



## Best management practices for reducing nitrous oxide (N<sub>2</sub>O) emissions in vegetable production systems

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### ABSTRACT

**Context:** The increasing reliance on synthetic nitrogen (N) fertilizers and intensive soil management in vegetable production systems has led to substantial emissions of nitrogenous gases, including ammonia, nitric oxide, and nitrous oxide (N<sub>2</sub>O). Among these, N<sub>2</sub>O is a long-lived greenhouse gas with a high global warming potential (273 times that of CO<sub>2</sub>), making vegetable production a significant contributor to climate forcing due to high N demand and use, frequent irrigation, and low fertilizer recovery.

**Objective:** This review aims to synthesize current knowledge on best management practices (BMPs) for mitigating N<sub>2</sub>O emissions from vegetable production systems, with an emphasis on approaches that enhance N use efficiency while sustaining crop productivity and profitability.

**Methods:** A comprehensive review of peer-reviewed literature was conducted to evaluate N use patterns, N<sub>2</sub>O production pathways, emission drivers, and mitigation strategies in vegetable cropping systems. Studies examining practices such as fertilizer management, soil amendments, irrigation, microbial use, precision technologies, and integrated approaches were critically reviewed, and knowledge gaps were identified.

**Results:** The reviewed evidence indicates that excessive N application, poor synchronization between N supply and crop demand, and intensive irrigation are the primary drivers of elevated N<sub>2</sub>O emissions in vegetable cultivation. BMPs such as nitrification inhibitors; optimized fertilizer rates, timing, and placement; precision fertigation; negative pressure irrigation; and biochar amendments consistently reduced N<sub>2</sub>O emissions, often without yield penalties. The effectiveness of these strategies varies with soil type, climate, and crop type.

**Conclusions:** Mitigating N<sub>2</sub>O emissions in vegetable production requires shifting from input-intensive practices toward precise, holistic N management that integrates fertilizer, water, and soil management strategies. Single interventions can reduce emissions, but their effectiveness is strongly enhanced when implemented as part of coordinated management efforts.

**Implications:** Adopting BMPs and integrated N management can substantially reduce the climate footprint of vegetable production while maintaining economic viability. Future research should prioritize system-level assessments, long-term field studies including N<sub>2</sub>O emissions, and region-specific guidelines to support scalable, climate-smart vegetable production.

### 1. Introduction

Nitrogen (N) is an indispensable element in global agriculture and serves as a key nutrient for crop growth and food security [1]. Although the development and widespread adoption of synthetic N fertilizers

dramatically increased agricultural productivity, their overuse has led to severe planetary costs, including soil degradation, N leaching and water pollution, and greenhouse gas (GHG) emissions of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). This has pushed N pollution beyond sustainable thresholds [2,3].

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Among the various GHGs emitted from agricultural systems, N<sub>2</sub>O has emerged as a critical concern due to its high potency and long atmospheric persistence. According to the Intergovernmental Panel on Climate Change (IPCC) AR6, N<sub>2</sub>O has a global warming potential 273 times greater than that of CO<sub>2</sub>, making agriculture and N fertilizer use significant contributors to climate change [4]. Atmospheric N<sub>2</sub>O concentration reached 336 parts per billion in 2022, representing a 25 % increase over pre-industrial levels and significantly exceeding earlier IPCC projections, reflecting intensified anthropogenic emissions, with global N<sub>2</sub>O emissions estimated to have increased by 40 % over the last four decades [5]. By 2022, annual global N<sub>2</sub>O emissions reached approximately 17.7 Tg (teragram) of N, with agriculture as the dominant source, contributing about 60 % of total emissions. Within this sector, soil management and fertilizer use are the primary contributors, with agricultural soils emitting around 3.9 Tg of N annually, equivalent to 41.8 % of anthropogenic N<sub>2</sub>O emissions [5–7]. The N footprint also extends beyond field emissions, as synthetic fertilizer production and distribution account for 10.6 % of agricultural emissions and 2.1 % of global GHG emissions, corresponding to approximately 1.13 gigatonnes of CO<sub>2</sub> equivalent (GtCO<sub>2</sub>e) in 2018 [8]. Major agricultural economies, including China, India, the United States, and the European Union, account for a large share of these emissions due to their N-intensive production [8].

Within this broader agricultural context, vegetable production, although occupying a relatively small proportion of global croplands, accounts for exceeding 9 % of the world's total fertilizer consumption and 9.1 % of global N fertilizer use (118 Mt) in 2022 [9], reflecting the intensive management associated with vegetable production [10,11]. This intensity is driven by the high-value of vegetables, where fertilizer costs represent a small fraction of production expenses incentivizing over-application to minimize the yield risk, the rapid growth rates and short production cycles of vegetables requiring readily available soil N, and the premium quality standards demanded by fresh markets, driving farmers to apply high N to ensure optimal appearance, size, and marketability. This exacerbates inefficiencies as vegetable crops tend to exhibit lower N use efficiency [12]. The situation is particularly acute in intensive production regions. In China, for instance, in greenhouse vegetable cultivation, N rates exceeding 2000 kg per hectare per year are common, with synthetic fertilizers accounting for approximately 64.4 % of total N input, underscoring the environmental burden of these intensive systems [13]. Comparative analyses reveal that N input in vegetable production has increased 175.6 % faster than in other crops, necessitating new regional strategies to curb emissions [14].

Despite these challenges, vegetable production systems have significant N<sub>2</sub>O mitigation potential, with an estimated 16 % of cropland (0.7 Tg N<sub>2</sub>O year<sup>-1</sup>) [15]. However, realizing this potential requires addressing key gaps in region- and crop-specific N management strategies that account for diverse soil types, climatic conditions, and production systems; reliable metrics for tracking N losses; and promoting outcome-based mitigation practices [16–18].

Addressing these challenges requires implementing evidence-based Best Management Practices (BMPs), such as optimized nutrient and fertilizer management, good soil and water management, careful crop residue management, and precision agriculture, tailored to vegetable production contexts, which offer practical pathways to enhance N use efficiency (NUE) and reduce gaseous N losses. The effectiveness of BMPs should be reinforced by an improved understanding of the biological mechanisms regulating N<sub>2</sub>O dynamics. Given the disproportionate contribution of vegetable production to agricultural N<sub>2</sub>O emissions, their substantial mitigation potential, and unknown knowledge gaps, this review was undertaken with the following objectives:

- Evaluate current knowledge on N<sub>2</sub>O emissions from vegetable production systems.
- Review and assess the effectiveness of agronomic BMPs for N<sub>2</sub>O emission mitigation.

- Identify practices and strategies that balance vegetable productivity with environmental sustainability.
- Highlights knowledge gaps and research priorities for reducing N<sub>2</sub>O emissions in vegetable production.

## 2. Understanding the nitrogen cycle

With N<sub>2</sub>O emissions ranging from 1.13 to 48.1 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup>, accounting for approximately 9 % of global direct emissions from synthetic fertilizers, the N cycling in the vegetable sector needs to be understood and managed effectively [19–21]. To understand how these emissions are generated, we must consider the broader N cycle in agricultural systems, which comprises five major steps. In brief, the cycle begins with biological N fixation, which converts atmospheric N into reactive forms such as ammonia and nitrate; followed by ammonification; nitrification, which oxidizes ammonia to nitrate; microbial assimilation; and finally denitrification, in which nitrate is reduced to dinitrogen, nitric oxide (NO), and N<sub>2</sub>O under low-oxygen conditions [22]. N<sub>2</sub>O emissions arise from both natural and anthropogenic sources, including fossil fuel combustion, industrial activities, and biogeochemical soil processes, but agricultural soils represent the largest contributor, primarily through microbial nitrification and denitrification, which together account for approximately 70 % of the global N<sub>2</sub>O emissions [23] (Fig. 1).

Various microbial pathways, including ammonia oxidation, nitrifier denitrification, heterotrophic denitrification, and anaerobic ammonium oxidation, govern N<sub>2</sub>O production and consumption in soils. Nitrification and heterotrophic denitrification are the most significant sources of N<sub>2</sub>O emissions [24,25]. The availability of N substrates, such as ammonium and nitrate, strongly influences microbial production of N<sub>2</sub>O through these processes. In greenhouse vegetable production systems, the microbial processes are even more complex. A global meta-analysis by Wang et al. [26] found that heterotrophic nitrification is a major contributor to N<sub>2</sub>O emissions in greenhouse vegetable production systems. Estimates from the N trace model and N<sub>2</sub>O source partitioning indicate that N<sub>2</sub>O accounts for up to 84 % of gross N<sub>2</sub>O emissions, though net emissions vary due to concurrent N<sub>2</sub>O consumption. In comparison, autotrophic nitrification and denitrification contribute 0.3–31.4 % and 22.5–57.7 %, respectively. In vegetable systems, N losses are pronounced due to high input rates and suboptimal management practices [27,28]. Yao et al. [29] reported emission factors ranging from 1.1 % to 2.3 % in vegetable fields, highlighting the influence of intensive cultivation and frequent irrigation. Similarly, Zhang et al. [30] demonstrated that high-frequency irrigation in high-N vegetable rotation (amaranthus-bok choy-coriander-tung choy) significantly enhances denitrification. These findings are consistent with Gamayunova and Sydiakina [31], who identified excessive N application as a major cause of N losses. N losses are multifaceted and include leaching losses (56.1 % of total N input), surface runoff (11.7 %), and direct N<sub>2</sub>O emissions (1.6 % of N input), indicating an urgent need for more efficient management practices [32].

Cropland nutrient balances serve as important indicators of nutrient flows that can signal excess or insufficient conditions on agricultural lands, with excess nutrient loads pose risks, including nitrate leaching, erosion or runoff into water bodies, ammonia volatilization, and emissions of N<sub>2</sub>O and nitrogenous gases [16] (Fig. 2). A global meta-analysis by Conant et al. [33] which tracked N inputs and recovery rates by country and crop from 1960 to 2007, revealed that while N fertilization has increased globally, efficiency disparities remain significant between regions. For example, Organisation for Economic Co-operation and Development (OECD) countries exhibit higher yields and N recovery rates than non-OECD countries, although they also release more reactive N into the environment [33].

Effective mitigation of N<sub>2</sub>O emissions in vegetable production requires integrating evidence-based practices tailored to local conditions. With the potential to lower N<sub>2</sub>O emissions by 30–80 % through practices

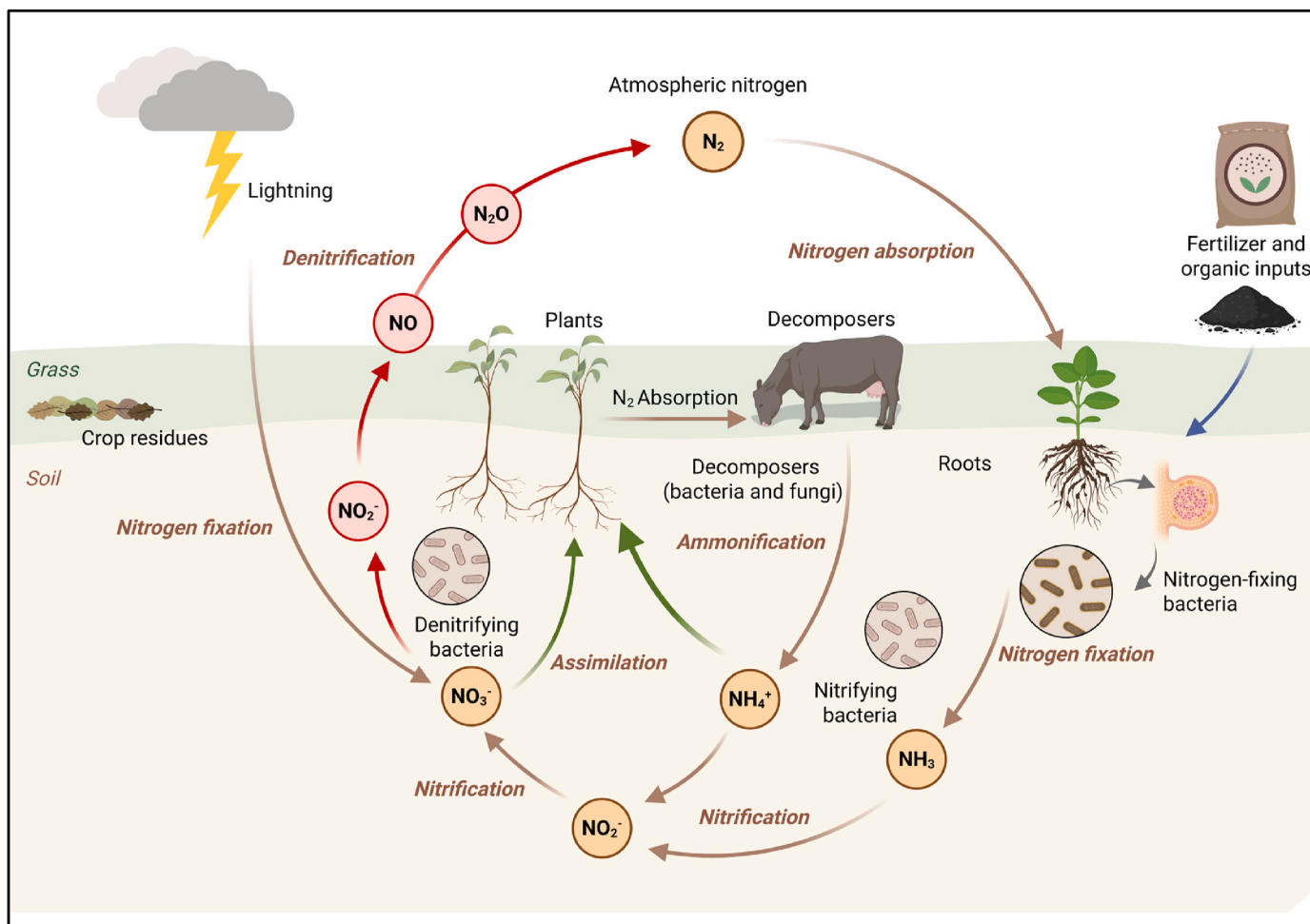


Fig. 1. Schematic representation of the nitrogen cycle.

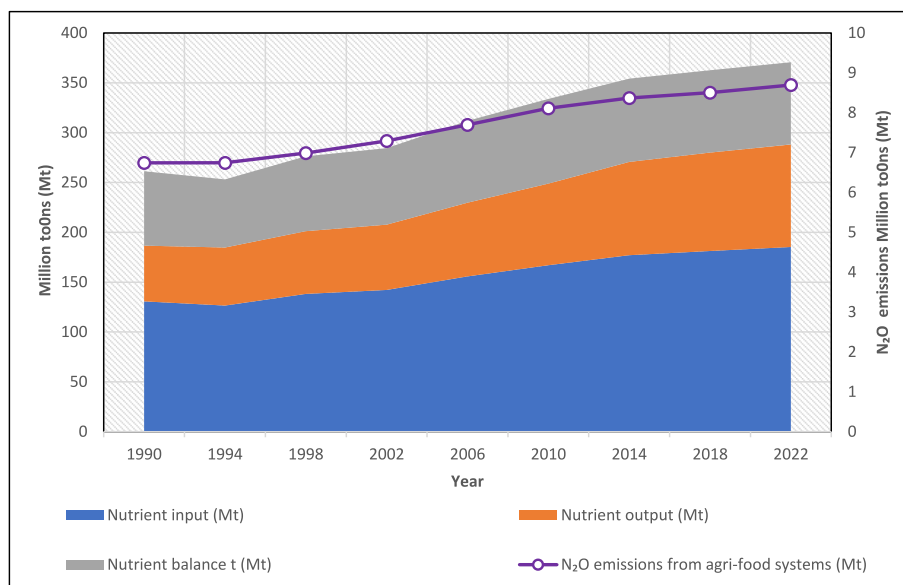


Fig. 2. The figure shows global trends in nutrient input, output, balance, and N<sub>2</sub>O emissions from agri-food systems between 1990 and 2022. Nutrient inputs (blue) rose steadily with agricultural intensification, while outputs (orange) increased more slowly, creating a widening nutrient surplus (grey) and associated environmental risks. N<sub>2</sub>O emissions (purple) have stayed relatively constant, underscoring the link between inefficient nitrogen use and greenhouse gas emissions. (Source: FAOSTAT: <https://www.fao.org/faostat/en/#data/ESB>. Accessed: 2025-11-11). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

such as combining organic amendments with reduced tillage and reducing CO<sub>2</sub> emissions through decarbonized fertilizer production, the sector can make a substantial contribution to climate mitigation [34, 35].

### 3. Soil, climatic, and environmental conditions affecting N<sub>2</sub>O emissions in cropping systems

#### 3.1. Soil physico-chemical properties

Soil physico-chemical properties play a pivotal role in regulating N<sub>2</sub>O emissions in agricultural systems directly and indirectly through shaping microbial communities. Soil properties drive basal emissions, explaining up to 56 % of variance, while microbial abundance and diversity dominate high emissions (microbial abundances explain 23 % of the 95th percentile). Key predictors include soil pH, SOM, C/N ratio, N<sub>2</sub>O -producer abundance, and nosZII community diversity. Soil texture and structure play equally crucial roles. Gotze et al. [36] and Cui et al. [15] found that sandy soils exhibit delayed, but the highest N<sub>2</sub>O emissions, whereas clayey soils have the potential to mitigate NH<sub>3</sub> emissions due to their superior water-holding capacity. Furthermore, soil organic matter (SOM) plays a critical role in regulating N<sub>2</sub>O emissions, and research has indicated that higher SOM levels can increase emissions by stimulating nitrifying and denitrifying microorganisms [37,38]. Soil microbial biomass, which accounts for 1–5 % of total SOM, drives these transformations. For example, converting rice paddies to vegetable fields can elevate emissions by increasing SOM mineralization under aerobic conditions [39]. Additionally, greenhouse vegetable systems cultivating lettuce, tomato, and capsicum under high N and organic inputs exhibit pronounced heterotrophic nitrification [26].

Notably, soil moisture emerges as the master variable. When water content increases, soils transition to anaerobic conditions, favoring denitrification and amplifying N<sub>2</sub>O release [40,41]. The concept of water-filled pore space (WFPS) captures this state by governing the balance between aerobic and anaerobic conditions, with values exceeding 60 % favoring denitrification [42,43] and N<sub>2</sub>O accumulation, as observed in tomato production [44] and vegetable rotations [42]. In addition, bulk density and aeration influence gas diffusion and the rate at which N<sub>2</sub>O can be reduced to dinitrogen. Even transient anoxic zones, if supplied with labile carbon, such as oxalic acid or glucose, can trigger intense denitrification pulses [43,44].

Finally, Soil pH adds yet another dimension. Rather than acting uniformly, it tilts the microbial balance in different directions, as evidenced by Li et al. [45] and Lin et al. [46], which showed that alkaline soils enhance the activity of ammonia-oxidizing bacteria, increasing N<sub>2</sub>O production. In contrast, Qiu et al. [47] found that acidic soils promote fungal denitrification pathways, and Signor and Cerri [48] established that pH effects are process-dependent, where denitrification-dominated systems show reduced emissions with increasing pH, whereas nitrification-dominated systems stimulate production at higher pH levels.

#### 3.2. Climatic and environmental conditions

Climatic and environmental conditions play pivotal roles in regulating N<sub>2</sub>O emissions from vegetable production, with temperature and moisture serving as primary drivers that are expected to intensify under climate-change scenarios [49,50]. Temperature is a critical factor, as warmer conditions substantially enhance emissions through accelerated nitrification and denitrification, with peak emissions at 35 °C [51]. Similarly, wet organic soils with high moisture content exhibit significantly higher N<sub>2</sub>O emissions than drier conditions due to the enhanced activity of ammonia-oxidizing bacteria and denitrifying microorganisms [40]. For instance, Huang et al. [52] reported substantial increases of  $2.50 \pm 0.98$  Tg N<sub>2</sub>O per 100 mm of precipitation in arid regions, attributed to enhanced microbial activity stimulating both nitrification

and denitrification. However, this relationship is nonlinear, as very high moisture content can decrease N<sub>2</sub>O production by inhibiting microbial activity, while alternating wet and dry periods amplify emissions [53]. According to Wu et al. [39], the combined effects of temperature and moisture show the greatest interactions, with 73 % of emission variation explained by soil temperature and WFPS. Schafler et al. [54] confirmed that emissions generally increase with rising temperature and soil moisture through nonlinear interactions. Liu et al. [55] demonstrated that nitrification is the primary source of N<sub>2</sub>O production, contributing 33–87 % depending on moisture and temperature. Ammonia-oxidizing archaea (AOA) often surpass bacteria in production under extremely wet conditions.

Climate change is expected to intensify these environmental effects through altered precipitation patterns and extreme weather events, creating self-reinforcing cycles that worsen the greenhouse effect, particularly in tropical regions [56]. According to Winiwarter et al. [57], extreme precipitation and high humidity amplify emissions while enhancing the emission factors for N inputs, underscoring the critical need for integrated N and water management strategies. Regional climatic differences further complicate emission patterns. Li et al. [58] note that colder regions experience seasonal changes in temperature and moisture that strongly affect long-term emission dynamics, while the effectiveness of management practices depends heavily on environmental conditions. For example, Aguilera et al. [59] showed that N fertilizer applications during wet weather increase emissions. Liang et al. [60] demonstrated that high-elevation vegetable production areas exhibit N and carbon footprints 16.2–17.3 % lower than those at low elevations, with 26.5 % higher yields under best management practices, potentially reducing footprints by 44–45 %. Environmental factors, including freeze-thaw cycles, are particularly significant, as Wagner-Riddle et al. [61] estimated that seasonally frozen croplands contribute  $1.07 \pm 0.59$  Tg of N as N<sub>2</sub>O annually, potentially underestimating global agricultural emissions by 17–28 %. According to Wu et al. [62], emission dynamics during these periods depend heavily on soil available N content, texture, and bulk density, emphasizing the complex interplay between climatic conditions and soil properties in determining N<sub>2</sub>O emission patterns across diverse vegetable production systems.

### 4. Management practices and their optimization for reduced N<sub>2</sub>O emissions in vegetable production

Management practices strongly regulate N availability, microbial activity, and soil-water environment, making them essential for controlling N<sub>2</sub>O emissions in vegetable production. Key strategies include optimized fertilizer and nutrient management, conservation tillage, precise irrigation, biofertilizers, cover cropping, and soil amendments like biochar and liming. System-level approaches, such as climate-smart crop rotations and integrated production systems, can also mitigate emissions. These practices collectively offer pathways to reduce N<sub>2</sub>O emissions while sustaining vegetable productivity. The main strategies are described in subsections 4.1–4.8 below.

#### 4.1. Fertilizer and nutrient management

Fertilizer and nutrient management have emerged as central themes in discussions on N<sub>2</sub>O emissions from vegetable production. N fertilizers are the dominant contributors to these emissions because excessive application stimulates microbial processes such as nitrification and denitrification, which drive N<sub>2</sub>O production [63].

The application mode of fertilizers, including rate, form, and timing, largely determines the emission dynamics. Yan et al. [64] observed that N<sub>2</sub>O fluxes in vegetable soils tend to peak shortly after fertilization, particularly when soluble synthetic fertilizers are used. These inputs rapidly release N, thereby intensifying emissions more rapidly compared to organic amendments [65]. The situation is compounded when N is

supplied at superoptimal levels, as highlighted by Harrison et al. [66], who reported a nonlinear escalation in emissions with increasing application rates. Moreover, the interaction between organic and inorganic nutrient sources appears complex. Interestingly, Lin et al. [67] reported contrasting findings, noting that mixing organic and synthetic fertilizers produced the highest emission factors in vegetable fields, with mineral fertilization resulting in N<sub>2</sub>O and NO emission rates of 1.43 % and 1.15 %, respectively, and mixed fertilization showing slightly lower values of 0.99 % and 0.67 %, respectively. Additionally, Wang et al. [26] observed that combining organic manure (rape cake, chicken manure, and rice hull ash) with synthetic N fertilizers in greenhouse vegetable production increased heterotrophic nitrification, leading to higher N<sub>2</sub>O emissions. This effect likely varies with climatic conditions, soil type, and the specific organic materials used, which can influence N availability and microbial processes.

The form of fertilizer adds another layer of complexity to N dynamics. Inputs prone to nitrate (NO<sub>3</sub><sup>-</sup>) leaching and ammonia (NH<sub>3</sub>) volatilization often led to higher N<sub>2</sub>O emissions, depending on the fertilizer formulation and management practices [59]. However, the evidence remains inconsistent across cropping systems. For instance, in open-field vegetable systems in China, Wang et al. [68] reported that emission patterns were more closely linked to application rates than to fertilizer type. A broader synthesis by Yang et al. [69] further demonstrated that yield-scaled emissions differ widely across vegetable groups in the following order: stem < root < leafy < fruit < seed.

Historically, much research has focused on optimizing fertilizer and nutrient management to improve crop yields, particularly in vegetable crops such as potato [70] and tomato [71,72], rather than addressing the environmental consequences of nutrient overuse. In recent years, attention has shifted toward balancing yield gains with environmental sustainability [11]. Strategies such as integrated and precision nutrient management are now receiving considerable attention, as they have demonstrated the potential to reduce N losses and emissions while sustaining yields [73–75]. Based on the present literature review, the following strategies for fertilizer and nutrient management have been identified as effective in reducing N<sub>2</sub>O emissions:

#### 4.1.1. Enhanced-efficiency fertilizers and nitrification inhibitors

Enhanced-efficiency fertilizers (EEFs), including slow-release formulations and nitrification inhibitors, are currently among the most effective tools for reducing agricultural N<sub>2</sub>O emissions [76]. Guertal [77] reported that slow-release N fertilizers, categorized as either chemically reactive (e.g., urea-formaldehyde and isobutylidene diurea) or coated (e.g., sulfur-coated urea and resin-coated urea), play a significant role in improving N management in vegetable production. These fertilizers release N gradually, either through chemical reactions or controlled dissolution of their coatings, thereby synchronizing N availability with crop demand. Such controlled-release mechanisms help minimize N leaching losses, particularly in sandy soils where nutrient mobility is high. Moreover, they allow for N to be applied as a single preplant treatment rather than through multiple split applications, reducing labor and operational costs. Overall, the use of slow-release fertilizers enhances N use efficiency, lowers production costs, and reduces the ecological footprint in vegetable production.

Nitrification inhibitors (NIs), such as 3,4-dimethylpyrazole phosphate (DMPP) and dicyandiamide (DCD), have shown promising results. Scheer et al. [78] demonstrated that DMPP reduced N<sub>2</sub>O emissions by 75 % in broccoli production. Muller et al. [79] reported a 51 % reduction in N<sub>2</sub>O emissions in sweet corn using DMPP and Piadin with a 20 % reduction in N fertilizer rates. Yan et al. [64] reported a 24.7 %–34.6 % reduction in N<sub>2</sub>O emissions through DCD. These strategies enhance N use efficiency by slowing the conversion of ammonium to nitrate, thereby reducing substrate availability for nitrifiers [80]. However, extending N in the ammonium form can increase ammonia volatilization. Zhang et al. [81] found that ammonium-based fertilizers combined with NIs significantly reduced emissions. Yang et al. [69] concluded that

EEFs were more effective in greenhouses than in open-field systems and worked better for leafy vegetables than for root crops. Ding et al. [82] demonstrated that combining NIs with biochar reduced N<sub>2</sub>O emissions by 23.4 % in greenhouse vegetable fields in North China. The effectiveness of different inhibitors varies, with Li et al. [83] showing that GHG emission reductions followed the order N-(n-butyl) thiophosphoric triamide (NBPT) > DCD > DCD + NBPT > 2-chloro-6-(trichloromethyl) pyridine (CP) + NBPT > CP. Other studies, as presented in Table 1, have demonstrated the benefits of EEFs in various contexts, such as reducing N<sub>2</sub>O emissions in vegetable rotations (50–85 % with slow-release fertilizers in heavy clay soils, 64–76 % with NIs in celery, and 45.9 % with DCD + biochar in red soils) and improving N use efficiency across different soil types.

#### 4.1.2. Fertilizer application methods and timing

Localized application methods, such as banding, fertigation, and starter fertilizers, enhance nutrient uptake by targeting the root zone in vegetables like lettuce [109]. These methods improve crop performance, quality, and maturity [110]. Placement of fertilizer at a 5 cm depth under reduced or no-tillage practices has also been effective as it minimizes nutrient leaching and runoff, particularly in humid conditions [111].

Matching fertilizer application to crop growth stages is vital for emission reduction. By synchronizing nutrient availability with plant demand, losses and emissions can be minimized [112]. Precision fertilization in small-scale multi-crop systems has been shown to improve nutrient-use efficiency and reduce N<sub>2</sub>O emissions [113]. This approach can also lead to higher yields at lower application rates than conventional broadcasting methods [112]. For example, research on head lettuce has revealed that 70–80 % of its N uptake demand occurs between heading and harvest, creating a concentrated period of N demand that can guide application timing [110]. By understanding crop-specific uptake patterns, farmers can implement precise fertilizer scheduling that maximizes plant N capture while minimizing soil N availability for the microbial conversion to N<sub>2</sub>O. Similarly, studies on potatoes have demonstrated the importance of timing in fertilizer application. Burton et al. [91] found that split applications of fertilizer N can lead to superior emission control compared to single large applications, as the timing of application influences the availability of nitrate as a substrate for denitrification. By adopting precision fertilization techniques, farmers can reduce N<sub>2</sub>O emissions while improving crop yields. Other studies, as shown in Table 1, highlight that precision fertilization techniques like split applications (60 % at planting, 40 % at hilling) and targeted placement (in furrows, not hills) reduce N<sub>2</sub>O emissions in potatoes by 31–39 % and 67 %, respectively, minimizing N losses and increasing yield [114].

#### 4.1.3. Fertilizer rate reduction

Zhang et al. [30] indicated that reducing N application rates by one-third from conventional levels can significantly lower yield-scaled N<sub>2</sub>O emissions without compromising crop productivity. BMPs that align with the 4R nutrient stewardship (right source, right rate, right time, and right place) framework can reduce N<sub>2</sub>O emissions by 30–80 % without negatively affecting yields [115]. A case study by Wang et al. [116] on greenhouse pepper production found that integrated soil–crop system management reduced reactive N losses, including N<sub>2</sub>O emissions, by 28 % compared to conventional practices. Lin et al. [67] found that the sole application of organic fertilizers not only improved vegetable yields but also avoided increases in NO and N<sub>2</sub>O emissions, highlighting their potential as sustainable alternatives. Emission factors from vegetable-specific case studies typically range between 1 and 3 % of applied N, highlighting variability and the potential for targeted practices to bridge knowledge gaps and improve emission mitigation strategies [117]. Some studies, as provided in Table 1, demonstrate that reducing N application by 1/3 in intensive production (>60 % emission reduction in celery, sandy soils) and combining residue with fertilizer

**Table 1**  
Integrated best management strategies for N<sub>2</sub>O emission reduction in vegetables.

Strategy	Technical Details	N <sub>2</sub> O Reduction Potential	Crop	Soil	Mechanism/Implementation Protocol	References
<b>1. Fertilizer and nutrient management</b>						
<i>a) Enhanced efficiency fertilizers (EEFs)</i>						
Slow-Release Fertilizers (SRFs)	Not mentioned	Not quantified	Chinese cabbage	Heavy clay	Single application per season	[84]
Organic + Conservation System	Organic + conservation agriculture practices	50–85 %	Vegetable rotation	Loamy sand	Organic fertilizer, tillage reduction, crop rotation	[85]
Nitrification Inhibitors (NIs)	Use 3,4-dimethylpyrazole phosphate (DMPP) at 0.5–1.5 kg ha <sup>-1</sup> or dicyandiamide (DCD) at 5–10 kg ha <sup>-1</sup>	64–76 %	Celery	Sandy	Apply NIs with fertilizer at the start of the season start	[86]
Nitrification Inhibitors (NIs)	DMPP	20–60 %	Vegetable rotation	Black vertisol	Adjust N rates to avoid post-harvest oversupply	[87]
Combined Approach (DCD + Biochar)	DCD + biochar	45.9 %	Vegetable rotation	Red soil	DCD with fertilizer + biochar incorporation	[88]
Lime-Nitrogen (LN) application (CaCN <sub>2</sub> )	LN100 (100 % lime-nitrogen)	30.9 %	–	Andosol	Apply alone or with chemical fertilizer	[89]
<i>b) Optimized nitrogen application</i>						
Reduced N Application	Reduce N by 1/3 in intensive systems	>60 %	Celery	Sandy	Reduce N without yield loss	[90]
Reduced N Application	Reduce N by 40 %	Not quantified	Vegetable rotation	–	Include legumes in rotation	[32]
Split Application	Apply 60 % at planting, 40 % at hilling	31–39 %	Potato	Coarse loamy	Timed split application	[91]
Precision Application	Apply in furrows, not hills	67 %	Potato	Coarse loamy	Fertilize in furrows	[91]
Residue + Fertilizer application	Surface mulch + mineral N	84 % (residue); 62 % (fertilizer)	Basil	Vertisol	Combine the residue with fertilizer	[92]
Fertigation	Fertilizer via irrigation	80 %	Tomato	Calcareous	Adjust N based on tissue tests	[93]
Manure Types	Composted vs raw manure	Not quantified	Vegetable rotation	Black vertisol	Prefer composted manure	[94]
N Source Selection	Nitrate vs urea	Not quantified	–	–	Split nitrate applications, limited irrigation	[20]
<i>c) Soil amendments</i>						
Biochar Amendment	20–40 Mg ha <sup>-1</sup>	4–39 %	Vegetable rotation	Anthrosols	Apply 20–30 Mg ha <sup>-1</sup>	[35]
Biochar	20 t ha <sup>-1</sup>	N <sub>2</sub> O 10–23 %; NO 18–19 %	–	Anthrosols	Use in greenhouse fields	[95]
Biochar + N Fertilizer	Maize straw biochar + urea/manure	77–86 %	Choy sum-amaranth	Anthrosols	Apply 30 Mg ha <sup>-1</sup> with fertilizer	[96]
Biochar in Vegetable Systems	Biochar amendment	12–22 %	Vegetable rotation	Silt loam	Use in high-N fields	[97]
Composted Manure	Composted vs raw chicken manure	Not quantified	Vegetable rotation	Black vertisol	Use composted instead of raw manure	[94]
Straw Incorporation	Straw + drip irrigation + less fertilizer	5–10 ×	Tomato	Cambisol	Use drip fertigation + straw	[93]
<i>d) Microbial amendments</i>						
Potting Mixture	Replace peat with sphagnum	55 %	Lettuce	Sphagnum	Apply at planting	[98]
Bio-Organic Fertilizer	Manure + <i>Trichoderma guizhouense</i>	18.7 %	Cucumber	Yellow brown	Apply 5–8 t ha <sup>-1</sup> before planting	[99]
<b>2. Tillage and traffic management</b>						
<i>a) Tillage practices</i>						
No Tillage	No soil disturbance	Not quantified	Organic rotation	Sandy loam	Apply on coarse soils w/ winter cover crops	[100]
Strip Tillage	Tillage in planting rows	Not quantified	Organic rotation	Sandy loam	Use winter cover crops	[100]
<i>b) Traffic management</i>						
SCTF	Wheel traffic in fixed lanes	20–50 %	Organic rotation	Loam	Use precise machinery	[101]
Reduced Compaction	Manage traffic zones	Not quantified	Organic rotation	Loam	Create non-trafficked zones	[101]
<b>3. Irrigation management</b>						
Negative Pressure Irrigation (NPI)	Porous pipes (–5 to –10 kPa), 105 kg N ha <sup>-1</sup>	32 %	Lettuce	Sandy loam	20–30 cm depth; 70 % N pre-planting	[102]
Subsurface Drip Irrigation (SDI)	15 cm depth, 40 cm spacing	10.7 %	Chinese cabbage	Clay loam	15 cm depth; 4–6 fertigations	[103]
Non-Aerated Deficit Irrigation	No-air delivery with water	Not quantified	Tomato	Silt clay loam	Manage aeration under deficit irrigation	[104]
Negative Pressure Irrigation (NPI)	Stable soil moisture	Area: 15 %; Yield-scaled: 29 %	Amaranthus, lettuce	Silty loam	Subsurface pipes at 30 cm	[105]
<b>4. Cropping system adaptations</b>						
<i>a) Cover crops</i>						
Mixed Cover Crops	Radish, clover, rye (varied seeding)	~7 % w/covers; ~70 % early planting	Rye-radish-clover	Sandy	Early planting, late killing	[106]

(continued on next page)

Table 1 (continued)

Strategy	Technical Details	N <sub>2</sub> O Reduction Potential	Crop	Soil	Mechanism/Implementation Protocol	References
Legume Cover Crops	N-fixing legumes in rotation	74 %	Not mentioned	Silty	Timely planting	[107]
<i>b) Crop management</i>						
Low-N Varieties	High nitrogen use efficiency	Up to 50 %	–	–	Select efficient varieties	[80]
Crop Rotation	Diverse crops in sequence	Up to 50 %	–	–	Include legumes	[80]
Intercropping	Multiple crops simultaneously	20 %	Onion-wheat	Cambisol	Mix species for synergy and efficiency	[108]
<i>c) Integrated production systems</i>						
ORG (organic conservation practices) +	Organic + conservation practices	Not quantified	Rotation	Sandy loam	Use organic inputs in rotations	[85]
DIF (drip fertigation)	Drip fertigation + straw incorporation	5–10 ×	Tomato	Cambisol	Use drip irrigation with reduced fertilizer	[93]

(84 % and 62 % reductions in basil, vertisol) can effectively minimize N<sub>2</sub>O emissions and improve crop yields. Overall, optimizing fertilizer type, rate, timing, and placement remains the most direct and effective strategy for mitigating N<sub>2</sub>O emissions in vegetable systems, particularly when aligned with precision and integrated nutrient management approaches.

#### 4.2. Tillage practices

Tillage practices play a crucial role in shaping soil structure, microbial dynamics, and N cycling, which in turn influence N<sub>2</sub>O emissions. Conventional tillage disrupts soil aggregates, stimulates microbial activity, and accelerates N mineralization and organic matter decomposition, thereby increasing N<sub>2</sub>O emissions [48]. Chen et al. [114] found that frequent soil disturbance from conventional tillage in organic vegetable production is associated with elevated N<sub>2</sub>O emissions, driven by increased aeration and N mineralization. However, the effects of tillage are highly context-dependent and not always predictable. A global meta-analysis by Mei et al. [118] found that conservation tillage increased N<sub>2</sub>O emissions by 17.8 % overall, with the highest increase of 70.1 % observed in tropical agricultural lands. Moreover, specific tillage configurations, such as ridge-furrow systems, create spatially heterogeneous emission patterns, with higher N<sub>2</sub>O fluxes observed on growing beds compared to furrows [119]. Interactions with other practices, such as cover crops in strip-tillage systems, can further alter N dynamics and unexpectedly increase emissions [120].

In contrast, conservation tillage practices (no-tillage and strip-tillage) often mitigate N<sub>2</sub>O emissions by preserving soil structure and fostering stable microbial habitats. Studies on vegetable crops, such as Chinese cabbage, indicate that good soil management enhances soil biological resilience while reducing emissions under certain conditions [121,100]. Case studies in Chinese cabbage fields showed that no-tillage reduced N<sub>2</sub>O emissions by 31–77 % relative to conventional tillage across seasons [122]. Low-disturbance systems also suppress microbial nitrification and denitrification, the primary biological processes driving N<sub>2</sub>O production [98]. These findings collectively demonstrate that conservation tillage moderates microbial activity and maintains stable soil ecosystems, thereby lowering emission risks.

The long-term effectiveness of conservation tillage depends on consistent implementation and integration with complementary practices such as crop rotation, cover cropping, or mulching. Van Kessel et al. [111] noted that significant reductions in N<sub>2</sub>O emissions from no-till and reduced-till systems typically appear only after a decade of continuous practice, particularly in drier climates. When combined with strategies like weed cover mulching, conservation tillage can maintain soil health without causing substantial emission spikes [123]. Additionally, Controlled Traffic Farming (CTF) has been shown to improve soil porosity and water infiltration while limiting nitrate leaching, offering an effective means to manage emissions through improved soil structure [101]. Overall, adopting reduced-tillage systems supports long-term soil resilience, productivity, and greenhouse gas mitigation, emphasizing

their value in sustainable vegetable production. Studies in Table 1 demonstrate that no-tillage and seasonal controlled traffic farming (SCTF) (20–50 % compaction reduction) support soil health in organic rotations. In addition to soil disturbance, water management strongly influences oxygen availability and N transformations, thereby shaping N<sub>2</sub>O emissions.

#### 4.3. Irrigation management

Water management plays a crucial role in regulating N<sub>2</sub>O emissions in vegetable production systems. Over-irrigation can lead to anaerobic microsites, favoring denitrification and increasing N<sub>2</sub>O emissions [124]. The irrigation method significantly affects emission levels, with flood irrigation promoting higher emissions due to increased heterotrophic denitrification under saturated conditions [125]. For example, in melon crops, furrow irrigation resulted in N<sub>2</sub>O emissions up to 70 % higher than those under surface drip irrigation due to higher denitrification rates caused by soil waterlogging [126]. Similarly, Kallenbach et al. [127] found that N<sub>2</sub>O emissions were approximately 50 % higher from furrow-irrigated tomatoes than from subsurface drip irrigation in California. Poor irrigation timing, such as irrigation before heavy rainfall, can also lead to oversaturation and increased N<sub>2</sub>O emissions [128]. Furthermore, practices such as black plastic mulch can retain excessive moisture, thereby increasing N<sub>2</sub>O emissions [100]. Under water-stress conditions, reduced plant nutrient uptake can leave more reactive N in the soil, which is available for microbial conversion into N<sub>2</sub>O [129]. Irrigation events in the presence of reactive N can elevate N<sub>2</sub>O emissions by 50–140 % [130]. Implementing the following water management can help address N<sub>2</sub>O emissions:

##### 4.3.1. Drip irrigation systems

Drip irrigation helps maintain lower moisture levels, thereby reducing denitrification potential, although it may lead to elevated soil inorganic-N concentrations [125]. A global meta-analysis by Li et al. [49] showed that drip fertigation combined with reduced N application can lower nitric oxide and N<sub>2</sub>O emissions by 40–57 % compared to conventional fertilization, although this may slightly increase ammonia volatilization. Drip fertigation reduced N<sub>2</sub>O emissions by 41 % compared to traditional flood irrigation in Chinese greenhouse vegetable production by optimizing soil moisture levels, which altered soil microbial N turnover processes, primarily by reducing denitrification [131]. Drip irrigation reduced N<sub>2</sub>O emissions by 44.7 mg m<sup>-2</sup> compared to furrow irrigation, which was attributed to the fact that the dry-wet alternations of furrow irrigation promoted N<sub>2</sub>O emissions, whereas drip irrigation created a relatively stable environment that mitigated emissions in vegetable fields in North China [132]. These studies highlight the potential of drip irrigation and fertigation as effective strategies for mitigating N<sub>2</sub>O emissions in vegetable fields, particularly when combined with optimized N rates.

#### 4.3.2. Subsurface drip irrigation (SDI)

Subsurface drip irrigation offers additional benefits by optimizing water use at depth. Hamad et al. [103] reported that in Chinese cabbage, soil N<sub>2</sub>O emissions decreased with increasing SDI depth, with SDI at 10 cm and 15 cm reducing emissions by 7.1 % and 10.7 %, respectively, compared to SDI at 5 cm as shown in Table 1. This reduction was attributed to the decreased NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations at greater depths. However, Edwards et al. [133] found that N<sub>2</sub>O emissions were not significantly different between surface and subsurface drip irrigation in tomato fields on sandy loam soils, indicating soil-specific responses to irrigation methods. .

#### 4.3.3. Other irrigation strategies

Deficit irrigation strategies, where crops receive less water than their full water requirements (approximately 0.6 W), can effectively reduce emissions by altering soil moisture, which in turn influences soil temperature and the availability of N substrates such as NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N [134]. For instance, Hui et al. [135] reported that full irrigation in greenhouse tomato production resulted in significantly higher N<sub>2</sub>O emissions than deficit irrigation, highlighting the need to optimize the water management. Complementing this approach, negative pressure irrigation (NPI), an innovative subsurface technique, delivers water precisely and consistently when soil water content declines due to evapotranspiration, thereby maintaining stable soil moisture conditions [136,137]. Li et al. [105] observed that NPI reduced N<sub>2</sub>O emissions by 15.1 % while increasing vegetable yields by 16.6–20.3 % compared to traditional furrow irrigation, demonstrating its capacity to minimize N leaching and promote sustainable agriculture. Further enhancing water-use efficiency, sensor-based precision irrigation uses real-time soil moisture data to optimize irrigation timing and volumes, preventing post-irrigation N<sub>2</sub>O surges and ensuring that water is applied only as needed [138]. Studies reveal NPI reduces N<sub>2</sub>O emissions by up to 32 %, with effectiveness varying by crop and soil type, as shown in Table 1. Taken together, irrigation strategies that optimize soil moisture and N rate can significantly reduce N<sub>2</sub>O emissions without affecting yields.

#### 4.3.4. Integrated water-nutrient management

N<sub>2</sub>O emissions in vegetable cultivation are strongly influenced by both fertilization and water management. For instance, Riya et al. [135] observed this in greenhouse tomato cultivation, highlighting the interplay between N supply and irrigation. Research on intensive greenhouse vegetable production demonstrates that precise irrigation scheduling combined with optimized N application can reduce N<sub>2</sub>O emissions by 30–40 % without compromising yields [139]. Implementing weather-responsive irrigation strategies further mitigates emissions, as avoiding irrigation when rain is forecasted conserves water, prevents nutrient leaching, and limits N<sub>2</sub>O spikes [128]. Despite these findings, Han et al. [124] emphasize that comprehensive studies evaluating diverse irrigation strategies alongside variable N rates remain scarce, restricting our understanding of how integrated water and nutrient management can be optimized. This knowledge gap is particularly significant for vegetable crops, which are inherently water-demanding, underscoring the need for more research [140,141]. While integrated water–nutrient management primarily targets physical and chemical controls on N availability, biological regulation of N cycling represents an additional mitigation pathway.

#### 4.4. Biofertilizers and native microorganisms

Beyond irrigation and fertilization strategies, the role of soil microorganisms has gained increasing attention as a fundamental driver of N<sub>2</sub>O dynamics in vegetable crops. Soil is a dynamic ecosystem in which microbial communities play a crucial role in regulating N cycling. Native microorganisms, particularly those involved in nitrification and denitrification, are key to controlling N<sub>2</sub>O fluxes in vegetable production systems [142]. Recent discoveries have illustrated how plant-microbe

interactions can shift the balance between N conservation and loss. For example, specific root metabolites, such as n-hexadecanoic acid, have been shown to stimulate *Pseudomonas stutzeri*, a bacterium associated with reduced gaseous emissions [143]. Conversely, organic inputs, such as animal manure, may unintentionally promote the growth of taxa such as *Acinetobacter*, whose genetic potential (*mcrA*, *amoA*, *nirK*, *nirS*) can drive higher N<sub>2</sub>O production [144].

Biofertilizers have emerged as a promising strategy to reconcile the need for nutrient supply with the imperative to curb N losses. While commercial inoculants often struggle to persist in field soils [145], their potential lies in complementing rather than replacing native microbial networks. A global synthesis revealed that partially replacing conventional peat with microbial consortia-based sphagnum substrates in greenhouse vegetable cultivation produced contrasting effects on N<sub>2</sub>O emissions. Specifically, a 25 % substitution (25SP) reduced emissions by 55.35 % by suppressing fungal denitrification and bacterial nitrification processes [98]. However, such outcomes are not universal; their success depends strongly on site-specific microbial composition and environmental context [67]. This recognition is steering research toward advanced multi-omics approaches that can unravel the microbial lineages and biochemical pathways most responsible for shaping N<sub>2</sub>O dynamics in organic and integrated systems [146].

Along with bacteria, arbuscular mycorrhizal fungi (AMF), belonging to the *Glomeromycota*, form intimate associations with many vegetable crops, influencing N<sub>2</sub>O fluxes [147]. Beyond providing essential nutrients, they also reshape microbial assemblages and suppress populations that harbor denitrification genes, such as *nirS* and *nirK* [142,148,149]. These fungi enhance plant N uptake efficiency, reduce the pool of available substrates for nitrifiers and denitrifiers, and diminish ammonia volatilization [150]. Improvements in root morphology and absorption capacity further tighten the N cycle, leaving less N vulnerable to escape into the atmosphere [145].

AMF also exert indirect effects by improving soil structure and hydrological balance. Their hyphal networks promote aggregation, aeration, and water retention, thereby limiting anaerobic microsites that fuel denitrification [17,146]. Evidence from field trials and meta-analyses suggests that AMF can reduce N<sub>2</sub>O emissions by up to 42 %, mainly through N immobilization and microbial regulation [148,151]. Despite such promising evidence, their potential has rarely been examined in conjunction with agroecological practices, such as intercropping, crop rotation, mulching, or reduced tillage, which may amplify their benefits [152]. Leveraging these synergies with AMF and other beneficial microbes could help to sustain productivity while curbing GHG outputs. Harnessing native microbial communities and beneficial symbioses thus represents a biologically grounded mitigation strategy, with synergistic potential when integrated into holistic agroecological management frameworks.

#### 4.5. Cover cropping and crop residue management

N<sub>2</sub>O emissions from vegetable systems are closely linked to residue management and practices such as cover-cropping, which are important for soil health. Also, anaerobic soil disinfection (ASD), which is used to control soilborne pests and pathogens of vegetables, relies on readily degradable organic amendments and has been identified as a particularly significant source of emissions, accounting for more than half of the total N<sub>2</sub>O released during the tomato growing period [153]. The choice of residue incorporated into the soil plays an important role in moderating these fluxes. Crop residues, such as rice shells or maize straw, which decompose more slowly than nutrient-rich inputs like chicken manure, can be low-emission alternatives for organic amendments in vegetable production [154]. In contrast, removing residues from the system has been shown to reduce emissions substantially. Seiz et al. [155] reported that removing crop residues from cauliflower and broccoli, instead of incorporating them, reduced N<sub>2</sub>O emissions by up to 74 % in silty soils in the temperate region.

Cover crops present another pathway for more dynamic and sustainable N management. A large body of evidence highlights their ability to deliver multiple ecosystem services, including N retention, reduced nitrate leaching, and improved soil organic carbon storage, while simultaneously lowering N<sub>2</sub>O emissions [156]. In organic vegetable systems (lettuce, leaf spinach, broccoli), winter cover crops have proven particularly effective in enhancing N uptake and availability, supporting higher yields, and reducing soil N surplus [157]. However, their impact on N<sub>2</sub>O emissions is not uniform across different environments. Sedghi et al. [158] demonstrated that soil texture plays a decisive role, with emissions nearly eightfold higher in silty soils than in sandy soils due to greater moisture retention. Interestingly, the same study found that cover crops decreased indirect N<sub>2</sub>O emissions by approximately 7 % overall and that early planting could reduce direct emissions by as much as 70 %.

Vegetable residues present notable emission challenges, primarily influenced by their carbon-to-nitrogen (C/N) ratio. Low C/N residues, rich in water-soluble carbon, stimulate microbial activity and elevate emissions [159], while high C/N residues do not necessarily ensure mitigation due to complex residue-microbe interactions [160]. High labile N and low carbon content, coupled with intensive fertilizer and irrigation in coarse-textured soils with low water holding capacity, further promote N<sub>2</sub>O release [161]. Reported N<sub>2</sub>O emissions range from 0.13 to 14.6 % of applied N for white cabbage, Brussels sprouts, and broccoli [1,162] 0.1–3.7 % for cauliflower [163]. NH<sub>3</sub> volatilization is minimal (0.07 %) when residues are incorporated, but can reach 10.8 % when left on the soil surface [164]. Cauliflower residues emit up to 2.3–3.4 kg N<sub>2</sub>O–N ha<sup>-1</sup> across soil types [165]. Low C/N residues generally intensify emissions, especially in sandy soils [166]. Co-application of organic manure with residues can further increase emissions compared to synthetic fertilizers, due to the high degradability of vegetable residues [76]. Mitigation strategies include using nitrification inhibitors before residue incorporation [167] or mixing high-emission residues (e.g., broccoli) with wheat straw or water-washed straw, which can cut emissions by over 70 % [107].

The timing of emissions from residues and cover crops must be considered. N<sub>2</sub>O release often increases during the decomposition phase of cover crops compared to their growth phase, although the net annual impact is generally neutral [168]. A substantial portion of annual emissions occurs after harvest, as decomposing residues release N that was accumulated during crop growth. Scheer et al. [87] estimated that these post-harvest fluxes account for 50–70 % of the annual total as decomposing residues release stored N. Addressing this challenge requires careful adjustment of N applications during the cropping season to avoid surplus availability during decomposition, as well as strategic residue management to synchronize the N release with crop demand. Cover crops, including mixed species and legumes, can reduce N<sub>2</sub>O emissions by 7–74 %, with benefits influenced by planting timing, species selection, and soil type (Table 1). Therefore, strategic residue selection, timing, and cover crop management are essential for minimizing post-harvest N<sub>2</sub>O emissions and stabilizing annual emission budgets in vegetable crops.

#### 4.6. Amendments

Beyond mineral fertilizers, a considerable share of N<sub>2</sub>O emissions in vegetable production arises from organic amendments. For example, manure application has long been recognized as a major contributor, particularly in alkaline soils, where enhanced nitrification and mineralization processes accelerate the conversion of N to N<sub>2</sub>O [105]. Pig and poultry manure are especially problematic in sandy or coarse soils, where both nitrification and denitrification are promoted [169]. In contrast, the incorporation of decomposed straw often exerts a mitigating influence, as dissolved organic matter from straw fosters denitrifying bacterial communities that promote N<sub>2</sub>O reduction [170]. However, the effects of crop residues are highly context-dependent. In

acidic soils (pH < 6.5), residue incorporation stimulates emissions by intensifying denitrification activity [171]. This distinction is consistent with reports that heterotrophic denitrification dominates acidic conditions, whereas nitrification pathways prevail in alkaline soils [92].

##### 4.6.1. Liming

Lime is widely used in vegetable production systems to raise soil pH, which plays a pivotal role in regulating N cycling and N<sub>2</sub>O emissions. According to Yamamoto et al. [172], liming acidic soils enhances N use efficiency by promoting plant uptake and reducing the accumulation of unused N that would otherwise contribute to gaseous losses. A global meta-analysis by Ref. [173] demonstrated that liming can effectively suppress soil nitrification and increase the abundance of N<sub>2</sub>O reductase (*nosZ*) genes, thereby facilitating the conversion of N<sub>2</sub>O to inert N<sub>2</sub> and lowering overall emissions. Liming is known to decrease the fungi-to-bacteria ratio, which is linked to a shift in microbial community structure toward more complete denitrification pathways [173]. According to Pfulb et al. [174], the effects of liming vary significantly by soil texture. While fresh liming may increase denitrification in sandy soils, it tends to reduce N<sub>2</sub>O emissions in loamy soils by supporting a more efficient denitrification process.

In addition, combining liming with nitrate-based fertilizers under anaerobic conditions reduces N<sub>2</sub>O emissions [175]. Furthermore, Zhang et al. [173] reported that liming stimulates plant N uptake, thereby reducing residual soil nitrate and limiting the substrate available for microbial N<sub>2</sub>O production. A global meta-analysis by Shaaban et al. [176] demonstrated that various liming materials, such as CaMg (CO<sub>3</sub>)<sub>2</sub>, CaCO<sub>3</sub>, Ca (OH)<sub>2</sub>, and CaO reduced N<sub>2</sub>O emissions from acidic soils, with Ca (OH)<sub>2</sub> being the most effective, primarily due to its strong impact on raising soil pH. In another study, Yamamoto et al. [172] found that lime N application in sandy clay loam soil reduced N<sub>2</sub>O emissions by 64.6 %, due to its decomposition into DCD, a known nitrification inhibitor, particularly after rainfall events in Komatsuna cultivation. Ikezawa et al. [177] emphasized the importance of maintaining soil pH within an optimal range of 6–7, where nitrifying bacteria function efficiently, enhancing N use while limiting denitrification-induced N<sub>2</sub>O emissions. These contrasting findings highlight that the mitigation potential of liming depends on soil type, fertilizer form, and timing of application relative to rainfall and fertilization events.

##### 4.6.2. Biochar application

Recently, biochar, a product of organic residue pyrolysis, has re-emerged as a promising approach for reducing N<sub>2</sub>O emissions while simultaneously enhancing soil fertility [178]. Experimental studies have shown notable reductions in N<sub>2</sub>O emissions, ranging from 15 % to 40 %, in a morning glory-pak choy-coriander-lettuce system when biochar is incorporated at effective rates (20 t ha<sup>-1</sup>), although this can vary depending on soil type [179]. Ding et al. [82] further demonstrated that incorporating biochar into soil reduced NO and N<sub>2</sub>O emissions by 10–23 % and 18–19 %, respectively, without compromising vegetable yields. Integrating biochar into rotational cropping systems, such as lettuce–water spinach, has proven particularly effective, achieving reductions of up to 34 % during lettuce and 40.5 % during water spinach without compromising yields [180]. Duan et al. [181] and Han et al. [124] suggested that the mechanisms underlying these reductions include improved soil structure, increased nutrient retention, and modulation of microbial communities, thereby reducing the need for N inputs. However, the results were not universally positive. Field-aged biochar has, in some cases, stimulated N<sub>2</sub>O production by intensifying nitrification and denitrification processes [182]. A global meta-analysis by Cayuela et al. [183] confirmed this duality, emphasizing that the age and chemical properties of biochar strongly influence its effects on N cycling. Fresh biochar may transiently enhance emissions by promoting ammonia oxidation, whereas aged biochar tends to inhibit N<sub>2</sub>O formation and stimulate microbial communities carrying the *nosZ* gene, which reduces N<sub>2</sub>O to N<sub>2</sub> [178,184]. Biochar amendments show promise in reducing

emissions by 4–86 % across various vegetable crops and soil types, with application rates of 20–40 Mg ha<sup>-1</sup> yielding notable benefits as shown in Table 1. Overall, soil amendments such as liming and biochar can substantially influence N<sub>2</sub>O dynamics, but their effectiveness in mitigating N<sub>2</sub>O depends strongly on soil properties, amendment characteristics, and management context.

#### 4.7. Climate-smart crop rotations

Cropping sequences are critical for regulating the N cycle and directly influencing N<sub>2</sub>O emissions in vegetable production systems [92, 185]. Field experiments in China have shown substantial variability in emissions across crops and seasons, emphasizing the importance of crop-specific and seasonal factors [186]. Crop rotation and N application rates exert stronger effects on N<sub>2</sub>O emissions than tillage, suggesting that well-designed crop sequences can act as effective mitigation measures [187]. A recent study reported that alternating high-N requiring crops, such as broccoli, with less demanding crops, such as carrots, significantly reduces emissions. Similarly, integrating legumes and cover crops into rotations can enhance N use efficiency, reduce reliance on synthetic fertilizers, and decrease N<sub>2</sub>O emissions [188]. In addition, replacing a conventional celery–tomato–lettuce sequence with a clover–tomato–lettuce rotation reduced N inputs by one-quarter while cutting N<sub>2</sub>O emissions and overall GWP [189]. These outcomes highlight that diversified cropping sequences not only sustain yields but also reduce greenhouse gas intensity (GHGI), a yield-scaled indicator of emissions efficiency [190]. However, despite growing evidence, most studies still emphasize single-crop assessments, leaving gaps in understanding the long-term emission dynamics of multi-seasonal systems [191].

Equally important is the selection of crop species, which strongly affects N<sub>2</sub>O fluxes through differences in N demand, uptake, and influence on soil microbial processes. Leguminous vegetables help mitigate emissions by fixing atmospheric N and reducing fertilizer needs [192], whereas high-N requiring crops such as cabbage often act as emission hotspots under high fertilizer and water inputs [187]. A meta-analysis by Nicolardot et al. [193] revealed that crops such as lettuce, endive, cabbage, and sweet corn exhibit sharp increases in emissions above specific N thresholds, illustrating their sensitivity to fertilization. Moreover, plant species alter microbial pathways, shifting the balance between nitrification and denitrification [194]. Thus, strategic crop selection and rotation can optimize N use and cycling [195]. Looking ahead, breeding programs focusing on varieties with higher N use efficiency and stress resilience, such as drought tolerance, offer promising avenues to further reduce emissions [196]. While crop rotation focuses on temporal diversification, broader system integration offers additional opportunities to close nutrient loops and reduce emission intensity.

#### 4.8. Integrated production systems

In recent years, integrated crop–livestock systems (ICLS) have emerged as a compelling pathway for reconciling productivity with sustainability. Rather than managing crops and animals in isolation, these systems integrate the two, enhancing soil processes and reducing greenhouse gas emissions. For instance, grazing reduced N<sub>2</sub>O emissions by 62 %, with an average emission of 0.80 kg ha<sup>-1</sup> compared to 2.09 kg ha<sup>-1</sup> in ungrazed pasture. The N<sub>2</sub>O emission factors were 1.7 % and 1.1 % for 75 and 150 kg ha<sup>-1</sup> N application rates, respectively, aligning with the IPCC's default 1 % emission factor in rye–oat–bean rotations, perhaps due to possible denitrification of N<sub>2</sub>O to N<sub>2</sub> resulting from soil compaction by trampling [197]. Similar trends have been reported in Chinese cabbage, where livestock integration improved soil carbon stocks and reduced emissions [122]. Incorporating livestock into croplands creates a closed-loop cycle in which manure serves as a valuable nutrient source, reducing reliance on synthetic fertilizers and thereby lowering the risk of N<sub>2</sub>O emissions from introduced inputs [198].

Beyond nutrient recycling, livestock-derived organic inputs promote the accumulation of stable soil organic matter, enhance microbial diversity, and strengthen soil capacity to regulate N transformations [199]. Integrated production systems, therefore, represent a promising pathway for closing nutrient loops, enhancing soil resilience, and reducing N<sub>2</sub>O emissions, particularly in intensive and smallholder vegetable production.

### 5. Synergies and trade-offs in nitrogen-carbon cycling and emission reduction

#### 5.1. Synergistic solutions for climate-positive nitrogen and carbon cycling

Integrated soil management practices can simultaneously mitigate N<sub>2</sub>O emissions, enhance SOC sequestration, and improve soil health and crop productivity. A global meta-analysis confirmed that combining organic matter-building practices improves long-term carbon storage and N cycling efficiency [200]. For instance, compost application increased total SOC, while frequent cover cropping boosted labile carbon fractions, such as permanganate-oxidizable carbon (POX-C), enhancing nutrient availability and vegetable yields [157]. Practices like biochar application and organic amendments significantly enhance long-term SOC accumulation [34], and optimized crop rotations can reduce net global warming potential by balancing carbon sequestration with greenhouse gas emissions [185]. Co-application of biochar with N fertilizers increases SOC and active organic carbon (AOC) more effectively than either alone [71], while biochar plus nitrate fertilizers elevates dissolved organic carbon (DOC) and reduces both CO<sub>2</sub> and N<sub>2</sub>O emissions [201].

Methane (CH<sub>4</sub>) dynamics are also important, especially in waterlogged greenhouses or rice-vegetable rotations, where anaerobic conditions promote methanogenesis [202], and some practices, like straw incorporation, may reduce N<sub>2</sub>O but increase CH<sub>4</sub> emissions [203]. Mitigation strategies must consider trade-offs among greenhouse gases to avoid burden-shifting [204]. Synchronizing nutrient inputs with crop demand via biochar and organic amendments can reduce N<sub>2</sub>O emissions by 23.9 % [205], while inoculation with AMF reduces N<sub>2</sub>O and DOC leaching [142]. Legume cover crops fix atmospheric N and enrich SOC, reducing synthetic fertilizer needs [206], and integrating legumes into rotations with high-biomass or deep-rooted species enhances long-term carbon storage [76]. High-temperature biochar further reduces CO<sub>2</sub> and N<sub>2</sub>O emissions [207]. Additionally, nitrification inhibitors such as DMPP reduce emissions [87], and optimized fertigation lowers both N<sub>2</sub>O and NO emissions in lettuce fields [208].

#### 5.2. Trade-offs in nitrogen and carbon emission reduction

Mitigation strategies for N and carbon emissions often involve complex interactions that can lead to trade-offs among different GHGs, underscoring the need for integrated, context-specific approaches to address this issue. According to Abdalla et al. [204], reducing one type of greenhouse gas may inadvertently increase another, a pattern observed in multiple studies. For example, Zhang et al. [178] demonstrated that although biochar effectively reduces N<sub>2</sub>O emissions in N-rich soils, it may simultaneously enhance CH<sub>4</sub> emissions. Similarly, Ding et al. [208] and Zhou et al. [139] reported that although optimized fertigation decreases N<sub>2</sub>O emissions, but can increase NH<sub>3</sub> volatilization, revealing an environmental trade-off. According to Lee et al. [203], straw incorporation improves SOC and yield but may also elevate CH<sub>4</sub> emissions. Similarly, Yang et al. [71] observed that combining biochar with N fertilizers enhances SOC but also increases CO<sub>2</sub> emissions due to the stimulated microbial activity. Maenhout et al. [209] found that leguminous cover crops can build SOC while elevating N<sub>2</sub>O emissions, highlighting a common dilemma in N-rich systems.

A global meta-analysis by Rashti et al. [20] emphasized that the efficacy of mitigation tools, such as biochar or fertilizers, depends heavily

on soil type, pyrolysis conditions, feedstock origin, and climatic variability. For instance, Scheer et al. [78] showed that the post-harvest effectiveness of nitrification inhibitors, such as DMPP, is limited by residual soil N, which delays N<sub>2</sub>O release. Liu et al. [55] added that in high-N soils, organic amendments such as manure or compost can substantially increase N<sub>2</sub>O emissions, particularly when nutrient release exceeds plant uptake. Moreover, Wang et al. [121] noted that although no-till farming benefits carbon retention, it may initially increase N<sub>2</sub>O emissions because of soil compaction and the development of anaerobic microsites. According to Sharma et al. [210], the use of technologies such as drones and GPS systems enhances N use efficiency through precise/varied N application but advertently increase CO<sub>2</sub> emissions unless powered by renewable energy. These findings collectively underscore the importance of conducting long-term, holistic assessments of GHG mitigation practices, as emphasized by Abalos et al. [159] meta-analysis, which calls for balancing emission reductions with agronomic performance and broader environmental outcomes.

## 6. Technologies for holistic N management to minimize N<sub>2</sub>O emissions and economic considerations

Current vegetable production systems exhibit alarmingly low N use efficiency. Evidence from Ti et al. [211], which found a N recovery rate of only 23 %, highlights the critical need to advance N management. A holistic management approach should balance short-term N optimization with long-term soil health, considering broader environmental, economic, and social dimensions [156]. As an initial step, the 4R nutrient stewardship can be followed, as it has been shown to significantly improve N use efficiency and reduce gaseous N losses [212]. To achieve precise N management, a suite of diagnostic, laboratory, and modelling tools can enable real-time monitoring, predictions, and informed long-term decision-making [213,214]. Techniques such as soil testing, nutrient mapping, plant tissue analysis, leaf color charts, chlorophyll meters, and spectral scanning and sensing can guide crop-, season-, and field-specific N application rates [213]. Nevertheless, implementing real-time N measuring and data analysis may present several challenges, including selecting appropriate sensing technologies, effective data management, and the need for specialized knowledge [215]. Measuring actual N<sub>2</sub>O and other gases further complicates the situation, requiring access to specialized research equipment such as chambers, gas analyzers, and analytical software.

Additionally, simulation models such as DNDC, DAYCENT, and APSIM provide robust platforms for predicting cycling, crop responses, and emission outcomes under different scenarios, integrating biological, chemical, and physical processes to simulate the impact of management decisions on N fate in the soil-plant-atmosphere continuum [216].

**Table 2**

Integrated strategies for nitrogen management through diagnostic, lab, and modelling tools for reducing N<sub>2</sub>O emissions and enhancing the nitrogen use efficiency.

Category	Tool/Method	Purpose	Use Region	Benefits	Key References
<b>Field Diagnostics</b>	Soil & Tissue Testing	Measures N levels in soil/plants (SPAD meters, leaf tests)	General, global	Avoids overuse, supports mid-season adjustments	[213]
	Remote Sensing & Drones	NDVI/canopy analysis for N status	Precision agriculture, global	Targeted N use lowers emissions	[219]
	Crop-Based Methods	Destructive (leaf sap) & non-destructive (reflectance sensors)	General use	Real-time N monitoring	[214,219]
<b>Lab-Based Tests</b>	Mineralization & C:N Ratio	Assess soil N release potential and synchronization with crop needs	High OM soils, global	Reduces excess fertilization	[220,221]
	Nitrification/Denitrification Tests	Predict N <sub>2</sub> O emissions	Global	Helps plan N timing	[214]
<b>Modeling Tools</b>	Nmin, KNS, N-expert Systems	Estimate crop N needs using soil/organic matter data	NW & Central Europe	Improves fertilizer efficiency	[213]
	Nitrate Monitoring	Soil solution sampling for fertigated crops	Israel, Spain	Prevents leaching	[219]
	Nutrient Models & DSS	Weather-soil-data-driven N recommendations (e.g., Adapt-N, FARMSCAPE)	Global	Real-time optimization	[217]
	Process Models (DNDC, DAYCENT)	Simulate N cycling/emissions	Scenario analysis, global	Guides emission-reducing practices	[216]

Combining the diagnostic and modelling tools enables site-specific nutrient recommendations and long-term predications, optimizing nutrient inputs and enhancing N use efficiency [217], ultimately supporting the development of sustainable fertilization strategies [218]. Studies reveal that N management tools empower farmers to optimize fertilizer use, reduce emissions, and boost crop yields by providing real-time insights into soil and plant N status and enabling data-driven decision-making and precision agriculture, as shown in Table 2. The challenge with the existing models is that they were developed mainly for field crops, so additional calibration for specific vegetable crops and locations may be needed. To ensure wider adoption, economic and practical feasibility is crucial, requiring cost-effective technologies, targeted incentives, and farmer education programs [212]. Importantly, to maximize efficiency, strategies must be tailored to regional contexts [157] (Fig. 3).

Economic feasibility, adoption barriers, and potential solutions of BMPs in vegetable crops are closely interlinked, particularly for smallholder farmers. Especially in developing countries, where farmers growing vegetables face economic hurdles such as high upfront costs for nitrification inhibitors [222]. While many practices, such as nitrification inhibitors and sustainable tillage approaches, can improve efficiency and lower long-term operational costs, their adoption is limited by significant initial investments, restricted market access, and knowledge gaps [223,224]. Inconsistent supply chains, inadequate irrigation, and climate-related uncertainties compound these challenges. To overcome these barriers, integrated strategies are critical [225]. This may include financial support, technical training through field schools, and partnerships to enhance market access and reduce costs [226]. Furthermore, disseminating localized guidelines via extension services and implementing supportive policy instruments, such as incentive programs, are essential to increase the viability and scale of adoption for sustainable vegetable production [227].

## 7. Limitations, knowledge gaps and research priorities

This review has several limitations. The evidence synthesized is primarily derived from studies conducted in well-studied regions (China, Europe, and America) and intensive production systems, with limited representation from underrepresented regions, smallholder farming contexts, and low-input production systems. Due to the scattered quantitative evidence across different practices and vegetable crops, this review is primarily qualitative in nature and does not include a quantitative meta-analysis. The studies included in this review are mainly conducted under current climatic conditions and at small-plot short-term experimental scales, with few considering climate change scenarios and larger scales.

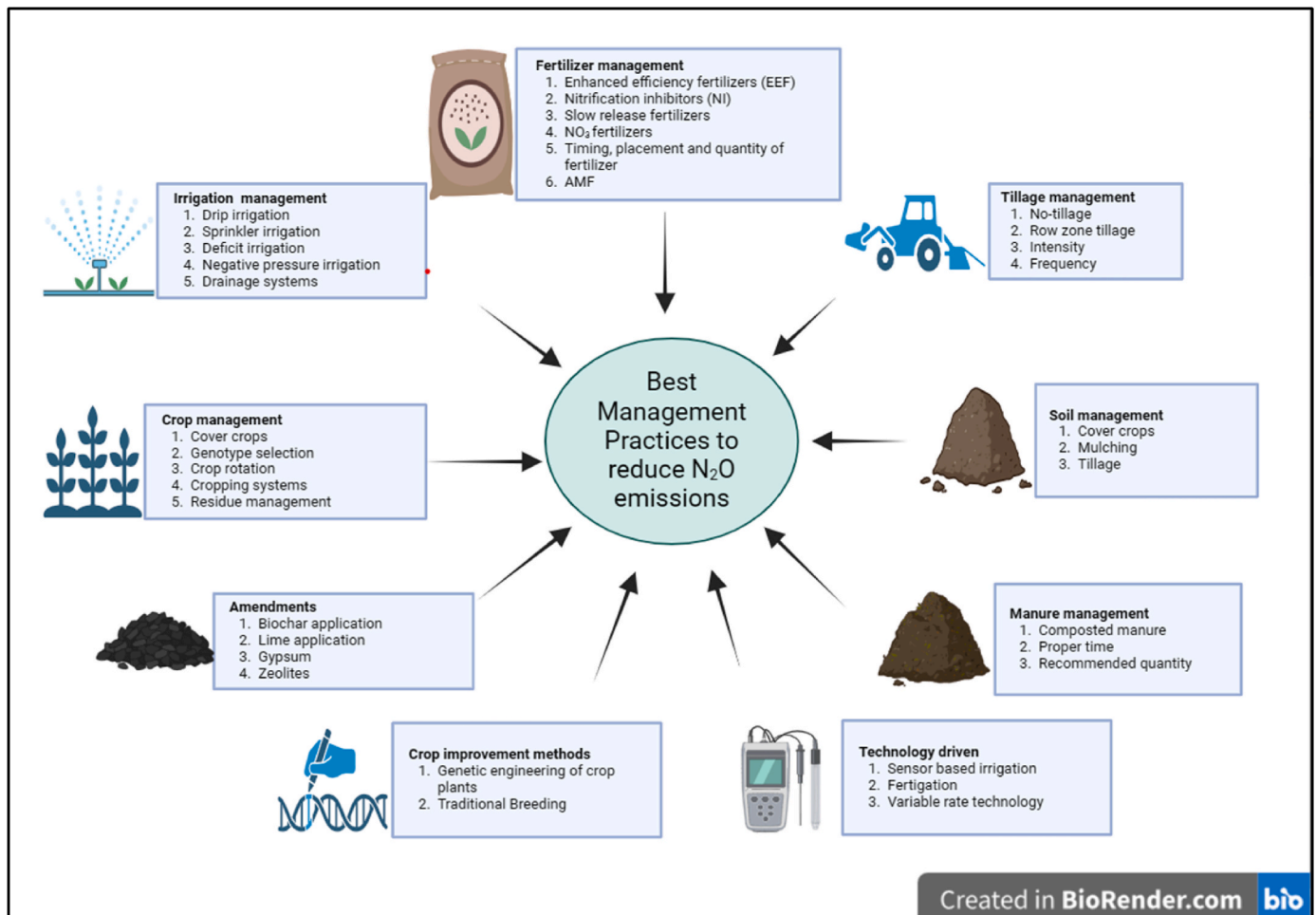


Fig. 3. Implementing best management practices to minimize nitrous oxide ( $N_2O$ ) emissions from vegetable production systems for low carbon agriculture.

Despite increasing awareness of GHG emissions from agriculture, the effects of some practices, such as tillage on  $N_2O$  emissions in vegetable production, remain poorly understood and with mixed results [100]. According to Maaz et al. [228] and Li et al. [229], most long-term assessments of  $N_2O$  emissions have been conducted in field crops, with vegetable systems being significantly underrepresented. For instance, long-term experiments spanning 10–20 years are largely absent in vegetable production, limiting our ability to predict the long-term effects of management practices on emission trends.

To address these critical knowledge gaps, future research should prioritize six actionable research priorities: (1) establish multi-year field experiments (minimum 5–10 years) across diverse vegetable types and soil textures to quantify whether emission mitigation benefits persist under year-to-year climate variability; (2) quantify the synergistic effects of integrating practices such as drip fertigation with nitrification inhibitors (DMPP, DCD) in greenhouse tomato systems, conservation tillage with legume cover crops and biochar in organic rotations, and AMF inoculation with organic mulching in leafy vegetables to determine whether combined practices produce additive or synergistic emission reductions [20,67]; (3) employ multi-omics approaches to identify which microbial taxa and functional genes (*amoA*, *nirK*, *nirS*, *nosZ*) are most responsive to vegetable management practices and whether targeted application of *nosZ*-harboring bacterial consortia can consistently reduce emissions [142]; (4) evaluate how soil type, climatic conditions, and crop species modulate the cost-effectiveness of BMPs, including the efficacy of slow-release fertilizers across soil pH gradients, deficit irrigation strategies in humid versus arid climates, and economic feasibility of precision technologies in smallholder versus large-scale operations

[230,231]; (5) validate the emission reduction potential and return on investment of sensor-based precision irrigation, real-time  $N_2O$  flux monitoring coupled with machine learning, and satellite-derived vegetation indices for adaptive fertilizer management [232]; and (6) investigate how climate change-induced shifts in temperature and precipitation alter BMP effectiveness, whether breeding programs for N-efficient cultivars contribute to mitigation, and the life-cycle GHG footprint of vegetable crops under future climate scenarios [39]. Thus, advancing scientific understanding of GHG emissions mitigation in vegetables requires broader and deeper investigations of context-specific practices and their long-term agronomic, economic, and ecological consequences.

## 8. Conclusions

Vegetable production systems, due to their intensive management, are prone to high N losses and  $N_2O$  emissions. Implementing BMPs is therefore essential to enhance N use efficiency and mitigate environmental impacts. This review demonstrates that substantial emission reductions, ranging from 30 % to 80 %, can be achieved through strategic deployment of BMPs. Among these, nitrification inhibitors, optimized fertilizer timing and placement, precise fertigation and negative pressure irrigation, and biochar have shown the greatest potential for reducing  $N_2O$  emissions across diverse vegetable crops and environments. However, realizing the full mitigation potential requires a fundamental shift toward integrated, system-based approaches that quantify synergistic effects of combined interventions. Future research must adopt holistic frameworks that simultaneously evaluate agronomic

performance, economic viability, soil health trajectories, and life cycle GHG footprints under projected climate scenarios to ensure recommended practices deliver sustained benefits across environmental, social, and economic dimensions. Field-scale assessment using novel IoT approaches and decision-support tools can further facilitate BMP adoption by enabling real-time monitoring of N dynamics and timely site-specific management. Although this review outlines a comprehensive set of management strategies to improve N use efficiency and reduce N<sub>2</sub>O emissions, significant knowledge gaps remain, particularly in intensively managed vegetables with large residue inputs and in hot, humid regions, which are particularly prone to high emissions. Addressing these gaps will require long-term, multi-site studies to elucidate better the complex interactions among management practices, climate variability, N cycling processes, crop productivity, and the long-term sustainability of vegetable production systems.

### CRedit authorship contribution statement

**Lokeshwar Kesamreddy:** Writing – original draft, Visualization, Conceptualization. **Somasundaram Eagan:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Samuel Mathu Ndungu:** Writing – review & editing, Conceptualization. **Parameswari Ettiyagounder:** Writing – review & editing. **Winnie Ntinyari:** Writing – review & editing. **Lukas Pawera:** Writing – review & editing, Visualization, Supervision, Resources, Conceptualization.

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### Declaration of competing interest

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

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### Data availability

All data supporting the findings of this study are available in the published literature cited within this article. No new datasets were generated or analyzed during the current study.

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