ha^{-1} year^{-1} with well-irrigated tea and 300 kg N ha^{-1} year^{-1} with unirrigated tea); there were reduced yield increases despite higher application rates [28]. Ma et al. (2021) in the Zhejiang province of China also reported a significant increase in the yield of harvested shoots with application of N fertilisers [29], with yields reaching a plateau at an application rate of 367 kg N ha^{-1} year^{-1}. In a short-term pot experiment, Xiao et al. (2018) reported a yield response of tea up to a level of 3.88 g N (kg soil)$^{-1}$ [23]. The potential tea yield in a given location is primarily dependent on the climate conditions [28].

Table 1. Comparative studies of application rates of fertilisers and impacts on yields in tea plantations. * Data from Stephens and Carr (1991) is reported for optimized irrigation management.

Location	Type of Fertiliser	Application Rate (kg N ha^{-1})	Yield (t ha^{-1})	Reference
Hangzhou, China	No fertiliser	0	1.25	Liu et al. (2012)
Hangzhou, China	Urea and $CaH_6O_9P_2$	548	2.97	Liu et al. (2012)
Hangzhou, China	Organic	548	2.60	Liu et al. (2012)
Hangzhou, China	Slow release	548	2.75	Liu et al. (2012)
Hangzhou, China	Urea	0	2.50	Ma et al. (2021)
Hangzhou, China	Urea	119	3.00	Ma et al. (2021)
Hangzhou, China	Urea	285	3.50	Ma et al. (2021)
Hangzhou, China	Urea	569	3.10	Ma et al. (2021)
South India	Urea	0	2.12	Venkatesan et al. (2004)
South India	Urea	150	2.37	Venkatesan et al. (2004)
South India	Urea	300	2.79	Venkatesan et al. (2004)
South India	Urea	450	3.11	Venkatesan et al. (2004)
Tanzania	NPK	0	1.87	Stephens and Carr (1991) *
Tanzania	NPK	110	2.80	Stephens and Carr (1991) *
Tanzania	NPK	170	2.91	Stephens and Carr (1991) *
Tanzania	NPK	230	3.40	Stephens and Carr (1991) *
Tanzania	NPK	280	3.70	Stephens and Carr (1991) *
Tanzania	NPK	350	4.50	Stephens and Carr (1991) *
Fujian, China	NPK	0	4.20	Ji et al. (2018)
Fujian, China	NPK	300	6.46	Ji et al. (2018)
Fujian, China	NPK (75%) + organic (25%)	300	6.65	Ji et al. (2018)
Fujian, China	NPK (50%) + organic (50%)	300	6.18	Ji et al. (2018)
Fujian, China	NPK (25%) + organic (75%)	300	6.23	Ji et al. (2018)
Fujian, China	Organic	300	5.36	Ji et al. (2018)

3.1.2. Crop Quality

A lack of N in tea plants affects the quality of both green and black tea [26,30–33]. Owuor (1997) demonstrated that the quality of green tea increases progressively with an increase in the N supply [26]. Tokuda and Hayatsu (2004) report that Japanese tea growers add as much as 1200 kg N ha^{-1} year^{-1} to increase quality [32]. In contrast to green tea, the quality of black tea decreases with excessive N application [33]. The optimum N rate in black tea has been reported to be between 100–200 kg N ha^{-1} year^{-1} [33,34]. Increases in the supply of N fertiliser were reported to increase amino acid concentrations and decrease polyphenol concentrations in leaves. These can be useful indicators for estimating tea quality [35] with amino acid concentration being a strong indicator for green tea [36]. Polyphenols are responsible for the bitter and acidic taste present in tea [37], so a higher concentration of polyphenols is less desirable for green tea.

3.1.3. Application Rates and Types of Fertilisers

Nitrogen and other nutrients can be applied in different inorganic forms. For example, urea and calcium superphosphate are reported in Liu et al. (2012) [30], urea in Ma et al.

(2021) [28] and Venkatesan et al. (2004) [27], and NPK fertilisers in Stephens and Carr (1991) [27] and Ji et al. (2018) [31]. Overall, the evidence suggests that organic fertilisers performed worse than traditional inorganic fertilisers in terms of benefits to yield (Table 1) but better than the application of no fertiliser. In some examples, a combination of organic and inorganic fertiliser for a given supply of N can provide a marginally higher yield than inorganic fertiliser alone [37]. However, our ability to make wider conclusions based on these results is limited given the sparsity of studies and limited information regarding soil type and other key soil parameters. Taken together, these results do, however, demonstrate that very high N application rates do not necessarily result in greater yields and highlight the need to manage N application rates depending on plant and soil requirements.

Ruan et al. (2007) reported that applications of ammonium (NH_4^+) rather than nitrate (NO_3^-) fertilisers improved nitrogen uptake due to the higher capacity of roots to take up NH_4^+ compared with NO_3^- [38]. This is one reason why tea plantation managers often select NH_4^+ or urea-based N fertilisers [38,39].

3.2. Environmental Impacts of Excessive Nitrogen Applications

3.2.1. Soil Health

Plant growth depends on a regular supply and balance of nutrients from the soil, which must also act as a suitable medium for root growth, maintaining moisture, and supporting the microbial community [40]. Soil acidification is a major problem and can be exacerbated by high N fertiliser use. Acidification results in the leaching of cationic nutrients including potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) leading to a reduction in plant productivity and potential increases in GHG fluxes [40–43].

In tea plantations, the heavy dependence on N fertilisers has led to significant pH reductions from 3.32 to 3.15 and 3.67 to 3.35 at depths of 0–0.4 m and 0.4–1.0 m, respectively [44]. Yan et al. (2018) also reported lower soil pHs in older tea gardens compared with younger tea gardens at depths of 0–2.0 m [43]. This was attributed to the continuous application of fertilisers throughout the life of the gardens. Cheng et al. (2015) found the soil pH of tea plantations declined from 5.3 to 4.9 after continuous application of fertilisers for about six years [44]. Willson (1975) noted that the increase in soil acidity leads to the accumulation of manganese (Mn) in the leaves which can be harmful at higher concentrations [45]. Wang et al. (2018) also noted that there was a decrease in the soil pH as the cultivation time increased but also noted that NO_3^- fertilisers had a more gradual decline in pH compared with NH_4^+ fertilisers [39]. Similarly, Wang et al. (2020) found that the effect of N addition on the soil pH was dependent on the type of N added, with ammonium bicarbonate and urea acidifying the soil while ammonium sulphate fertilisers had no effect on the soil pH [46].

Soil acidification impacts the soil microbial community, with consequences for fundamental ecosystem processes. Yang et al. (2019) noted that the long-term addition of N fertilisers led to the reduction in microbial biomass, inhibited respiration, and reduced the microbial diversity [47]. Similarly, Ma et al. (2021) found that there was microbial community destabilisation and a reduction in the complexity of bacterial networks [29]. Many microbes have evolved to produce enzymes that release N from recalcitrant organic matter. High levels of N or substrate N concentrations can inhibit the production of enzymes by microbes which in turn reduces C availability to microbes, and thereby reduces microbial biomass and activity.

3.2.2. Water Pollution

Excessive N fertilisers in tea plantations can result in N leaching into surface waters and groundwaters and can be aggravated through the improper application of fertilisers and irrigation [48]. N can be washed off from the tea plantations and seep into the groundwater or through surface waters (Figure 2). This leads to a risk of eutrophication and toxicity in water bodies and the water table [30].

Liu et al. (2012) investigated the application of different fertilisers in a tea plantation and studied the amount of N loss in the surface runoff [30]. They compared conventional fertilisers (urea), organic fertiliser (made from pig manure, chicken manure, oil tea seed meal, and humic acid), and slow-release fertiliser (polymer-coated fertiliser) and noticed that there was a higher nitrification rate in the chemical fertiliser treatment than in the slow release and organic fertilisers. The authors also noticed that there was an increase in nitrifying bacteria when ammoniacal fertilisers were added. Xu et al. (2017) also reported that high use of chemical fertilisers resulted in an annual N leaching loss of about 50 kg N ha^{-1} $year^{-1}$, equivalent to about 12% of the total N that was applied to the plots [49]. Maghanga et al. (2013) reported that application of NPK fertilisers can also increase surface water NO_3^- levels [50]. However, this increase was small and not to toxic levels, most likely due to the presence of well-draining soil. This suggests that site-specific soil properties [50], climate and fertiliser type [30], and the slope [51] play an important role in determining N loss through the surface water and groundwater leaching.

3.2.3. Gaseous Emissions

The extent of tea plantation greenhouse gas (GHG) emissions is dependent on the type of fertiliser applied and the application rate [52]. Globally, about 2–3% of the nitrogen applied as fertiliser is lost through N_2O emissions, with high rates requiring anaerobic conditions (water-saturated conditions) as well as a carbon source [53,54]. In China, where urea was applied to tea at a rate of 450 kg N ha^{-1}, emissions of N_2O (14–21 kg N ha^{-1} $year^{-1}$) and NO (18–19 kg N ha^{-1} $year^{-1}$) were greater than those for equivalent croplands [55]. Wang et al. (2020) reported mean N_2O emissions of 17.1 kg N ha^{-1} $year^{-1}$, equivalent to 8008 kg CO_2-eq ha^{-1}, approximately double the GHG footprint of rice [20]. In Japan, Tokuda and Hayatsu (2004) reported an annual N_2O emission of 25 kg N ha^{-1} after the application of 1200 kg N ha^{-1} $year^{-1}$, but only 0.6 kg N ha^{-1} with the application of 600 kg N ha^{-1} $year^{-1}$ [32]. Moreover, in Japan, Hirono and Nonaka (2012) reported mean annual N_2O emissions of 10.6–14.8 kg N ha^{-1} $year^{-1}$ from the application of 510 kg N ha^{-1} $year^{-1}$, with 65% of the emissions derived from an area of fertilizer application between the tea bushes and 35% from soils under the tea canopy [56]. The highest diurnal fluxes were associated with periods of high rainfall. The N_2O emissions from under the tree canopy were related to the falling leaves which were estimated to contribute 115–258 kg N ha^{-1} $year^{-1}$ [56]. Yao et al. (2015) also observed that rainfall events were a dominant driver of N_2O emissions [55].

Alongside N_2O, ammonia (NH_3) is also released from fertilisers (particularly urea) although the extent is dependent on soil conditions. NH_3 can have significant negative effects on human health as well as the natural environment [57]. In the atmosphere, NH_3 has the capacity to bind with other gases such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) to form fine particulate matter less than 2.5 µm [58]. This can cause health issues when inhaled, including impacts on cardiovascular and respiratory health by contributing to chronic conditions such as heart attacks, cerebrovascular disease, chronic obstructive pulmonary disease (COPD), asthma, and lung cancer [59–62].

3.3. Alternative Nitrogen Management Strategies

3.3.1. Integrated Nutrient Management

As a result of the wide-ranging adverse environmental impacts, there is a growing need to identify and apply alternative N management practices, alongside altering the application rates of conventional mineral fertilisers. These range from using organic or control release fertilisers, using a mixture of organic and inorganic fertilisers, intercropping with legumes, adding nitrification inhibitors, biofertilisers, soil amendments, applying such approaches in combination, and changing farm-scale management practices (Figure 3). Alongside studies of individual techniques, no studies were identified that have specifically investigated potential interactive effects between different management practices (for example combined soil amendments (biochar) with organic fertilisers), despite evidence from other agroecosystems on the potential benefits of such approaches [63].

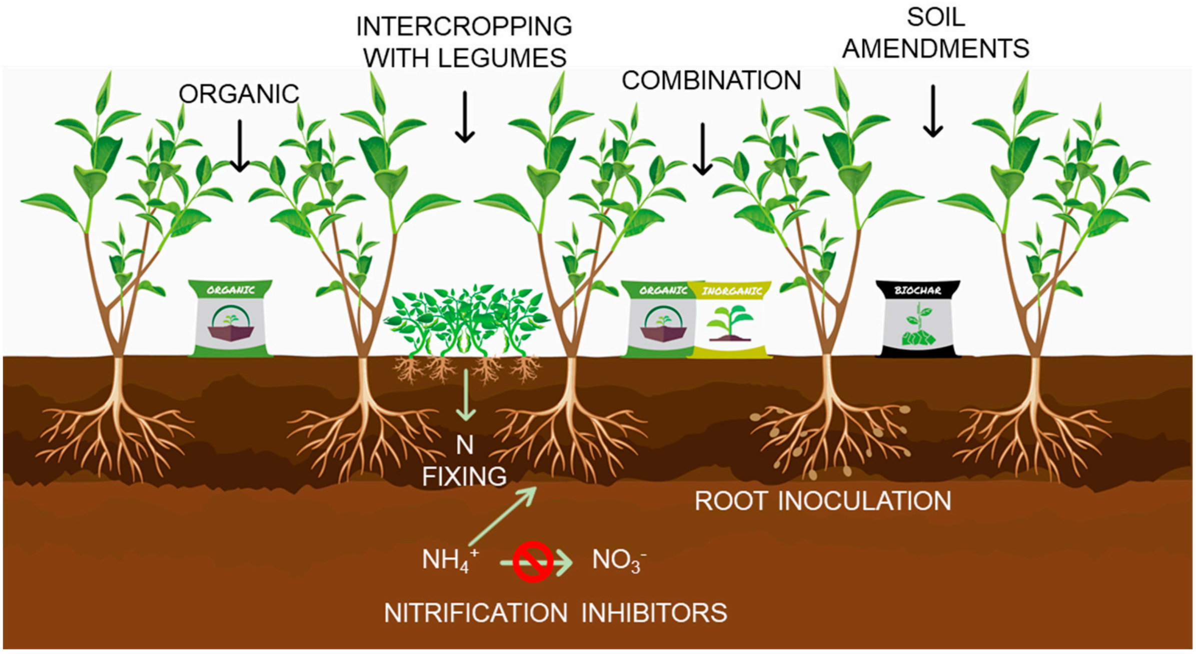

Figure 3. Integrating alternative nitrogen management practices for tea plantations.

There are a number of trade-offs associated with the use of these alternatives which range from lower yields, enhanced N_2O emissions, and the need for training or education to improve the adoption rates of the alternatives by farmers. This is highlighted by Hamid et al. (2021) who noted that when farmers are aware of potential benefits from reduced N fertiliser use, they are more likely to alter practices [64].

A limited number of studies assessed using a variety of integrated nutrient management practices and alternative application approaches to help address issues arising from the excessive use of N fertilisers. For example, Liu et al. (2012) [30] suggested the application of conventional fertilisers but at times when there was no rain anticipated to minimise surface runoff N losses. This was also suggested by Wang et al. (2018) but this approach depends on having accurate weather data and since tea plantations are located in regions that receive moderate to heavy rainfall, the reliance on there being a period of no rainfall for fertiliser application would be quite difficult [51]. Since many tea plantations are grown on hills with a slope, Wang et al. (2018) also suggested the use of contour planting to help in reducing the N losses due to surface runoff. However, such an approach is largely limited to the development of new plantations [51]. Liu et al. (2014) examined the effect of fertigation—applying nutrients in irrigation water. They showed that applying 83 kg N ha^{-1} through drip irrigation enabled similar tea yields as plots conventionally receiving 138 kg N ha^{-1}. Higher yields with fertigation were also matched by lower levels of nitrogen lost through runoff and leaching. Where irrigation is used, fertigation is one approach to maintain yield whilst minimising fertiliser inputs and negative environmental effects [65].

In China, Tang et al. (2021) investigated using the Nutrient Expert system, originally developed for optimizing fertiliser regimes in maize, rice, and wheat (i.e., non-perennial crops) [66]. The system relies on understanding the relationship between yield response (the difference between the yield in the treatment receiving NPK and that with no fertiliser) and agronomic efficiency (the yield increase per unit of N, P, and K applied). The use of the Nutrient Expert system contributed to a 14% increase in yields compared with conventional practices, as well as increased tea quality (increased total amino acid concentration).

Tang et al. estimated that the system was able to reduce N_2O emissions by approximately 28% compared with conventional practices [66].

3.3.2. Alternative Fertilisers

Organic fertilisers can be broadly classified into plant-based and animal-based fertilisers. Examples of plant-based fertilisers are compost, cottonseed meal, alfalfa and soyabean meal, and seaweed. Animal-based fertilisers include farmyard manure, blood meal, bone meal, and fish emulsion or fish meal [67]. Wang et al. (2014) found that when commercial organic fertilisers made from pig and chicken manure were used in tea plantations, the increase in soil bacteria and archaea communities was greater than with any of the other fertilisation methods [68]. Gu et al. (2019) observed that soils in tea plantations receiving long-term treatments with organic fertilisers showed an increase in the soil microbial diversity and thereby potential improvements in the ecosystem function when compared with synthetic fertilisers [69]. Xie et al. (2021) found that organic rapeseed cake fertilisers were useful in increasing the soil pH, total organic matter (from 1.6% to 2.0%), and total NH_4^+ and NO_3^- [70]. Xie et al. (2019) reported a reduction in NH_4^+ and NO_3^- concentrations in runoff compared with traditional fertilisers [71]. A decline in overall N losses and leaching was also reported by Liu et al. (2016) who reported a 59% reduction in total N losses and a 76% reduction in leaching into waters compared with traditional fertilisers [72].

However, organic fertilisers are also associated with several trade-offs. When compared with conventional fertilisers, Liu et al. (2012) found that organic fertilisers (made from pig manure, chicken manure, oil tea seed meal, and humid acid) resulted in a 21.5% and 12.2% lower yield compared with chemical fertiliser over two years [30]. Yao et al. (2015) and Han et al. (2021) also note that there was an increase in the N_2O emissions by 71% when organic fertilisers were used instead of chemical fertilisers, but it was suggested that this depended on the fertiliser type, climate, and geographical location of the tea plantation [55,73]. The dependence on fertiliser type was noted by He et al. (2019) who found that soya bean cake fertiliser significantly increased the N_2O emissions (5.4 kg N ha^{-1} $year^{-1}$) by 11% compared with chemical fertiliser (4.8 kg N ha^{-1} $year^{-1}$) [1], while livestock manures decreased the N_2O emission rates by 41–50% to 2.0–2.6 kg N ha^{-1} $year^{-1}$ [74].

To moderate the issues that arise with using only organic fertilisers, some studies have investigated the use of organic and inorganic fertilisers in combination. In China, Xie et al. (2019) found that combining 50% of organic fertilisers with 50% of conventional fertilisers and a 50% reduction in pesticide application resulted in yields of 5.4 t ha^{-1}, compared with 4.9 t ha^{-1} in a control treatment with only mineral fertilisers and full pesticide applications [71]. Xie et al. also found that organic fertilisers reduced the ratio of polyphenols to amino acids, broadly indicative of a superior aroma and taste in green tea. The authors also reported a 1.95% increase in caffeine levels. Debere et al. (2014) noted that combining fertilisers increased the height, the number of leaves per plant, the number of branches, and the root length of young plants [75]. Ji et al. (2018) found a significant increase in the soil bacterial community and diversity, the accumulation of soil carbon, and nutrients, with an application of 25% of organic fertiliser providing the best yield and quality [37].

Alongside organic fertilisers, biofertilisers (produced from substances that contain living microorganisms that colonise the plant rhizosphere to help in increasing the supply or availability of nutrients) may also provide benefits, although these are less well understood [76]. Xu et al. (2017) found that the application of a *Trichoderma viride* biofertiliser resulted in a 45% reduction in N leaching compared with the application of just conventional fertilisers [49]. This reduction was attributed to the ability of *T. viride* biofertilizers to promote root growth and nutrient uptake, and the slow release of NO_3^-.

3.3.3. Intercropping with Legumes

Leguminous plants can develop root nodules which enable them to fix N_2 in symbiosis with rhizobia bacteria and they may provide benefits through intercropping in tea plantations [77]. If the tea has an incomplete canopy cover, intercrops can help to reduce soil erosion and run-off [77–79]. Duan et al. (2019) investigated the impacts of intercropping young tea plants with soya bean and found that the soil NH_4^+ concentrations were higher in the intercropped tea than in the monoculture tea during the flowering period of the soybean. The variation in NH_4^+ and effective N remained the same, meaning that intercropping maintained soil N levels, findings that were also reported by Koenig and Cochran (1994) [79]. Duan et al. (2019) also reported increased free amino acids and caffeine concentrations with intercropping, suggesting that there was an improvement in the quality of the tea compared with monoculture tea plantations. The creation of tea varieties able to fix N through a symbiosis with rhizobia has also been proposed [80–83]. Rhizobia can fix N_2 [84] and increase N use efficiency [80].

3.3.4. Nitrification Inhibitors and Control Release Fertilisers

Nitrification inhibitors work by delaying the bacterial oxidation of NH_4^+ by depressing the activities of *Nitrosomonas* bacteria, which drive the transformation of NH_4^+ in the soil. The resultant NO_2^- is then reduced to NO_3^-, mediated by *Nitrobacter* and *Nitrosolobus* bacteria [85]. Considering the need to maintain the soil mineral N as NH_4^+ for longer and alleviate soil acidification, Wang et al. (2020) recommended that when fertilising with urea, urease and nitrification inhibitors are applied to limit N losses [46]. Qiao et al. (2021) found that with the application of DMPP (3,4–dimethylpyrazole phosphate, a nitrification inhibitor), soil pH increased at a urea application rate of 500 kg N ha^{-1} and above, due to reduced nitrification and increased plant uptake of NO_3^- [86]. The leaching losses of nitrates and total inorganic N were also noticed to decrease with the addition of DMPP.

A study by Han et al. (2008) found that control release fertilisers (CRFs) coated with nitrification inhibitors in a pot experiment resulted in an N use efficiency (46%) that was 17% higher than that (29%) with uncoated fertilisers [87]. CRFs which are sometimes referred to as slow-release fertilisers (SRFs) have been developed as an approach towards solving the issues that arise from the application of conventional fertilisers [85,88–90]. CRFs are designed with the aim to release the active ingredient at a controlled rate and to support by providing adequate nutrients for crop production [91,92]. Comparing three treatments each receiving 105 N ha^{-1} $year^{-1}$ from oilcake, Wu et al. (2018) found that the plots receiving 120 kg N CRF ha^{-1} $year^{-1}$ had 31% higher yields (4.1 t ha^{-1} $year^{-1}$) than those (3.1 t ha^{-1} $year^{-1}$) in plots receiving 345 kg N-urea ha^{-1} $year^{-1}$ [93]. However, the plots receiving 345 kg N CRF ha^{-1} $year^{-1}$ had the lowest yield (2.9 t ha^{-1} $year^{-1}$), which was associated with an inhibition of photosynthesis. In Sri Lanka, Raguraj et al. (2020) noted a 10–17% yield increase from the application of urea-coated "nanohybrid" CRF fertilisers compared with standard fertiliser treatments [92]. In China, Liu et al. (2012) [30] reported a 6–13% decrease in yields from CRFs-treated crops when compared with conventional fertilisers in a two-year study, but the difference was not statistically significant. Wu et al. (2018) reported that the N use efficiency was greater using CRFs compared with the conventional urea application when expressed as a function on tea yield [93]. However, in many instances, the benefits and trade-offs from CRFs and other fertiliser alternatives have only been investigated in the short term.

3.3.5. Soil Amendments

A range of soil amendments have been trialled in tea plantations with the view to improving soil health, including enhancing N availability to crops and mitigating GHG emissions. Pramanik, Safique, and Jahan (2018) found applying humic substances (HS) increased tea productivity and enhanced N availability, increasing the populations of nitrifying, ammonifying, and denitrifying bacteria [94]. An increase in yield was also reported. An HS application of 1.2 kg ha^{-1} delivered a yield of 1.8 t ha^{-1} for a period after application approximately 18% higher than non-HS treated fields. In China, Yang et al. (2021) reported that biochar increased annual tea yields from 2.6 t ha^{-1} to 2.8 t ha^{-1} for unfertilized tea and from 3.0 t ha^{-1} to 3.6 t ha^{-1} for tea receiving NPK fertiliser [95]. Yang et al. reported that the biochar-based fertiliser treatments had a higher diversity of fungal and soil bacteria, suggesting potential impacts on soil nutrient transformations. Wu et al. (2021) also reported an increase in mean annual tea yields by 17–26% from 3.1 t ha^{-1} to 3.6–3.9 t ha^{-1} when an addition of a wheat straw-derived biochar was introduced to the tea plantation [96].

Various studies also reported that additions of biochar decrease soil N_2O emissions in tea. In a field study, Han et al. (2021) used a biochar derived from herbaceous material in combination with different fertilizer types and reported a significant reduction in the soil N_2O emissions of 13% in the first year, irrespective of the type of fertiliser that was used [73]. Similarly, in a laboratory incubation, Oo et al. (2018) found that with the surface application of converted pruning residue biochar the soil N_2O emissions reduced by 36% compared with the control which had no addition of any biochar [97]. The field trial by Wu et al. (2021) found the N_2O emissions were dependent on the biochar application rate, with a low biochar amendment of 10 Mg ha^{-1} having mean annual N_2O emissions similar to conventional treatments [96]. A reduction in N leaching was also reported by Chen et al. (2021) in a laboratory leaching study. The authors reported that the addition of biochar significantly reduced the N leaching in the soils and enhanced soil N retention [98]. The authors also found that there was an inverse relationship between the application of biochar and N leaching, with an optimum application of 6% biochar (per unit mass of soil) found to have the highest mitigation of N leaching and retention of N, and also concurrently enhancing soil microbial biomass and enzyme activity. Lastly, in a field study, Yamamoto et al. (2014) assessed lime-N fertilisers as opposed to traditional inorganic fertilisers [99]. They found that the lime-N application significantly decreased soil N_2O emissions compared with conventional fertilisers.

4. Conclusions

Tea production requires the addition of N to replenish the N lost during the harvesting of tea leaves. Additional N can increase yields and the quality of green leaf tea, whereas the quality of black tea is reported to decline at high N applications. Higher yields are reported from the application of NH_4^+ rather than NO_3^- fertilisers. However, excessive and imprecise use of N fertilisers to increase tea yields has resulted in negative impacts on the environment such as soil acidification and the leaching of N into surface and groundwater, leading to eutrophication. The application of inorganic fertilisers also results in substantial emissions of N_2O, making tea plantations a net GHG source. A wide range of alternative N management techniques have been identified in the literature, and include the use of organic CRFs and biofertilisers, intercropping with legumes, root inoculation, use of nitrification inhibitors, and adding soil amendments. Collectively, these techniques may have an important role in reducing inorganic N inputs in tea plantations, but in general more evidence is needed before widespread adoption. Moreover, alternatives often have important trade-offs including lower yields and enhanced N_2O emissions.

Taken together, the available evidence suggests that the implementation of a site-specific management system which accounts for climate, soil nutrient levels, and field-specific fertiliser application data may help to combat the issues arising with the excess application of N fertilisers by monitoring the impacts and reducing them without negatively affecting the yield. The impacts of N fertilisers are site specific, with consequences that depend on the climate and the management practices used, therefore, requiring a tailored approach for each tea garden.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/nitrogen3010003/s1, Table S1: Studies identified on nitrogen management in tea plantations.

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