Approaches to Reduce Greenhouse Gas Emissions in Agriculture

Subjects: Agriculture, Dairy & Animal Science

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Agriculture is the second most important greenhouse gas (GHG: methane (CH4) and nitrous oxide (N2O) emissions)-emitting sector after the energy sector. Agriculture is also recognized as the source and sink of GHGs. Livestock production and feed, nitrogen-rich fertilizers and livestock manure application, crop residue burning, as well as water management in flood-prone cultivation areas are components of agriculture that produce and emit most GHGs. Although agriculture produces 72–89% less GHGs than other sectors, it is believed that reducing GHG emissions in agriculture would considerably lower its share of the global GHG emission records, which may lead to enormous benefits for the environment and food production systems.

environment greenhouse gas agriculture

1. Introduction

From the mid-nineteenth century (the 1860s) to the early twenty-first century (2016), the world experienced acute famine episodes that have taken away millions of lives. These historically disastrous occurrences and unprecedented challenges have set the ground for technological innovation and industrial revolution to address famine and global food crisis caused by environmental or natural disasters, among other factors, resulting in the shortage in food production and the imbalance between food supply and demand, and rise of food prices globally [1][2][3]. Today, climate change is recognized as one of the most life-threatening challenges humanity has ever faced, which puts at risk our common future [4]. The impact of climate change has been recorded on five dimensions known as the 5Ps: the people, planet, partnership, prosperity, and peace [5][6]. The major effects of climate change are persistent global warming and episodes of abiotic and biotic stresses that exacerbate the economic crisis [7], aggravate inequalities and social vulnerability [8][9], and increase food insecurity [10][11]. Empirical data reveals that the recorded gradual and persistent greenhouse gas (GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), etc.) emissions into the atmosphere are the major cause of the observed global warming events and climate crisis. GHGs are produced biologically or naturally (through the action of specific microorganisms in soil or via chemical reactions) and by the action of humans (anthropogenic source: energy sector (73.2%), industry (5.2%), waste (3.2%)), and the remaining is attributed to agriculture (crop production, agricultural soils, livestock), land use and forests.

Agriculture is a major source of food for human consumption and animal feeding, which makes it an essential component of many economies and people’s livelihoods. Major policies aiming at advancing the global economy and promoting agro-industrial development find their roots in agriculture and aim at adding value to raw agricultural products through food processing and transformation. Before the evolvement of the current global climate crisis that affects agriculture among other sectors, the world experienced several episodes of famines because of a complex mix of factors, including the imbalance between food supply and demand, especially during the mid-nineteenth century to early twenty-one century (from the 1860s until 2016s). Over this period, an estimated 128 million people perished in famines. However, the emergence of the modern industrial era contributed to reducing the salience of natural constraints in causing famine (https://ourworldindata.org/famines, accessed on 18 October 2023).

Agriculture, land use, and forests (herein referred to as ALF) are sinks and sources of GHGs. Sinks of GHGs are reservoirs of carbon removed from the atmosphere through biological carbon sequestration [12][13]. As sources, ALF accounts for about 18.4% of global GHG emissions. In the same way, agricultural soils and cultivation practices, especially due to the excessive applications of nitrogen (N)-rich fertilizers and livestock, are identified as leading sources of atmospheric GHG emissions that possess a high global warming potential (GWP) and the potential to exacerbate climate change effects [14]. Nevertheless, agriculture remains the economic sector that suffers the most from climate change. Of the well-identified GHGs emitted from agriculture (crop production and management, agricultural soils, agricultural practices, and livestock production and feed), CH_4 ranks number one and accounts for nearly 67%, followed by N_2O and CO_2 with 32% and 1%, respectively.

2. Approaches to Reduce GHG Emissions in Agriculture

Farming practices are not always the same around the world, although there are some common practices and similarities shared among certain regions of the world. The possible reasons explaining in part this situation may include the diversity of soil properties and characteristics, rainfall patterns, and climates varying from one region to another as well as cultural and social dimensions. In addition, different farming practices or methods may work better in a given environment but perform differently in other places. Furthermore, different areas of the world are better for growing certain types of crops, and some farms are huge, while others are small. Besides, there are also cases where farms are operated by large corporations or companies, middle-scale or small-scale farmers, with modern technologies or secular practices with limited resources [15]. In essence, agriculture is the process of producing food, including grains, fiber, fruits, and vegetables, raising livestock and producing feed for animals, among others. Since the invention of agriculture (about 10,000 before Common Era (BCE)), humans have taken control of their environment to produce their own food. As of today, modern agriculture, characterized by a linear production system, is a subject of controversy because of its contribution to global GHG emissions.

2.1. Improving Management of Crop Residues

The burning of crop residues continues to be utilized by farmers in many parts of the world to get rid of agricultural waste, regardless of the damage caused to the environment and people's health through air pollution and GHG emissions. Burning of crop residues is a global issue rooted in many farming systems, although in many countries, several initiatives are being implemented and measures are being taken to curb the use of this linear type of agricultural practice. Burning of crop residues remains harmful to the environment and human being and negatively affects agriculture and food production. To tackle this issue, a global attention is required. To reduce significantly the practice of crop or stubble burning, governing authorities and scientists in several countries are encouraging or introducing effective crop residue management practices as alternative solutions to crop residue burning. Scientists and governments have suggested a number of techniques of crop residue management to efficiently transition to more friendly agriculture.

To address this issue, Bhuvaneshwari, et al. [16] proposed policy measures and the use of technological interventions that have been overlooked for years. Among them, stringent policy measures can be mentioned such as (i) banning crop residues; (ii) promoting the technologies for optimum utilization and in-situ management of crop residue, to prevent loss of valuable nutrients or diversify uses of crop residue in industrial applications; (iii) developing and promoting appropriate crop machinery in farming practices such as modification of the grain recovery machines (harvesters with twin cutters to cut the straw); (iv) providing discounts and incentives for the purchase of mechanized sowing machinery such as the happy seeder, shredder and baling machines; (v) using satellite-based remote sensing technologies to monitor crop residue management, involving the designated government agencies; and (vi) providing financial support through multidisciplinary approach and fund mobilization for innovative ideas and project proposals.

At technical and technological levels: (i) incorporate crop residues into soils through adoption of conservation agriculture practices (although straw incorporation and organic matter amendments can increase CH_4 and N_2O production [17][18]) and to prevent soil erosion from wind and water, and augment the soil moisture; (ii) promote the use of crop residue for preparation of bio-enriched compost or vermi-compost and its utilization as farm yard manure; (iii) use of agri-machineries such as Happy seeder (used for sowing of crop in standing stubble), rotavator (used for land preparation and incorporation of crop stubble in the soil), zero till seed drill (used for land preparation directly sowing of seeds in the previous crop stubble), baler (used for collection of straw and making of bales for cereal crops stubble), paddy straw chopper (cutting of crop stubble for easily mixing with the soil), or reaper binder (used for harvesting paddy stubble and making into bundles), zero-seed-cum fertilizer drill, to facilitate in-situ management of crop residue and retaining the straw as surface mulching; (iv) use crop residue for mushroom cultivation.

Other alternative solutions include the (i) diversification of crop residue as fuel (for power plants, production of cellulosic ethanol, etc.); (ii) use of crop residue in paper making, board, panel and packing material industry; (iii) collection of crop residue for feed, brick making, etc. (https://www.downtoearth.org.in/blog/agriculture/stubble-burning-a-problem-for-the-environment-agriculture-and-humans-64912, accessed on 12 January 2023); (v) the use of crop residues as raw material for animal feed, composting, production of biochar, construction industry, among others. Agricultural residues equally offer a valuable resource worth saving, since crop stubble can be used as an energy source when converted into pellets, and straw is useful in livestock feed or bedding (https://www.ccacoalition.org/en/activity/open-agricultural-burning, accessed on 13 January 2023).

A sustainable management of agricultural waste can also get inspiration from municipal solid waste management practices [19]. There is a strong consensus that practicing conservation agriculture (minimizing soil disturbance by not tilling, maintaining soil cover, and diversifying crop species) can be an effective, sustainable, and productive method of agriculture that can play an important role in containing and curbing the practice of crop residues burning, which is regarded as this environmentally unjustifiable practice.

2.2. Enhancing Nitrogen Use Efficiency in Plants

Nitrogen use efficiency (NUE), also referred to as N uptake, transport, translocation, assimilation, and remobilization, is regarded as a way of understanding the relationship between the total nitrogen inputs compared to the nitrogen output (**Figure 1**). Breeding for enhanced NUE in plants is essential but a challenging task regarding the complexity surrounding N acquisition and assimilation by plants. Improving NUE would imply targeting genetic loci controlling various aspects of the NUE using a forward genetic approach, targeting specific genes or transcription factors encoding genes associated with N acquisition, transport, and assimilation events. These could be identified through quantitative trait locus (QTL) analysis and fine mapping of detected QTLs or genome-wide association studies. In addition, the application of reverse genetics that employs molecular techniques to elucidate the function of genes through genetic engineering, coupled with sequencing technologies has gained momentum in the scientific community [20][21][22]. These techniques offer a wide range of opportunities and open new paths to investigating genetic factors controlling important traits in plants under various environmental conditions. Nevertheless, developing crop varieties with a high NUE is a promising approach to reducing application rates of synthetic fertilizers, especially in wetlands cultivation areas.

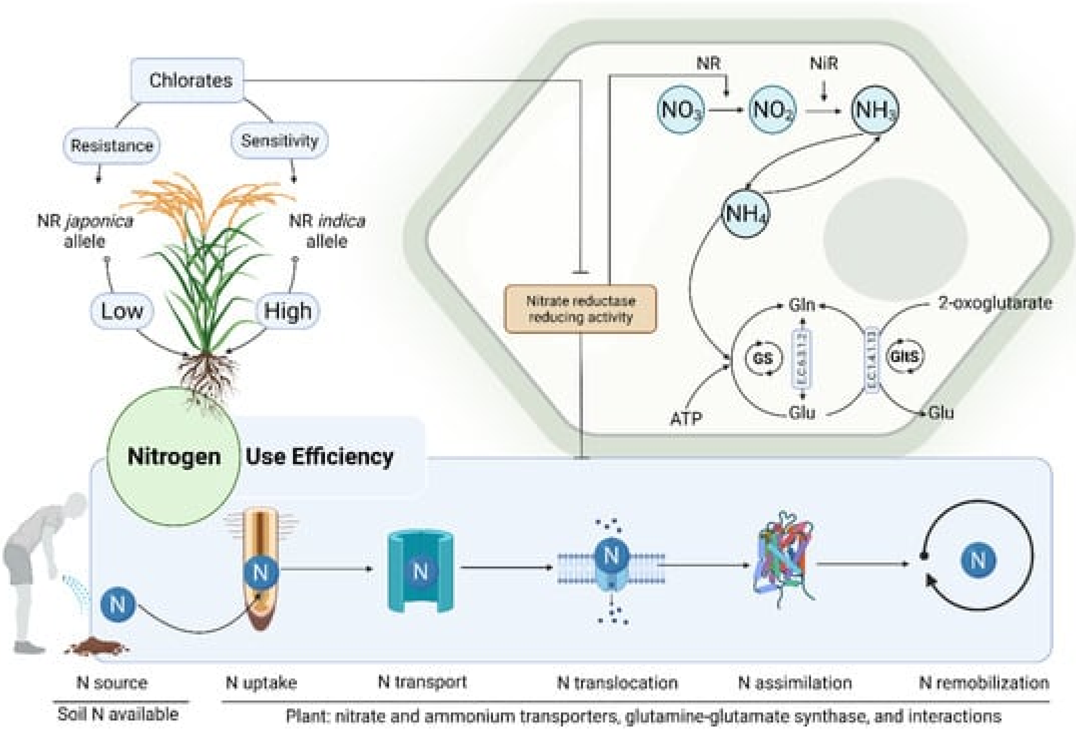

Figure 1. Schematic representation of nitrogen use efficiency in plants. This model was created using the biorender design platform (https://app.biorender.com/, accessed on 25 May 2023).

Although the mechanism of N acquisition, uptake, and assimilation by plants is well described [23][24], the molecular basis of NUE in plants has not been fully elucidated, and continues to be investigated. Studies aiming at investigating mechanisms underlying NUE identified key protein families with a high potential to control NUE in plants under various cultivation conditions [25][26], while others suggested methods for assessing and estimating NUE in plant crops [27][28][29]. NO_3 and NH_4 are the major forms of N taken up by plants, with NO_3 being the most abundant. N is acquired from soil through a combined action of low- and high-affinity NO_3 and NH_4 transporters. The latter are found within five protein families, including NO_3 transporter 1 (NRT1) and 2 (NRT2), chloride channel (CLC), and slow anion channel-associated/slow anion channel-associated homologs (SLAC/SLAH), while assimilation primarily involves glutamine and glutamate synthase encoding genes but not limited to [25][30][31]. The enzyme glutamate dehydrogenase (GDH), which protects the mitochondrial functions during episodes of high N metabolism takes part in N remobilization [32].

The application of synthetic N-rich fertilizers during crop cultivation dramatically increased in the last decades. This common agricultural practice has been shown to contribute to GHG emissions. In this regard, several strategies for reducing the emissions of GHGs from agriculture have been proposed. The number of methods employed to assess the NUE in different crop species are reported [33][34][35]. Of this number, various strategies aiming at improving NUE have been implemented, and their efficiency varies with crop species [36][37][38][39][40][41][42]. With the recent advances in plant breeding techniques and the advent of sequencing technologies, a wide range of opportunities are explored to identify high NUE in crop plants in various breeding populations. Screening for chlorates (ClO_3) sensitivity may also help identify rice varieties with an enhanced NUE [28].

Furthermore, in higher plants, phytohormones were originally known as a group of naturally occurring organic substances, which positively or negatively regulate plant growth and development. In addition to their basic roles, plant hormones are recognized as key players in coordinating multiple (both local and long-distance) signaling pathways at the whole-plant level [43]. As per some evidence, plant hormones interact with nitrogen (N) as well as other nutrients such as iron, sulfur, and phosphorus [44][45][46][47][48]. Among the well-studied phytohormones, abscisic acid (ABA), auxin, and cytokinin (CK) are closely associated with the N signaling. NO_3 availability differentially affects phytohormone accumulation. For instance, NO_3 signaling was proposed to interact with *AtIPT3* in Arabidopsis and regulate N acquisition events, while inhibiting auxin (AUX signaling and basipetal transport (translocation from shoot to root). Meanwhile, Vidal, et al. [49] suggested that NO_3 induces the activity of the auxin receptor gene *AFB3*, which in turn promotes lateral root, N acquisition, and uptake. In contrast, NO_3 was observed to repress the transcript accumulation of the auxin response factor ARF8.

Moreover, several studies target key N transporters and assimilation-related genes to attempt to improve the NUE in plants. Nitrate reductase (NR), nitrite reductase (NiR), plastidic glutamate synthase (GS2), and Fd-GOGAT are involved in the primary NO_3 assimilation events. In contrast, the cytosolic glutamate synthase (GS1) and nicotinamide dinucleotide hydrogen (NADH)-GOGAT are involved in the secondary NH_3 assimilation and remobilization. In this regard, Chen, et al. [50] suggested that genetic manipulation of NO_3 remobilization in plants, a key component of the N metabolism, would help improve NUE, while critically reducing N fertilizer demand and alleviating environmental pollution. To date, genetic engineering techniques are used to improve NUE in plants and crops [51][52][53]. **Figure 2** highlights some of the tools and methods employed to investigate the mechanisms and key players in the N metabolism to improve NUE in plants, as well as its beneficial outcomes.

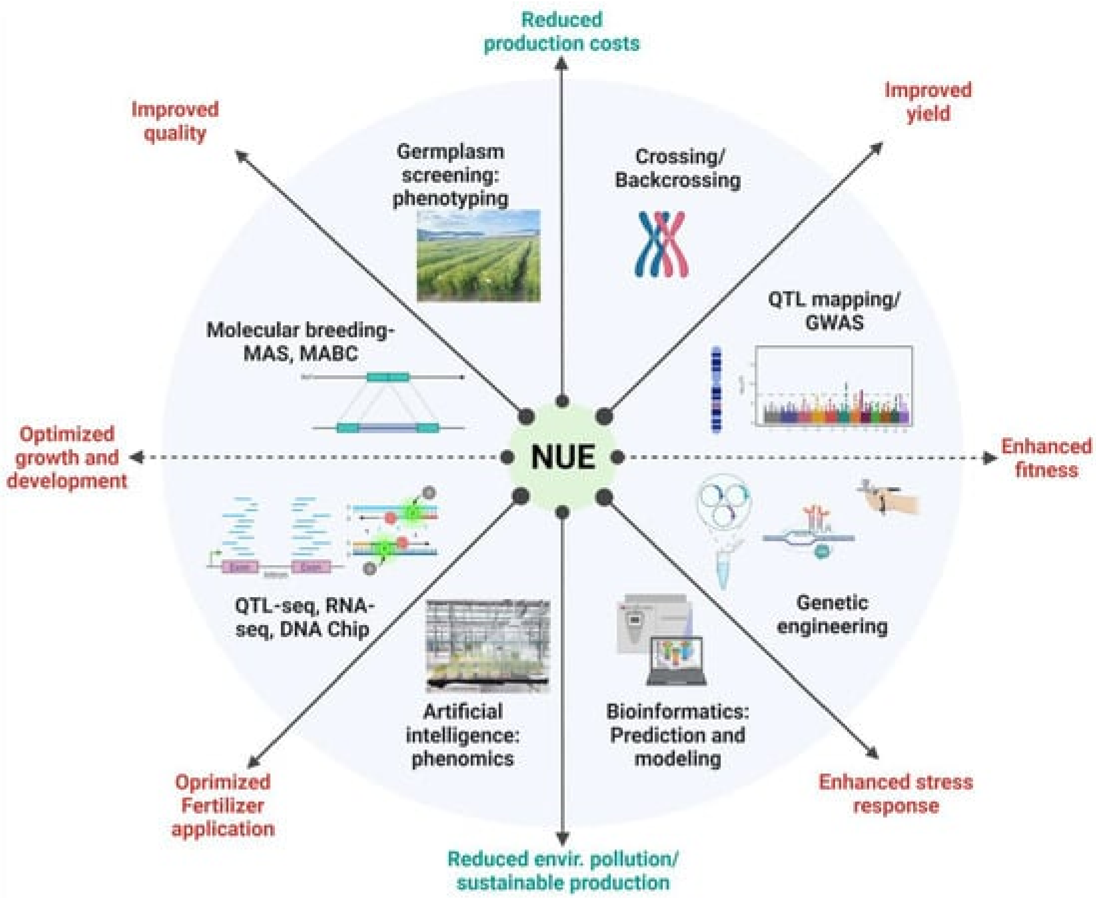

Figure 2. Illustration of different methods and tools employed to understand N metabolism and improve NUE in plants. Highlighted circular zone in different segments shows various methods, technologies, and tools employed to enhance the understanding of N metabolism in order to improve NUE. Continuous lines with an arrow connected to the origin denote the possible outcomes, but limited to, of an improved NUE for plants and the environment. This model was created using the biorender design platform (https://app.biorender.com/, accessed on 11 June 2023).

Heuermann, et al. [54] showed that NO_3 stimulates Cytokinin (CK) synthesis. However, elevated CK levels may delay plant senescence, while favoring a prolonged N uptake. Likewise, Ruffel, et al. [55] reported a NO_3-CK relay and distinct systemic signaling for N supply and demand. Gu, et al. [56] supported that nitrogen and CK signaling play a role in root-and-shoot communication, which maximizes plant productivity. CK biosynthetic genes including IPTs, play a key role in root development, bud outgrowth and shoot branching, and plant development. CK activity occurs in two stages. During the initial stage, CK is produced in the outer layer of the roots and translocates inward. In the second stage, the inner part of the root pushes outward and forms the nodule. This stage has been proposed to be controlled by *ITP3*. A study revealed that a knockout mutant plant lacking the *IPT3* gene failed to form nodules in the roots [57], which suggests that *IPT3* would play a key role in the formation of nodules and nitrogen fixation. Lin, et al. [58] recently observed that NO_3 restricted nodule organogenesis through CK biosynthesis inhibition. Similarly, Sasaki, et al. [59] supported that CK regulates root nodulation in plants. Moreover, growth-promoting microorganisms are widely used in agriculture for their roles in the promotion of plant growth and productivity. In their report, Singh, et al. [60] revealed that *Trichoderma* spp., known as a plant growth promoter and biocontrol fungal agent, can enhance NO_3 acquisition events, and was shown to encompass the ability to regulate transcripts level of high-affinity NO_3 transporters, in crosstalk with phytohormones.

2.3. Improving Abiotic Stress Tolerance in Plants

Nitrogen acquisition and uptake can be restricted under abiotic stress conditions, such as drought and salinity. External fluctuations of N supply to plants caused by abiotic stress occurrence have been shown to hinder NO_3 acquisition as well as other subsequent events due to water scarcity [61]. As per some evidence, high- and low-affinity NO_3 transporters and glutamate synthase-encoding genes [62], and phytohormones biosynthetic and signaling pathway genes [63][64] (in addition to well-characterized abscisic acid (ABA), jasmonic acid (JA)), would play important roles in the adaptive response mechanism towards abiotic stress tolerance in plants. In addition, Zhong, et al. [65] revealed that overexpression of a bZIP (basic leucine zipper) transcription factor encoding gene in Arabidopsis, *AtTGA4* conferred drought tolerance through the increase in NO_3 transport and assimilation mediated by high- and low-affinity NO_3 transporters and NO_3 encoding genes. Owing to the above, capitalizing on the recorded progress in terms of understanding plant nutrition and abiotic stress tolerance in plants, exploring the interplay between NUE and abiotic stress tolerance could serve as novel and exciting research directions. The outputs would provide more insights that allow breeding for abiotic stress tolerance, such as drought, while addressing NUE using an integrated or system thinking approach.

2.4. Exploring Radial Oxygen Loss and Intermittent Drainage

The importance of oxygen (O_2) in the life of plants has been established. O_2 plays a fundamental role in plant metabolism. For instance, O_2 serves as a terminal electron acceptor during electron transport, and its concentration plays an important role in regulating cellular respiration [66]. The internal transport of gases is said to be crucial for vascular plants inhabiting aquatic, wetland, or flood-prone environments [67]. O_2 is the rate-limiting substrate for the efficient production of energy in aerobic organisms. Therefore, they need to adjust their metabolism to the availability of O_2.

Plants have the ability to produce oxygen in the presence of light. However, when the O_2 diffusion from the environment cannot satisfy the demand set by metabolic rates, plants can experience low O_2 availability [68]. Flooding or waterlogging induces hypoxic conditions in plants, which may lead to reduced energy production. Under these conditions, the direct exchange of O_2 between the submerged tissues and the environment is strongly impeded and other programmed cell death (PCD) [69]. The diffusivity of O_2 in water is about 10,000 times slower than in the air. In addition, the transport of O_2 and other gases across the plant increases because of tissues' high porosity [70], which results from the intercellular gas-filled spaces formed as a constitute part of development [71][72][73][74] and may be enhanced further by the formation of aerenchyma [75]. The aerenchyma facilitates the flow of O_2 in and outside the plant, which provides roots with O_2 under flood-mediated hypoxia [76]. Colmer et al. [76] also indicated that aerenchyma provides a low-resistance internal pathway for gas transport between shoot and root extremities, and by this pathway, O_2 is supplied to the roots and rhizosphere; whereas, CO_2 and CH_4 move from the soil to the shoot and atmosphere by the same means. The O_2 that is released to the rhizosphere of the root system and the immediate environment through the aerenchyma is known as radial oxygen loss (ROL) [77]. In the same perspective, Mohammed, et al. [78] revealed that rice overexpressing the EPIDERMAL PATTERNING FACTOR 1 (OsEPF1)-mediated reduction of stomatal conductance resulted in an increased formation of root cortical aerenchyma, which would be in part explained by reduced O_2 diffusion from shoot to the root where EPF signaling may be involved.

Furthermore, flood-prone and wetland cultivation areas, where anaerobic conditions prevail and relatively high amounts of N-rich fertilizers are often applied, have proven to be major sources of GHG gas emissions during crop cultivation [79][80]. The flood status produces anoxic environments that are conducive to the production and emissions of CH_4. According to Bodelier, et al. [81], the only biological way of degrading CH_4, the second most important GHG globally but the first in agriculture, is by microbial oxidation. In the same way, Reim, et al. [82] studied methane-oxidizing bacteria (MOBs) under oxic-anoxic conditions in flooded paddy soil and suggested that MOBs act as a bio-filter in mitigating CH_4 emissions to the atmosphere. Biological emissions of CH_4 from wetlands are a major uncertainty in CH_4 budgets. MOBs use CH_4 as their sole source of carbon and energy, as long as oxygen is available [83], contrasting with the methanogenesis by Archaea, which is known as an anaerobic process accounting for most biological CH_4 production in nature.

According to Dalal, et al. [84], aerobic well-drained soils are generally a sink for CH_4, due to the high CH_4 diffusion rate into such soils and subsequent oxidation by methanotrophs. The capacity of soils to uptake CH_4 varies with land use, management practices [85], and soil conditions [86]. In contrast, large CH_4 emissions are usually observed in anaerobic conditions, such as wetlands, rice paddy fields, and landfills. Warm temperatures and the presence of soluble carbon provide optimal conditions for CO_2 production and incompletely oxidized substrates, thus enhancing the activity of methanogens. Likewise, a close relationship between the increase in atmospheric CO_2 levels and the subsequent increase in CH_4 emissions has been proposed. In this regard, studies suggested intermittent drainage to reduce the activity of anaerobic methanogens in the soil, especially in flooded crop cultivation systems, which may have a direct impact on the amount of CH_4 produced and released by up to 80%. Although in-season or intermittent drainage can result in a significant reduction in CH_4 production and emissions, this crop management technique aiming to mitigate CH_4 emissions can cause increased N_2O emissions, even if the overall warming potential remains lowered [17][18].

As for Walkiewicz, et al. [87], the activity of methanotrophs is favored under hypoxia in NH_4 fertilized soils. In **Figure 3**, researchers illustrate the action of ROL on methanogens and methanotrophs activity, which influences CH_4 production through the oxidation process to yield water and CO_2. Studies revealed that there are factors that may cause the reduction of ROL with the formation of an ROL barrier. Colmer, et al. [88] reported that low concentrations of organic acids may help trigger a barrier to ROL in roots. Ejiri and Shiono [89] supported that the prevention of ROL would be associated with exodermal suberin along adventitious roots. Abiko, et al. [90] observed the formation of an ROL barrier on lateral roots, in addition to adventitious roots, and reported a major locus controlling the formation of an ROL barrier in maize. The authors argued that the enhanced formation of aerenchyma and induction of a ROL barrier would confer waterlogging tolerance, which argument was supported by Ejiri, et al. [91] suggesting that a barrier to ROL helps the root system cope with waterlogging-induced hypoxia. In their study, Peralta Ogorek, et al. [92] reported a novel function of the root barrier to ROL in conferring diffusion resistance to H_2 and water vapor. In rice, the first genetic locus associated with ROL was recently identified, with a set of genes suggested to be involved in aerenchyma-mediated ROL in plants [93]. Therefore, with the growing concern about mitigating GHG emissions from agriculture, exacerbated by the application of excessive amounts of N-rich fertilizers, coupled with the hypoxic conditions and low diffusion of O_2 in waterlogged or flooded cultivation areas, breeding for high ROL in plants could serve as an alternative to conventional techniques such as intermittent drainage that are rarely employed in wetlands. This could be essential for areas such as paddy fields that require efficient water management and where drainage could not be applicable due to evident circumstances such as limited access to a water source. Moreover, it has been evidenced that respiration and nitrogen assimilation in plants are tightly linked. In this regard, studies exploring the interplay between the above factors supported that mitochondrial-associated metabolism can be used as a mean to enhance NUE in plants [94][95][96].

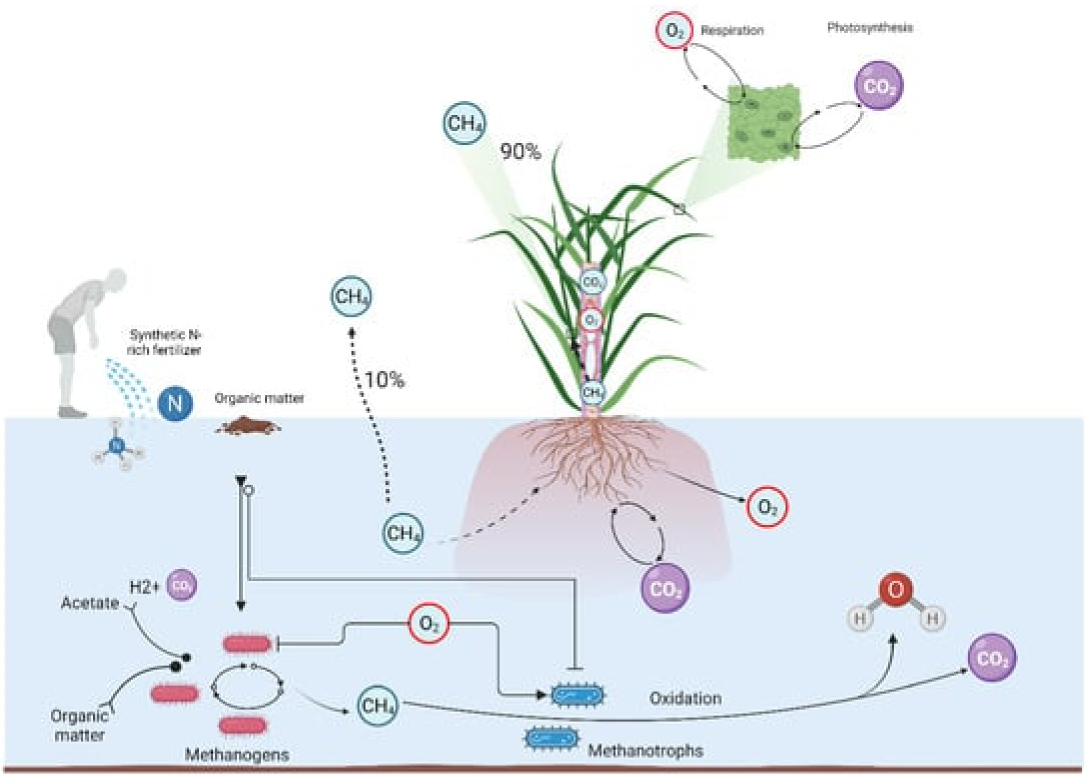

Figure 3. Illustration of ROL in plants and mitigation of GHG emissions. Internal transport of gases is crucial for vascular plants in wetland or flood-prone environments. The direct exchange of gases between submerged tissues and the environment is impeded due to the slow diffusivity of gases in water. Soil aeration can fluctuate and zones of low O_2 are widely spread in soil. In many wetland plants, aerenchyma is well developed even in drained conditions, and further enhanced in waterlogged conditions. Aerenchyma formation increases porosity above level due to the usual intercellular spaces. The O_2 released to the rhizosphere of roots and the immediate environment (ROL) exerts differential effects on soil microbial activity. ROL inhibits the metabolism of anaerobic microorganisms such as methanogens (Archaea). Consequently, ROL abundance reduces CH_4 production. In contrast, ROL

promotes the metabolism of obligate aerobic organisms (methanotrophs or methane-oxidizing bacteria), allowing them to oxidize CH_4 as their sole source of energy. Aerenchyma provides a low-resistance internal pathway for gas transport between the shoot-and-root extremities, and this pathway supplies O_2 to the roots and rhizosphere. About 90% of CH_4 emitted through crop cultivation is conveyed by plants during gas exchange events and long-distance transport. Whereas, nearly 10% is released through ebullition or diffusion from water or soil surface. This model was created using the biorender design platform (https://app.biorender.com/, accessed on 25 May 2023).

Carbon dioxide (CO_2) is the most abundantly emitted of all GHGs. However, CO_2 has a global warming potential 25 times less than that of CH_4 and 300 times less than that of N_2O. Global leaders and scientists, among others, stressed at the COP26 that CH_4 is a great threat to accelerate global warming over a 30-year period, which makes CH_4 much more potent than CO_2 and a greater climate change hazard. As indicated earlier, irrigated or flood-prone cultivation, systems are favorable environments for CH_4 production, which is by far the most abundantly emitted in agriculture. Rice (staple food for nearly half of the world's population) production occurs through irrigation/flooded or wet environments or upland/rainfed systems. For instance, the use of a system of rice intensification (SRI) [97], which focuses on changing the management of plants, soil water, and nutrients to create more productive and sustainable rice cultivation, while tending to reduce environmental impacts, could serve as a relevant alternative to reducing GHG emissions. Some of the fundamental concepts of SRI include the use of a smaller amount of seeds and greater planting distances, less use of inputs and intermittent irrigation instead of flood irrigation (savings in irrigation water and inputs), and reduced environmental footprint of rice farming. Regardless of the benefits of SRI, it is overly labor-intensive, and requires a higher level of technical knowledge and skill than conventional methods or rice cultivation [98].

Pereira-Mora, et al. [99] investigated the response of plants to organic acids, found that organic acids the abundance of methanogenic arechea and the *mcrA* gene in plants was reduced in treatment with organic acid under the SRI-rotational cultivation system.

2.5. Biochar Reduces Mineral Fertilizers Use, Improves Soil Properties and Mitigate Ghg Emissions

Biochar is widely used as a soil amendment in different agricultural ecosystems. The application of biochar in agriculture increased over the years for various purposes [100], and their recognition as an effective tool for reducing soil GHG emissions has been reinforced in recent years [101][102][103][104][105]. Joseph, et al. [106] define biochar as the carbon-rich product obtained when biomass, such as wood manure or leaves, is heated in a closed container with little or no available air. In other words, biochar is produced by thermal decomposition of organic material under limited O_2 supply, and at relatively low temperatures. Unlike charcoal, biochar is mainly produced to improve soil properties, carbon storage, or filtration of percolating soil water. Reports indicate that biochar is not only more stable than any other amendment to soil [107], but it helps increase the availability of nutrients beyond a fertilizer effect [100]. Biochar also contributes to (the): (i) improvement of water-holding capacity and other physical properties [108][109], (ii) increase in the stable pool of carbon [110], absorption/complexation of soil organic matter and toxic compounds [111], (iii) absorption and reaction with gases within the soil [112], affect carbon and nitrogen transformation and retention processes in soil [100][113], and (iv) promotion of the growth of beneficial soil microorganisms.

A number of studies proposed that incorporating biochar within soil reduces N_2O emissions and impacts on CH_4 uptake from soil [114][115][116]. However, the mechanisms through which biochar influences CH_4 and N_2O fluxes are not yet well elucidated. Studies suggest that the properties of biochar and its effects within agricultural ecosystems largely depend on feedstock and pyrolysis conditions. As biochar ages, it is incorporated into soil aggregates and promotes the stabilization of rhizodeposits and microbial products [116]. In addition, Joseph, et al. [117] indicated that the properties of biochar can vary with their element compositions, ash content, and composition, density, water absorbance, pore size, toxicity, ion absorption and release, recalcitrance to microbial or abiotic decay, surface chemical properties (i.e., pH), or surface area. Biochar can catalyze abiotic and biotic reactions in the rhizosphere, which may increase nutrient availability and uptake by plants, reduce phytotoxins, stimulate plant development, and increase resilience to disease and environmental stimuli [116]. Recent evidence suggests that biochar generally increases soil CO_2 emission, reduces N_2O emissions and NO_3 leaching [118][119], and has varying effects on CH_4 emissions [120][121]. Kalu, et al. [122] reported an increased CO_2 efflux after applying biochar 2–8 years before planting but did not observe any significant effect on the fluxes of N_2O or CH_4 in soil with a high soil organic carbon (SOC). A tendency of biochar to reduce N_2O fluxes was observed in soils with high silt content and lower soil carbon. The authors recorded an increased NUE in the long term, while soils with a high SOC underwent continuous freeze-thaw cycles, which may lead to differential effects of biochar. Thus, biochar is emerging as a sustainable source of plant nutrients for crops and soil quality, with interesting environmental benefits.

2.6. Enhancing Sink Strength

A growing interest in investigating the starch metabolism in plants to explore the possibility of reducing GHG emissions from agriculture, especially CH_4 has been observed [123][124]. A study by Su, et al. [125] suggested that increasing sink strength would help enhance the sugar metabolism, while reducing the substrates required for methanogenesis, therefore lowering the activity of methanogens, and consequently affecting CH_4 generation in the soil. However, a pending question on how the methanotrophs population would be affected in their role of contributing to the nitrification and denitrification processes [18][126] while relying on CH_4 as their sole carbon source for their metabolism remains unanswered.

Root exudation is an important process determining plant interactions with the soil environment [127]. On the one hand, the exudates (low molecular weight compounds: amino acids, organic acids, sugars, phenolics, and other secondary metabolites [128]; high molecular weight compounds: mucilage (polysaccharides) and proteins [129][130]) continuously secreted to the rhizosphere by the roots of plants, are involved in several processes [131]. Plants can modify soil properties to adapt and ensure their survival under adverse conditions, by modulating the composition of the root exudates [132]. Plant root exudates are important factors that structure the bacterial community and their interactions in the rhizosphere [130], or promoting the interactions between plants and soil microorganisms [133], and enhance resource use efficiency in the rhizosphere [134]. In addition, root exudates are involved in the inhibition of harmful microorganisms [135] or stimulating beneficial micro-organisms [127], keeping the soil moist and wet, mobilizing nutrients, stabilizing soil aggregates around the roots, changing the chemical properties of the soil, inhibiting the growth of competitor of plants [129][136], etc. It is well established that root exudates provide nutrients that favor enhanced growth and a higher prevalence of degrading strains of bacteria [137].

On the other hand, Lu, et al. [138] suggested that stronger roots could secrete more carbon-containing root exudates into the rhizosphere for methanogenesis. The authors found that soils amended with acetate or glucose, root exudates, and straw caused an increased CH_4 production. Likewise, Moscôso, et al. [139] recorded an increased CH_4 emission induced by short-chain organic acids in lowland soil. In the same way, Aulakh, et al. [140] assessed the impact of root exudates on CH_4 production and revealed that CH_4 production commenced soon after treatment, and the emission increased over time.

For grain crops, yield is the cumulative result of both source and sink strength for photoassimilates and nutrients during seed development. Source strength is determined by the net photosynthetic rate and the rate of photoassimilates remobilization from source tissues [141]. The long-distance transport (sugar export from leaves) and the corresponding demand by sinks have been examined as a possible target for improving plant productivity. The transfer of materials from source to sink is governed by a highly regulated signaling network elicited by resource availability. Sink strength is regarded as the function of size and sink activity, which is tightly related to the source availability. It is accepted that carbon allocation to various sinks is controlled by both sink demand (activity and size) and source control of photosynthate production [142].

Furthermore, Studies indicated that carbohydrate signaling gives insights into the understanding of changes in resources such as N. Increased N uptake and inorganic N availability in leaf tissue favors the synthesis of amino acids over gluconeogenesis. As a result, carbohydrates are retained in source tissue at the expense of allocation to heterotrophic tissues such as roots [142][143]. Similarly, a decreased leaf inorganic N leads to decreased amino acid synthesis but increases carbohydrate availability for transport to heterotrophic tissues, including roots. With the increase in carbon availability, genes involved in storage and use are induced [144], leading to root growth and increased N acquisition, more exudates secretion, and GHG production.

2.7. Use of Nitrification Inhibitors or Low GHG-Emitting Crop Cultivars

It is widely accepted that excessive application of N-rich fertilizers (mineral N source or organic matter) [145] significantly exacerbates CH_4 and N_2O production and emissions, especially during nitrification and denitrification processes (the microbial reduction of NO_3 to intermediate gases nitric oxide (NO) and N_2O and finally to N_2). Although N is an indispensable macronutrient for plant growth and development, productivity, quality of products, as well as plant defense, and knowing that doing agriculture without N is nearly utopic; however reducing N application, while optimizing its use, remains one of the major target and one the best options with multiple benefits for the environment and production costs. Organic matter is commonly applied to satisfy soil fertility and improve water retention capacity. The application of green manure, crop residues, manure, and composted products contributes to reducing CH_4 emissions as discussed earlier.

The application of straw often reduces N_2O emissions [17]. Generally, straw with a high carbon/nitrogen (C/N) ratio likely immobilizes available N, thus reducing its availability for both nitrification and denitrification [146][147]. However, the reducing effect of straw on N_2O emissions varies from one crop species to another [147], and long-term application of high C/N straw may result in increased N availability which, in turn, may increase N_2O emission [148]. Additionally, farmers can take advantage of the nitrification inhibitors, which have been widely shown to reduce N_2O emissions in a wide range of crop species [149][150][151]. Evidence showed that GHG emissions from crop production are also crop variety-dependent.

2.8. Improving Livestock Production and Feeding Efficiency

The global demand for meat and dairy products is growing, and over the past 50 years, meat production has significantly increased in recent years and is projected to increase by two to threefold by 2050 [152], reaching about 340 million tons each year. The contribution of livestock to the recorded global CH_4 emissions is high (https://ourworldindata.org/meat-production, accessed on 26 April 2023). Meat and dairy products are important sources of proteins, vitamins, and essential minerals useful to human health in many countries [153][154][155] but also present potential risks to health [156][157][158]. Likewise, the production of meat and dairy products has environmental impacts, as it contributes to GHG emissions such as CH_4, among others. Today, one of the most pressing global challenges is the sustainable production and consumption of meat, dairy, and other protein products.

The major source of GHG emissions from agricultural production is the enteric fermentation of ruminant livestock, and the interest in reducing CH_4 production in ruminants continues to grow globally [159]. According to the UNEP Emissions Gap Report 2022 [160], beyond the necessity to change diets, the reduction of CH_4 emissions from ruminants can be achieved via changes in feed level and feed composition, which can also increase animal productivity. Frank, et al. [161] found that the adoption of technical and structural mitigation options could help agriculture achieve a carbon price of USD 25/tCO_2 non-CO_2 reductions of around 1GtCO_2eq by 2030. In the same way, Arndt, et al. [162] indicated that to meet the 1.5 °C target, CH_4 from ruminants must be reduced by 11–30% by 2030 or 24–47% by 2050 as compared to the record in 2010. The authors identified strategies to decrease product-based (PB, CH_4 per unit meat or milk) and absolute (ABS) enteric CH_4 emissions, while maintaining or increasing animal productivity (AP, weight gain, or milk yield). Other independent studies [163] claimed that enhancing the activity of the major ruminal sulfate-reduction bacteria (SRB: *Desulfovibrio, Desulfohalobium, Sulfobus*) through dietary sulfate addition, can be used as an effective approach to mitigate CH_4 emissions in ruminants, which may lead to a decreased ruminal CH_4 production. The major target would be helium (H_2), which is the primary substrate for CH_4 production during ruminal methanogenesis. In the rumen, SRB have the ability to compete with methanogens for H_2, thus resulting in the inhibition of methanogenesis.

From another perspective, research indicates that CH_4 emission is also associated with dietary energy loss that reduces feed efficiency [164]. Another way of mitigating ruminal CH_4 identified in the literature is the use of saponins. According to Newbold, et al. [165], low concentrations of saponins act as antiprotozoal. In contrast, at higher concentrations, saponins are able to suppress methanogens [166] and inhibit ruminal bacterial and fungal species [167], limiting the H_2 availability for methanogenesis in the rumen, thereby lowering CH_4 production by up to 50% [166][168]. Other methods for ruminal CH_4 mitigation include forage quality [169][170][171], type of silage [172][173][174][175], proportion of concentrates [176][177][178] and composition [179][180][181][182], the use of organic acids [183][184][185], essential oils (secondary metabolites) [186][187][188], or probiotics [189][190][191][192]. Additionally, exogenous enzymes, such as cellulase and hemicellulose, are used in ruminant diets. These enzymes can improve the digestibility of fiber as well as animal productivity. They are also capable of lowering the acetate: propionate ratio in the rumen, ultimately resulting in the reduction of CH_4 production [193][194].

An indirect approach to reduce CH_4 production could be the use of antibiotics such as the antimicrobial monensin. The latter enhances the acetate: propionate ratio in the rumen [172] when added to the diet as a premix and has a methanogenic effect. According to Hook, et al. [195], ionophores do not alter the diversity of methanogens but change the bacterial population from Gram-positive to Gram-negative, therefore resulting in the change in the fermentation from acetate to propionate, and reducing CH_4 [196][197][198]. Researchers are thinking of employing breeding to explore the possibility of developing low CH_4/GHG-emitting cows/ruminants. Numerous studies have shown a substantial variation in CH_4 production from cows and sheep [164][199][200], which is associated with phenotypic traits and heritability. Thus, this variation suggests a possibility of breeding animals with low CH_4 emissions. However, a different view from Eckard, et al. [201] suggested that breeding for reduced CH_4 production is unlikely to be compatible with other breeding objectives.

Knowing that livestock manure represents an important source of GHGs from agriculture, their proper management is necessary to curb the share of agriculture to the global GHG emission records. Manure management practices such as anaerobic digestion, daily spread, pasture-based management, composting, solid storage, manure drying practices, semi-permeable covers, nature or induced crust, decreased manure storage time, compost bedded pack barns, solid separation of manure solids prior to entry into a wet/anaerobic environment have been shown to result in significant methane emissions (https://www.epa.gov/agstar/practices-reduce-methane-emissions-livestock-manure-management, accessed on 25 October 2023). In essence, anaerobic digestion is a process through which microorganisms break down organic matter (including animal manure) in the absence of oxygen. Anaerobic digestion with biogas flaring or utilization is suggested to reduce overall methane emissions and provides several benefits (conservation of agricultural land, energy independence, sustainable food production, diversified farm revenue, farm-community relationships, and rural economic growth). Designs such as covered anaerobic lagoons, plug flow digesters, and complete mix digesters can serve as leading technologies to transform livestock manure into energy for various uses. As for daily spread management practice (suitable for smaller farms and warmer climates. Daily labor and equipment costs associated with this management practice should be considered), manure is removed from a barn and is applied to cropland or pasture daily. Concerning pasture-based management, animals are kept on fenced pastures; they are rotated between grazing areas to improve the health of the pasture and to spread manure (manure is left as-is to return nutrients and carbon to the land).

In addition, composting involves the decomposition of manure or other organic material by microorganisms in the presence of oxygen [202]. In general, this process takes several weeks to months depending on the level of turning/aeration management. Composting methods include (i) composting in a vessel (in an enclosed vessel with continuous mixing providing aeration); (ii) composting in an aerated static pile (in piles with forced aeration without mixing); (iii) composting in intensive windrows (with regular turning for mixing and aeration); and (iv) composting in passive windrows (with infrequent turning for mixing and aeration). Furthermore, solid storage (typical in colder climates, covered facilities aid with snow and rainfall events) consists of manure storage, typically for a period of several months, either in an open area with unconfined piles or stacks or in a dedicated storage facility where the manure is confined within the wall of the facility [203]. Moreover, manure drying practices involve a variety of methods to reduce the liquid content of manure to achieve a solid content of 13% or more. This manure management practice is commonly used in poultry operations but can be used with other animals. It is suitable for hot, dry climates and smaller operations that have space available for drying. Nevertheless, it can be done year-round in any climate considering that manure can also be dried indoors [204].

Likewise, semi-permeable covers enclose open manure storage. Because of biological and physical activity that occurs in the manure, induced or natural crusts are formed. The covers can reduce methane, ammonia, and odor. This practice is suitable for dairy cattle operations. Straw covers are typically used for small, accessible manure storage areas. In the same way, compost-bedded pack barns are a housing system that comprises deep bedding (wood shaving, sawdust, or other absorbent bedding materials). Here, animals can freely roam on the pack and through walkways to access the feeding area. This system is generally an alternative to tie or free stalls for dairy cows [205][206]. Finally, solid separation of manure solids prior to entry into a wet/anaerobic environment is a technique consisting of separating solid particles from water based on density and size [207].

References

1. Clapp, J.; Cohen, M.J. The Global Food Crisis: Governance Challenges and Opportunities; Wilfrid Laurier University Press: Waterloo, Canada, 2009.
2. Singh, D.; Seager, R.; Cook, B.I.; Cane, M.; Ting, M.; Cook, E.; Davis, M. Climate and the Global Famine of 1876–1878. J. Clim. 2018, 31, 9445–9467.
3. Gooding, P. ENSO, IOD, Drought, and Floods in Equatorial Eastern Africa, 1876–1878. In Droughts, Floods, and Global Climatic Anomalies in the Indian Ocean World; Springer: Berlin/Heidelberg, Germany, 2022; pp. 259–287.
4. Holden, E.; Linnerud, K.; Banister, D. Sustainable development: Our common future revisited. Glob. Environ. Change 2014, 26, 130–139.
5. Sam, S.J.E. The people, planet, prosperity, peace and partnership: Why the sustainable development goals should matter to everyone. Ecodate 2016, 30, 7–12.
6. Mpabanga, D.; Sesa, L. Imperatives: The Five P’s: People, Planet, Prosperity, Peace and Partnerships and Sustainable Development Goals-The Need to Transform Public Administration and Management. Afr. J. Public Adm. Manag. 2020, 17, 44–58.

7. Papoulis, D.; Kaika, D.; Bampatsou, C.; Zervas, E.J.C. Public perception of climate change in a period of economic crisis. Climate 2015, 3, 715–726.
8. Adger, W.N.; Kelly, P.M. Social vulnerability to climate change and the architecture of entitlements. Mitig. Adapt. Strateg. Glob. Change 1999, 4, 253–266.
9. Otto, I.M.; Reckien, D.; Reyer, C.P.; Marcus, R.; Le Masson, V.; Jones, L.; Norton, A.; Serdeczny, O. Social vulnerability to climate change: A review of concepts and evidence. Reg. Environ. Change 2017, 17, 1651–1662.
10. Hasegawa, T.; Fujimori, S.; Havlík, P.; Valin, H.; Bodirsky, B.L.; Doelman, J.C.; Fellmann, T.; Kyle, P.; Koopman, J.F.; Lotze-Campen, H.; et al. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat. Clim. Change 2018, 8, 699–703.
11. Ericksen, P.J.; Thornton, P.K.; Notenbaert, A.M.O.; Cramer, L.; Jones, P.G.; Herrero, M.T. Mapping hotspots of climate change and food insecurity in the global tropics. In CCAFS Report; CCAFS: Copenhagen, Denmark, 2011.
12. Crutzen, P.J.J.N. Methane’s sinks and sources. Nature 1991, 350, 380–381.
13. Reay, D. Greenhouse Gas Sinks; CABI: Wallingford, UK, 2007.
14. Reay, D.; Smith, P.; Van Amstel, A. Methane sources and the global methane budget. In Methane and Climate Change; Earthscan: London, UK; Washington, DC, USA, 2010; pp. 1–13.
15. Casper, J.K. Agriculture: The Food We Grow and Animals We Raise; Infobase Publishing: New York, NY, USA, 2007.
16. Bhuvaneshwari, S.; Hettiarachchi, H.; Meegoda, J.N. Crop residue burning in India: Policy challenges and potential solutions. Int. J. Environ. Res. Public Health 2019, 16, 832.
17. Ma, J.; Li, X.L.; Xu, H.; Han, Y.; Cai, Z.C.; Yagi, K. Effects of nitrogen fertiliser and wheat straw application on CH4 and N2O emissions from a paddy rice field. Soil Res. 2007, 45, 359–367.
18. Horwath, W. Greenhouse gas emissions from rice cropping systems. In Understanding Greenhouse Gas Emissions from Agricultural Management; ACS Publications: Washington, DC, USA, 2011; pp. 67–89.
19. Hoornweg, D.; Bhada-Tata, P. What a Waste: A Global Review of Solid Waste Management; World Bank: Washington, DC, USA, 2012.
20. Rakotoson, T.; Dusserre, J.; Letourmy, P.; Frouin, J.; Ratsimiala, I.R.; Rakotoarisoa, N.V.; Vom Brocke, K.; Ramanantsoanirina, A.; Ahmadi, N.; Raboin, L.M. Genome-wide association study of nitrogen use efficiency and agronomic traits in upland rice. Rice Sci. 2021, 28, 379–390.
21. Bandyopadhyay, T.; Swarbreck, S.M.; Jaiswal, V.; Maurya, J.; Gupta, R.; Bentley, A.R.; Griffiths, H.; Prasad, M. GWAS identifies genetic loci underlying nitrogen responsiveness in the climate

resilient C4 model Setaria italica (L.). J. Adv. Res. 2022, 42, 249–261.

22. Akhatar, J.; Goyal, A.; Kaur, N.; Atri, C.; Mittal, M.; Singh, M.P.; Kaur, R.; Rialch, I.; Banga, S.S. Genome wide association analyses to understand genetic basis of flowering and plant height under three levels of nitrogen application in Brassica juncea (L.) Czern & Coss. Sci. Rep. 2021, 11, 4278.
23. Nazish, T.; Arshad, M.; Jan, S.U.; Javaid, A.; Khan, M.H.; Naeem, M.A.; Baber, M.; Ali, M. Transporters and transcription factors gene families involved in improving nitrogen use efficiency (NUE) and assimilation in rice (Oryza sativa L.). Transgenic Res. 2021, 31, 23–42.
24. Wang, Q.; Su, Q.; Nian, J.; Zhang, J.; Guo, M.; Dong, G.; Hu, J.; Wang, R.; Wei, C.; Li, G.; et al. The Ghd7 transcription factor represses ARE1 expression to enhance nitrogen utilization and grain yield in rice. Mol. Plant 2021, 14, 1012–1023.
25. Han, M.L.; Lv, Q.Y.; Zhang, J.; Wang, T.; Zhang, C.X.; Tan, R.J.; Wang, Y.L.; Zhong, L.Y.; Gao, Y.Q.; Chao, Z.F.; et al. Decreasing nitrogen assimilation under drought stress by suppressing DST-mediated activation of Nitrate Reductase 1.2 in rice. Mol. Plant 2022, 15, 167–178.
26. Zhang, Z.; Chu, C. Nitrogen-use divergence between indica and japonica rice: Variation at nitrate assimilation. Mol. Plant 2020, 13, 6–7.
27. Teng, W.; He, X.; Tong, Y. Genetic Control of Efficient Nitrogen Use for High Yield and Grain Protein Concentration in Wheat: A Review. Plants 2022, 11, 492.
28. Kabange, N.R.; Park, S.Y.; Shin, D.; Lee, S.M.; Jo, S.M.; Kwon, Y.; Cha, J.K.; Song, Y.C.; Ko, J.M.; Lee, J.H. Identification of a novel QTL for chlorate resistance in rice (Oryza sativa L.). Agriculture 2020, 10, 360.
29. Anas, M.; Liao, F.; Verma, K.K.; Sarwar, M.A.; Mahmood, A.; Chen, Z.-L.; Li, Q.; Zeng, X.-P.; Liu, Y.; Li, Y.-R. Fate of nitrogen in agriculture and environment: Agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. Biol. Res. 2020, 53, 47.
30. Li, Q.; Lu, X.; Wang, C.; Shen, L.; Dai, L.; He, J.; Yang, L.; Li, P.; Hong, Y.; Zhang, Q.; et al. Genome-wide association study and transcriptome analysis reveal new QTL and candidate genes for nitrogen-deficiency tolerance in rice. Crop J. 2022, 10, 942–951.
31. Fan, X.; Naz, M.; Fan, X.; Xuan, W.; Miller, A.J.; Xu, G. Plant nitrate transporters: From gene function to application. J. Exp. Bot. 2017, 68, 2463–2475.
32. Lea, P.J.; Miflin, B.J. Glutamate synthase and the synthesis of glutamate in plants. Plant Physiol. Biochem. 2003, 41, 555–564.
33. Prasad, L.R.V.; Mailapalli, D.R. Evaluation of nitrogen fertilization patterns using DSSAT for enhancing grain yield and nitrogen use efficiency in rice. Commun. Soil Sci. Plant Anal. 2018, 49, 1401–1417.

34. Nakidakida, T.; Hayashi, H. Nitrogen recovery and nitrogen use efficiency of potatoes in an integrated compost fertilization system in an Andosol soil. In Proceedings of the III International Symposium on Organic Matter Management and Compost Use in Horticulture 1146, Murcia, Spain, 6 April 2015; pp. 41–48.
35. Li, H.; Hu, B.; Chu, C. Nitrogen use efficiency in crops: Lessons from Arabidopsis and rice. J. Exp. Bot. 2017, 68, 2477–2488.
36. Duan, Y.H.; Zhang, Y.L.; Ye, L.T.; Fan, X.R.; Xu, G.H.; Shen, Q.R. Responses of rice cultivars with different nitrogen use efficiency to partial nitrate nutrition. Ann. Bot. 2007, 99, 1153–1160.
37. Djaman, K.; Mel, V.C.; Ametonou, F.Y.; El-Namaky, R.; Diallo, M.D.; Koudahe, K. Effect of nitrogen fertilizer dose and application timing on yield and nitrogen use efficiency of irrigated hybrid rice under semi-arid conditions. J. Agric. Sci. Food Res. 2018, 9, 223.
38. Gallais, A.; Hirel, B. An approach to the genetics of nitrogen use efficiency in maize. J. Exp. Bot. 2004, 55, 295–306.
39. Liu, X.; Hu, B.; Chu, C. Nitrogen assimilation in plants: Current status and future prospects. J. Genet. Genom. 2021, 49, 394–404.
40. Hirel, B.; Tétu, T.; Lea, P.J.; Dubois, F. Improving nitrogen use efficiency in crops for sustainable agriculture. Sustainability 2011, 3, 1452–1485.
41. Yamaya, T.; Obara, M.; Nakajima, H.; Sasaki, S.; Hayakawa, T.; Sato, T. Genetic manipulation and quantitative-trait loci mapping for nitrogen recycling in rice. J. Exp. Bot. 2002, 53, 917–925.
42. Zhang, S.; Zhu, L.; Shen, C.; Ji, Z.; Zhang, H.; Zhang, T.; Li, Y.; Yu, J.; Yang, N.; He, Y.; et al. Natural allelic variation in a modulator of auxin homeostasis improves grain yield and nitrogen use efficiency in rice. Plant Cell 2021, 33, 566–580.
43. Kiba, T.; Kudo, T.; Kojima, M.; Sakakibara, H. Hormonal control of nitrogen acquisition: Roles of auxin, abscisic acid, and cytokinin. J. Exp. Bot. 2011, 62, 1399–1409.
44. Séguéla, M.; Briat, J.F.; Vert, G.; Curie, C. Cytokinins negatively regulate the root iron uptake machinery in Arabidopsis through a growth-dependent pathway. Plant J. 2008, 55, 289–300.
45. Maruyama-Nakashita, A.; Nakamura, Y.; Yamaya, T.; Takahashi, H. A novel regulatory pathway of sulfate uptake in Arabidopsis roots: Implication of CRE1/WOL/AHK4-mediated cytokinin-dependent regulation. Plant J. 2004, 38, 779–789.
46. Wagner, B.M.; Beck, E. Cytokinins in the perennial herb Urtica dioica L. as influenced by its nitrogen status. Planta 1993, 190, 511–518.
47. Franco-Zorrilla, J.M.; Martin, A.C.; Solano, R.; Rubio, V.; Leyva, A.; Paz-Ares, J. Mutations at CRE1 impair cytokinin-induced repression of phosphate starvation responses in Arabidopsis. Plant J. 2002, 32, 353–360.

48. Nacry, P.; Canivenc, G.; Muller, B.; Azmi, A.; Van Onckelen, H.; Rossignol, M.; Doumas, P. A role for auxin redistribution in the responses of the root system architecture to phosphate starvation in Arabidopsis. Plant Physiol. 2005, 138, 2061–2074.

49. Vidal, E.A.; Araus, V.; Lu, C.; Parry, G.; Green, P.J.; Coruzzi, G.M.; Gutiérrez, R.A. Nitrate-responsive miR393/AFB3 regulatory module controls root system architecture in Arabidopsis thaliana. Proc. Natl. Acad. Sci. USA 2010, 107, 4477–4482.

50. Chen, K.-E.; Chen, H.-Y.; Tseng, C.-S.; Tsay, Y.-F. Improving nitrogen use efficiency by manipulating nitrate remobilization in plants. Nat. Plants 2020, 6, 1126–1135.

51. Ueda, Y.; Yanagisawa, S. Transcription factor-based genetic engineering to increase nitrogen use efficiency. In Engineering Nitrogen Utilization in Crop Plants; Springer: Berlin/Heidelberg, Germany, 2018; pp. 37–55.

52. Wu, J.; Zhang, Z.S.; Xia, J.Q.; Alfatih, A.; Song, Y.; Huang, Y.J.; Wan, G.Y.; Sun, L.Q.; Tang, H.; Liu, Y. Rice NIN-LIKE PROTEIN 4 plays a pivotal role in nitrogen use efficiency. Plant Biotechnol. J. 2021, 19, 448–461.

53. Li, Q.; Ding, G.; Yang, N.; White, P.J.; Ye, X.; Cai, H.; Lu, J.; Shi, L.; Xu, F. Comparative genome and transcriptome analysis unravels key factors of nitrogen use efficiency in Brassica napus L. Plant Cell Environ. 2020, 43, 712–731.

54. Heuermann, D.; Hahn, H.; Von Wirén, N. Seed yield and nitrogen efficiency in oilseed rape after ammonium nitrate or urea fertilization. Front. Plant Sci. 2021, 11, 2197.

55. Ruffel, S.; Krouk, G.; Ristova, D.; Shasha, D.; Birnbaum, K.D.; Coruzzi, G.M. Nitrogen economics of root foraging: Transitive closure of the nitrate–cytokinin relay and distinct systemic signaling for N supply vs. demand. Proc. Natl. Acad. Sci. USA 2011, 108, 18524–18529.

56. Gu, J.; Li, Z.; Mao, Y.; Struik, P.C.; Zhang, H.; Liu, L.; Wang, Z.; Yang, J. Roles of nitrogen and cytokinin signals in root and shoot communications in maximizing of plant productivity and their agronomic applications. Plant Sci. 2018, 274, 320–331.

57. Azarakhsh, M.; Lebedeva, M.A.; Lutova, L.A. Identification and expression analysis of Medicago truncatula isopentenyl transferase genes (IPTs) involved in local and systemic control of nodulation. Front. Plant Sci. 2018, 9, 304.

58. Lin, J.; Roswanjaya, Y.P.; Kohlen, W.; Stougaard, J.; Reid, D. Nitrate restricts nodule organogenesis through inhibition of cytokinin biosynthesis in Lotus japonicus. Nat. Commun. 2021, 12, 6544.

59. Sasaki, T.; Suzaki, T.; Soyano, T.; Kojima, M.; Sakakibara, H.; Kawaguchi, M. Shoot-derived cytokinins systemically regulate root nodulation. Nat. Commun. 2014, 5, 4983.

60. Singh, B.N.; Dwivedi, P.; Sarma, B.K.; Singh, G.S.; Singh, H.B. A novel function of N-signaling in plants with special reference to Trichoderma interaction influencing plant growth, nitrogen use efficiency, and cross talk with plant hormones. 3 Biotech 2019, 9, 109.
61. Mundim, F.M.; Pringle, E.G. Whole-plant metabolic allocation under water stress. Front. Plant Sci. 2018, 9, 852.
62. Rolly, N.K.; Yun, B.-W. Regulation of Nitrate (NO3) Transporters and Glutamate Synthase-Encoding Genes under Drought Stress in Arabidopsis: The Regulatory Role of AtbZIP62 Transcription Factor. Plants 2021, 10, 2149.
63. Rolly, N.K.; Mun, B.-G.; Yun, B.-W. Insights into the Transcriptional Regulation of Branching Hormonal Signaling Pathways Genes under Drought Stress in Arabidopsis. Genes 2021, 12, 298.
64. Sun, L.; Di, D.-W.; Li, G.; Li, Y.; Kronzucker, H.J.; Shi, W. Transcriptome analysis of rice (Oryza sativa L.) in response to ammonium resupply reveals the involvement of phytohormone signaling and the transcription factor OsJAZ9 in reprogramming of nitrogen uptake and metabolism. J. Plant Physiol. 2020, 246, 153137.
65. Zhong, L.; Chen, D.; Min, D.; Li, W.; Xu, Z.; Zhou, Y.; Li, L.; Chen, M.; Ma, Y. AtTGA4, a bZIP transcription factor, confers drought resistance by enhancing nitrate transport and assimilation in Arabidopsis thaliana. Biochem. Biophys. Res. Commun. 2015, 457, 433–439.
66. Gupta, K.J. Plant Respiration and Internal Oxygen: Methods and Protocols; Springer: Berlin/Heidelberg, Germany, 2017.
67. Armstrong, W.; Armstrong, J. Plant internal oxygen transport (diffusion and convection) and measuring and modelling oxygen gradients. In Low-Oxygen Stress in Plants; Springer: Berlin/Heidelberg, Germany, 2014; pp. 267–297.
68. Kosmacz, M.; Weits, D.A. Oxygen perception in plants. In Low-Oxygen Stress in Plants; Springer: Berlin/Heidelberg, Germany, 2014; pp. 3–17.
69. Guan, B.; Lin, Z.; Liu, D.; Li, C.; Zhou, Z.; Mei, F.; Li, J.; Deng, X. Effect of waterlogging-induced autophagy on programmed cell death in Arabidopsis roots. Front. Plant Sci. 2019, 10, 468.
70. Armstrong, W. Advances in Botanical Research, Volume 7. Aeration in Higher Plants; Woolhouse, H.W., Ed.; Academic Press: Cambridge, MA, USA, 1979.
71. Sifton, H.B. Air-space tissue in plants. Bot. Rev. 1945, 11, 108–143.
72. Roland, J.C. Cell wall differentiation and stages involved with intercellular gas space opening. J. Cell Sci. 1978, 32, 325–336.
73. Jeffree, C.; Dale, J.; Fry, S.C. The genesis of intercellular spaces in developing leaves of Phaseolus vulgaris L. Protoplasma 1986, 132, 90–98.

74. Raven, J.A. Into the voids: The distribution, function, development and maintenance of gas spaces in plants. Ann. Bot. 1996, 78, 137–142.
75. Wegner, L.H. Oxygen transport in waterlogged plants. In Waterlogging Signalling and Tolerance in Plants; Springer: Berlin/Heidelberg, Germany, 2010; pp. 3–22.
76. Colmer, T.D. Long-distance transport of gases in plants: A perspective on internal aeration and radial oxygen loss from roots. Plant Cell Environ. 2003, 26, 17–36.
77. Lai, W.-L.; Zhang, Y.; Chen, Z.-H. Radial oxygen loss, photosynthesis, and nutrient removal of 35 wetland plants. Ecol. Eng. 2012, 39, 24–30.
78. Mohammed, U.; Caine, R.; Atkinson, J.; Harrison, E.; Wells, D.; Chater, C.; Gray, J.; Swarup, R.; Murchie, E.H. Rice plants overexpressing OsEPF1 show reduced stomatal density and increased root cortical aerenchyma formation. Sci. Rep. 2019, 9, 5584.
79. Scheehle, E.A.; Kruger, D. Global anthropogenic methane and nitrous oxide emissions. Energy J. 2006.
80. Denmead, O.; Freney, J.; Simpson, J.R. Nitrous oxide emission during denitrification in a flooded field. Soil Sci. Soc. Am. J. 1979, 43, 716–718.
81. Bodelier, P.L.; Pérez, G.; Veraart, A.J.; Krause, S. Methanotroph ecology, environmental distribution and functioning. In Methanotrophs; Springer: Berlin/Heidelberg, Germany, 2019; pp. 1–38.
82. Reim, A.; Lüke, C.; Krause, S.; Pratscher, J.; Frenzel, P. One millimetre makes the difference: High-resolution analysis of methane-oxidizing bacteria and their specific activity at the oxic–anoxic interface in a flooded paddy soil. ISME J. 2012, 6, 2128–2139.
83. Trotsenko, Y.A.; Murrell, J.C. Metabolic aspects of aerobic obligate methanotrophy⋆. Adv. Appl. Microbiol. 2008, 63, 183–229.
84. Dalal, R.C.; Allen, D.E.; Livesley, S.J.; Richards, G. Magnitude and biophysical regulators of methane emission and consumption in the Australian agricultural, forest, and submerged landscapes: A review. Plant Soil 2008, 309, 43–76.
85. Saggar, S.; Tate, K.; Giltrap, D.; Singh, J. Soil-atmosphere exchange of nitrous oxide and methane in New Zealand terrestrial ecosystems and their mitigation options: A review. Plant Soil 2008, 309, 25–42.
86. Schütz, H.; Seiler, W.; Rennenberg, H. Soil and land use related sources and sinks of methane (CH4) in the context of the global methane budget. In Soils and the Greenhouse Effect; John Wiley and Sons Ltd.: Hoboken, NJ, USA, 1990; pp. 269–285.
87. Walkiewicz, A.; Brzezińska, M.; Bieganowski, A. Methanotrophs are favored under hypoxia in ammonium-fertilized soils. Biol. Fertil. Soils 2018, 54, 861–870.

88. Colmer, T.D.; Kotula, L.; Malik, A.I.; Takahashi, H.; Konnerup, D.; Nakazono, M.; Pedersen, O. Rice acclimation to soil flooding: Low concentrations of organic acids can trigger a barrier to radial oxygen loss in roots. Plant Cell Environ. 2019, 42, 2183–2197.
89. Ejiri, M.; Shiono, K. Prevention of radial oxygen loss is associated with exodermal suberin along adventitious roots of annual wild species of Echinochloa. Front. Plant Sci. 2019, 10, 254.
90. Abiko, T.; Kotula, L.; Shiono, K.; Malik, A.I.; Colmer, T.D.; Nakazono, M. Enhanced formation of aerenchyma and induction of a barrier to radial oxygen loss in adventitious roots of Zea nicaraguensis contribute to its waterlogging tolerance as compared with maize (Zea mays ssp. mays). Plant Cell Environ. 2012, 35, 1618–1630.
91. Ejiri, M.; Fukao, T.; Miyashita, T.; Shiono, K. A barrier to radial oxygen loss helps the root system cope with waterlogging-induced hypoxia. Breed. Sci. 2021, 71, 40–50.
92. Peralta Ogorek, L.L.; Pellegrini, E.; Pedersen, O. Novel functions of the root barrier to radial oxygen loss–radial diffusion resistance to H2 and water vapour. New Phytol. 2021, 231, 1365–1376.
93. Duyen, D.V.; Kwon, Y.; Kabange, N.R.; Lee, J.Y.; Lee, S.M.; Kang, J.W.; Park, H.; Cha, J.K.; Cho, J.H.; Shin, D.; et al. Novel QTL Associated with Aerenchyma-Mediated Radial Oxygen Loss (ROL) in Rice (Oryza sativa L.) under Iron (II) Sulfide. Plants 2022, 11, 788.
94. Foyer, C.H.; Noctor, G.; Hodges, M. Respiration and nitrogen assimilation: Targeting mitochondria-associated metabolism as a means to enhance nitrogen use efficiency. J. Exp. Bot. 2011, 62, 1467–1482.
95. Maier, R.J. Nitrogen fixation and respiration: Two processes linked by the energetic demands of Nitrogenase. In Respiration in Archaea and Bacteria; Springer: Berlin/Heidelberg, Germany, 2004; pp. 101–120.
96. Weger, H.G.; Turpin, D.H. Mitochondrial respiration Can support NO3− and NO2− reduction during photosynthesis: Interactions between photosynthesis, respiration, and N assimilation in the N-limited green alga Selenastrum minutum. Plant Physiol. 1989, 89, 409–415.
97. De Laulanié, H. Intensive rice farming in Madagascar. Tropicultura 2011, 29, 183–187.
98. Sinclair, T.R. Agronomic UFOs waste valuable scientific resources. Rice Today 2004, 3, 43.
99. Pereira-Mora, L.; Terra, J.A.; Fernández-Scavino, A. Methanogenic community linked to organic acids fermentation from root exudates are affected by rice intensification in rotational soil systems. Appl. Soil Ecol. 2022, 176, 104498.
100. Xu, Z.; Chan, K. Biochar: Nutrient properties and their enhancement. Biochar Environ. Manag. 2009, 1, 67–84.

101. Lehmann, J.; Cowie, A.; Masiello, C.A.; Kammann, C.; Woolf, D.; Amonette, J.E.; Cayuela, M.L.; Camps-Arbestain, M.; Whitman, T. Biochar in climate change mitigation. Nat. Geosci. 2021, 14, 883–892.

102. Roe, S.; Streck, C.; Beach, R.; Busch, J.; Chapman, M.; Daioglou, V.; Deppermann, A.; Doelman, J.; Emmet-Booth, J.; Engelmann, J.; et al. Land-based measures to mitigate climate change: Potential and feasibility by country. Glob. Change Biol. 2021, 27, 6025–6058.

103. Yang, W.; Feng, G.; Miles, D.; Gao, L.; Jia, Y.; Li, C.; Qu, Z. Impact of biochar on greenhouse gas emissions and soil carbon sequestration in corn grown under drip irrigation with mulching. Sci. Total Environ. 2020, 729, 138752.

104. Lyu, H.; Zhang, H.; Chu, M.; Zhang, C.; Tang, J.; Chang, S.X.; Mašek, O.; Ok, Y.S. Biochar affects greenhouse gas emissions in various environments: A critical review. Land Degrad. Dev. 2022, 33, 3327–3342.

105. Lin, X.; Xie, Z.; Zheng, J.; Liu, Q.; Bei, Q.; Zhu, J.G. Effects of biochar application on greenhouse gas emissions, carbon sequestration and crop growth in coastal saline soil. Eur. J. Soil Sci. 2015, 66, 329–338.

106. Lehmann, J.; Joseph, S. Biochar for environmental management: An introduction. In Biochar for Environmental Management; Routledge: London, UK, 2015; p. 1.

107. Lehmann, J.; Czimczik, C.; Laird, D.; Sohi, S. Stability of biochar in soil. In Biochar for Environmental Management; Routledge: London, UK, 2009; pp. 183–206.

108. Major, J.; Steiner, C.; Downie, A.; Lehmann, J. Biochar effects on nutrient leaching. In Biochar for Environmental Management; Routledge: London, UK, 2009; pp. 303–320.

109. Turunen, M.; Hyväluoma, J.; Heikkinen, J.; Keskinen, R.; Kaseva, J.; Hannula, M.; Rasa, K. Quantifying the pore structure of different biochars and their impacts on the water retention properties of Sphagnum moss growing media. Biosyst. Eng. 2020, 191, 96–106.

110. Gaunt, J.; Cowie, A. Biochar, greenhouse gas accounting and emissions trading. In Biochar for Environmental Management: Science and Technology; Routledge: London, UK, 2009; pp. 317–340.

111. Smernik, R.J. Biochar and sorption of organic compounds. In Biochar for Environmental Management; Routledge: London, UK, 2009; pp. 321–332.

112. Thies, J.E.; Rillig, M.C. Characteristics of biochar: Biological properties. In Biochar for Environmental Management; Routledge: London, UK, 2012; pp. 117–138.

113. DeLuca, T.H.; Gundale, M.J.; MacKenzie, M.D.; Jones, D.L. Biochar effects on soil nutrient transformations. In Biochar for Environmental Management: Science, Technology and Implementation; Routledge: London, UK, 2015; Volume 2, pp. 421–454.

114. Rondon, M.A.; Molina, D.; Hurtado, M.; Ramirez, J.; Lehmann, J.; Major, J.; Amezquita, E. Enhancing the productivity of crops and grasses while reducing greenhouse gas emissions through bio-char amendments to unfertile tropical soils. In Proceedings of the 18th World Congress of Soil Science, Philadelphia, PA, USA, 9–15 July 2006; pp. 9–15.

115. Yanai, Y.; Toyota, K.; Okazaki, M. Effects of charcoal addition on N2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. Soil Sci. Plant Nutr. 2007, 53, 181–188.

116. Joseph, S.; Cowie, A.L.; Van Zwieten, L.; Bolan, N.; Budai, A.; Buss, W.; Cayuela, M.L.; Graber, E.R.; Ippolito, J.A.; Kuzyakov, Y.; et al. How biochar works, and when it doesn’t: A review of mechanisms controlling soil and plant responses to biochar. Gcb Bioenergy 2021, 13, 1731–1764.

117. Joseph, S.; Peacocke, C.; Lehmann, J.; Munroe, P. Developing a biochar classification and test methods. In Biochar for Environmental Management; Routledge: London, UK, 2009; Volume 1, pp. 139–158.

118. Borchard, N.; Schirrmann, M.; Cayuela, M.L.; Kammann, C.; Wrage-Mönnig, N.; Estavillo, J.M.; Fuertes-Mendizábal, T.; Sigua, G.; Spokas, K.; Ippolito, J.A.; et al. Biochar, soil and land-use interactions that reduce nitrate leaching and N2O emissions: A meta-analysis. Sci. Total Environ. 2019, 651, 2354–2364.

119. Riley, W.; Ortiz-Monasterio, I.; Matson, P.A. Nitrogen leaching and soil nitrate, nitrite, and ammonium levels under irrigated wheat in Northern Mexico. Nutr. Cycl. Agroecosystems 2001, 61, 223–236.

120. Song, X.; Pan, G.; Zhang, C.; Zhang, L.; Wang, H. Effects of biochar application on fluxes of three biogenic greenhouse gases: A meta-analysis. Ecosyst. Health Sustain. 2016, 2, e01202.

121. He, Y.; Zhou, X.; Jiang, L.; Li, M.; Du, Z.; Zhou, G.; Shao, J.; Wang, X.; Xu, Z.; Hosseini Bai, S.; et al. Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. Gcb Bioenergy 2017, 9, 743–755.

122. Kalu, S.; Kulmala, L.; Zrim, J.; Peltokangas, K.; Tammeorg, P.; Rasa, K.; Kitzler, B.; Pihlatie, M.; Karhu, K. Potential of biochar to reduce greenhouse gas emissions and increase nitrogen use efficiency in boreal arable soils in the long-term. Front. Environ. Sci. 2022, 10, 914766.

123. Sass, R.L.; Cicerone, R.J. Photosynthate allocations in rice plants: Food production or atmospheric methane? Proc. Natl. Acad. Sci. USA 2002, 99, 11993–11995.

124. van Der Gon, H.D.; Kropff, M.; Van Breemen, N.; Wassmann, R.; Lantin, R.; Aduna, E.; Corton, T.; Van Laar, H.H. Optimizing grain yields reduces CH4 emissions from rice paddy fields. Proc. Natl. Acad. Sci. USA 2002, 99, 12021–12024.

125. Su, J.; Hu, C.; Yan, X.; Jin, Y.; Chen, Z.; Guan, Q.; Wang, Y.; Zhong, D.; Jansson, C.; Wang, F.; et al. Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice. Nature

2015, 523, 602–606.

126. Stein, L.Y.; Klotz, M.G. Nitrifying and denitrifying pathways of methanotrophic bacteria. Biochem. Soc. Trans. 2011, 39, 1826–1831.
127. Canarini, A.; Kaiser, C.; Merchant, A.; Richter, A.; Wanek, W. Root exudation of primary metabolites: Mechanisms and their roles in plant responses to environmental stimuli. Front. Plant Sci. 2019, 10, 157.
128. Rougier, M. Secretory activity of the root cap. In Plant Carbohydrates II: Extracellular Carbohydrates; Springer: Berlin/Heidelberg, Germany, 1981; pp. 542–574.
129. Abbott, L.K.; Murphy, D.V. Soil Biological Fertility: A Key to Sustainable Land Use in Agriculture; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2003.
130. Walker, T.S.; Bais, H.P.; Grotewold, E.; Vivanco, J.M. Root exudation and rhizosphere biology. Plant Physiol. 2003, 132, 44–51.
131. Nardi, S.; Concheri, G.; Pizzeghello, D.; Sturaro, A.; Rella, R.; Parvoli, G. Soil organic matter mobilization by root exudates. Chemosphere 2000, 41, 653–658.
132. Vives-Peris, V.; De Ollas, C.; Gómez-Cadenas, A.; Pérez-Clemente, R.M. Root exudates: From plant to rhizosphere and beyond. Plant Cell Rep. 2020, 39, 3–17.
133. De-la-Pena, C.; Badri, D.V.; Lei, Z.; Watson, B.S.; Brandao, M.M.; Silva-Filho, M.C.; Sumner, L.W.; Vivanco, J.M. Root secretion of defense-related proteins is development-dependent and correlated with flowering time. J. Biol. Chem. 2010, 285, 30654–30665.
134. Chai, Y.N.; Schachtman, D.P. Root exudates impact plant performance under abiotic stress. Trends Plant Sci. 2022, 27, 80–91.
135. Salem, M.A.; Wang, J.Y.; Al-Babili, S. Metabolomics of plant root exudates: From sample preparation to data analysis. Front. Plant Sci. 2022, 13, 5035.
136. Narula, N.; Kothe, E.; Behl, R.K. Role of root exudates in plant-microbe interactions. J. Appl. Bot. Food Qual. 2012, 82, 122–130.
137. Kumar, R.; Bhatia, R.; Kukreja, K.; Behl, R.K.; Dudeja, S.S.; Narula, N. Establishment of Azotobacter on plant roots: Chemotactic response, development and analysis of root exudates of cotton (Gossypium hirsutum L.) and wheat (Triticum aestivum L.). J. Basic Microbiol. 2007, 47, 436–439.
138. Lu, Y.; Wassmann, R.; Neue, H.; Huang, C.; Bueno, C.S. Methanogenic responses to exogenous substrates in anaerobic rice soils. Soil Biol. Biochem. 2000, 32, 1683–1690.
139. Moscôso, J.S.C.; Silva, L.S.d.; Pujol, S.B.; Giacomini, S.J.; Severo, F.F.; Marzari, L.B.; Molin, G.D. Methane emission induced by short-chain organic acids in lowland soil. Rev. Bras. Ciência Solo

2019, 43.

140. Aulakh, M.S.; Wassmann, R.; Bueno, C.; Rennenberg, H. Impact of root exudates of different cultivars and plant development stages of rice (Oryza sativa L.) on methane production in a paddy soil. Plant Soil 2001, 230, 77–86.
141. Smith, M.R.; Rao, I.M.; Merchant, A. Source-sink relationships in crop plants and their influence on yield development and nutritional quality. Front. Plant Sci. 2018, 9, 1889.
142. Andersen, C.P. Source–sink balance and carbon allocation below ground in plants exposed to ozone. New Phytol. 2003, 157, 213–228.
143. Wingler, A.; Einig, W.; Schaeffer, C.; Wallenda, T.; Hampp, R.; Wallander, H.; Nylund, J.E. Influence of different nutrient regimes on the regulation of carbon metabolism in Norway spruce seedlings. New Phytol. 1994, 128, 323–330.
144. Koch, K.E. Carbohydrate-modulated gene expression in plants. Annu. Rev. Plant Biol. 1996, 47, 509–540.
145. Mathur, J.; Hülskamp, M. Microtubules and microfilaments in cell morphogenesis in higher plants. Curr. Biol. 2002, 12, R669–R676.
146. Yao, Z.; Zhou, Z.; Zheng, X.; Xie, B.; Mei, B.; Wang, R.; Butterbach-Bahl, K.; Zhu, J. Effects of organic matter incorporation on nitrous oxide emissions from rice-wheat rotation ecosystems in China. Plant Soil 2010, 327, 315–330.
147. Zou, J.; Huang, Y.; Jiang, J.; Zheng, X.; Sass, R.L. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. Glob. Biogeochem. Cycles 2005, 19.
148. Eagle, A.J.; Bird, J.A.; Horwath, W.R.; Linquist, B.A.; Brouder, S.M.; Hill, J.E.; van Kessel, C. Rice yield and nitrogen utilization efficiency under alternative straw management practices. Agron. J. 2000, 92, 1096–1103.
149. Li, X.; Zhang, G.; Xu, H.; Cai, Z.; Yagi, K. Effect of timing of joint application of hydroquinone and dicyandiamide on nitrous oxide emission from irrigated lowland rice paddy field. Chemosphere 2009, 75, 1417–1422.
150. Akiyama, H.; Yan, X.; Yagi, K. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N2O and NO emissions from agricultural soils: Meta-analysis. Glob. Change Biol. 2010, 16, 1837–1846.
151. Majumdar, D. Methane and nitrous oxide emission from irrigated rice fields: Proposed mitigation strategies. Curr. Sci. 2003, 84, 1317–1326.
152. Mahesh, M.; Mohini, M. Crop residues for sustainable livestock production. J. Adv. Dairy Res. 2014, 2, e108.

153. Ritchie, H.; Rosado, P.; Roser, M. Meat and Dairy Production. Our World Data 2017. Available online: https://ourworldindata.org/meat-production (accessed on 18 October 2023).

154. Williams, P. Nutritional composition of red meat. Nutr. Diet. 2007, 64, S113–S119.

155. Porter, J.W.G. Milk as a source of lactose, vitamins and minerals. Proc. Nutr. Soc. 1978, 37, 225–230.

156. Shaheen, N.; Ahmed, M.K.; Islam, M.S.; Habibullah-Al-Mamun, M.; Tukun, A.B.; Islam, S.; MA Rahim, A.T. Health risk assessment of trace elements via dietary intake of ‘non-piscine protein source’foodstuffs (meat, milk and egg) in Bangladesh. Environ. Sci. Pollut. Res. 2016, 23, 7794–7806.

157. McAfee, A.J.; McSorley, E.M.; Cuskelly, G.J.; Moss, B.W.; Wallace, J.M.; Bonham, M.P.; Fearon, A.M. Red meat consumption: An overview of the risks and benefits. Meat Sci. 2010, 84, 1–13.

158. Willett, W.C.; Ludwig, D.S. Milk and health. N. Engl. J. Med. 2020, 382, 644–654.

159. Tricarico, J.; de Haas, Y.; Hristov, A.; Kebreab, E.; Kurt, T.; Mitloehner, F.; Pitta, D. Symposium review: Development of a funding program to support research on enteric methane mitigation from ruminants. J. Dairy Sci. 2022, 105, 8535–8542.

160. United Nations Environment Programme. Emissions Gap Report 2022: The Closing Window—Climate Crisis Calls for Rapid Transformation of Societies; UN: New York, NY, USA, 2022.

161. Frank, S.; Beach, R.; Havlík, P.; Valin, H.; Herrero, M.; Mosnier, A.; Hasegawa, T.; Creason, J.; Ragnauth, S.; Obersteiner, M. Structural change as a key component for agricultural non-CO2 mitigation efforts. Nat. Commun. 2018, 9, 1060.

162. Arndt, C.; Hristov, A.N.; Price, W.J.; McClelland, S.C.; Pelaez, A.M.; Cueva, S.F.; Oh, J.; Dijkstra, J.; Bannink, A.; Bayat, A.R.; et al. Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 C target by 2030 but not 2050. Proc. Natl. Acad. Sci. USA 2022, 119, e2111294119.

163. Zhao, Y.; Zhao, G. Decreasing ruminal methane production through enhancing the sulfate reduction pathway. Anim. Nutr. 2022, 9, 320–326.

164. Haque, M.N. Dietary manipulation: A sustainable way to mitigate methane emissions from ruminants. J. Anim. Sci. Technol. 2018, 60, 15.

165. Newbold, C.; El Hassan, S.; Wang, J.; Ortega, M.; Wallace, R.J. Influence of foliage from African multipurpose trees on activity of rumen protozoa and bacteria. Br. J. Nutr. 1997, 78, 237–249.

166. Bodas, R.; Prieto, N.; García-González, R.; Andrés, S.; Giráldez, F.J.; López, S. Manipulation of rumen fermentation and methane production with plant secondary metabolites. Anim. Feed. Sci. Technol. 2012, 176, 78–93.

167. Patra, A.K.; Saxena, J. Dietary phytochemicals as rumen modifiers: A review of the effects on microbial populations. Antonie Van Leeuwenhoek 2009, 96, 363–375.
168. Patra, A.; Saxena, J. The effect and mode of action of saponins on the microbial populations and fermentation in the rumen and ruminant production. Nutr. Res. Rev. 2009, 22, 204–219.
169. Milich, L. The role of methane in global warming: Where might mitigation strategies be focused? Glob. Environ. Change 1999, 9, 179–201.
170. Benchaar, C.; Pomar, C.; Chiquette, J. Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. Can. J. Anim. Sci. 2001, 81, 563–574.
171. Boadi, D.; Wittenberg, K.M. Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF6) tracer gas technique. Can. J. Anim. Sci. 2002, 82, 201–206.
172. Beauchemin, K.; Kreuzer, M.; O'mara, F.; McAllister, T.A. Nutritional management for enteric methane abatement: A review. Aust. J. Exp. Agric. 2008, 48, 21–27.
173. Tamminga, S.; Bannink, A.; Dijkstra, J.; Zom, R. Feeding Strategies to Reduce Methane Loss in Cattle; Animal Sciences Group: Wageningen, The Netherlands, 2007; pp. 1570–8616.
174. O'mara, F.; Fitzgerald, J.; Murphy, J.; Rath, M. The effect on milk production of replacing grass silage with maize silage in the diet of dairy cows. Livest. Prod. Sci. 1998, 55, 79–87.
175. Hassanat, F.; Gervais, R.; Julien, C.; Massé, D.; Lettat, A.; Chouinard, P.; Petit, H.; Benchaar, C. Replacing alfalfa silage with corn silage in dairy cow diets: Effects on enteric methane production, ruminal fermentation, digestion, N balance, and milk production. J. Dairy Sci. 2013, 96, 4553–4567.
176. Martin, C.; Morgavi, D.P.; Doreau, M. Methane mitigation in ruminants: From microbe to the farm scale. Animal 2010, 4, 351–365.
177. Ferris, C.; Gordon, F.; Patterson, D.; Porter, M.; Yan, T. The effect of genetic merit and concentrate proportion in the diet on nutrient utilization by lactating dairy cows. J. Agric. Sci. 1999, 132, 483–490.
178. Lovett, D.; Lovell, S.; Stack, L.; Callan, J.; Finlay, M.; Conolly, J.; O'Mara, F.P. Effect of forage/concentrate ratio and dietary coconut oil level on methane output and performance of finishing beef heifers. Livest. Prod. Sci. 2003, 84, 135–146.
179. Johnson, K.A.; Johnson, D.E. Methane emissions from cattle. J. Anim. Sci. 1995, 73, 2483–2492.
180. Murphy, M.; Baldwin, R.; Koong, L.J. Estimation of stoichiometric parameters for rumen fermentation of roughage and concentrate diets. J. Anim. Sci. 1982, 55, 411–421.

181. Hindrichsen, I.; Wettstein, H.; Machmüller, A.; Jörg, B.; Kreuzer, M. Effect of the carbohydrate composition of feed concentratates on methane emission from dairy cows and their slurry. Environ. Monit. Assess. 2005, 107, 329–350.

182. Hindrichsen, I.; Kreuzer, M. High methanogenic potential of sucrose compared with starch at high ruminal pH. J. Anim. Physiol. Anim. Nutr. 2009, 93, 61–65.

183. Castillo, C.; Benedito, J.; Méndez, J.; Pereira, V.; Lopez-Alonso, M.; Miranda, M.; Hernández, J. Organic acids as a substitute for monensin in diets for beef cattle. Anim. Feed. Sci. Technol. 2004, 115, 101–116.

184. McAllister, T.; Newbold, C.J. Redirecting rumen fermentation to reduce methanogenesis. Aust. J. Exp. Agric. 2008, 48, 7–13.

185. Beauchemin, K.; McGinn, S.M. Methane emissions from beef cattle: Effects of fumaric acid, essential oil, and canola oil. J. Anim. Sci. 2006, 84, 1489–1496.

186. Burt, S. Essential oils: Their antibacterial properties and potential applications in foods—A review. Int. J. Food Microbiol. 2004, 94, 223–253.

187. Benchaar, C.; Calsamiglia, S.; Chaves, A.V.; Fraser, G.; Colombatto, D.; McAllister, T.A.; Beauchemin, K.A. A review of plant-derived essential oils in ruminant nutrition and production. Anim. Feed. Sci. Technol. 2008, 145, 209–228.

188. Benchaar, C.; Greathead, H. Essential oils and opportunities to mitigate enteric methane emissions from ruminants. Anim. Feed. Sci. Technol. 2011, 166, 338–355.

189. Moss, A.R.; Jouany, J.-P.; Newbold, J. Methane production by ruminants: Its contribution to global warming. In Annales de Zootechnie; EDP Sciences: Les Ulis, France, 2000; pp. 231–253.

190. Lopez, S.; McIntosh, F.; Wallace, R.; Newbold, C.J. Effect of adding acetogenic bacteria on methane production by mixed rumen microorganisms. Anim. Feed. Sci. Technol. 1999, 78, 1–9.

191. McAllister, T.; Beauchemin, K.; Alazzeh, A.; Baah, J.; Teather, R.; Stanford, K. The use of direct fed microbials to mitigate pathogens and enhance production in cattle. Can. J. Anim. Sci. 2011, 91, 193–211.

192. Newbold, C.J.; Rode, L. Dietary additives to control methanogenesis in the rumen. In International Congress Series; Elsevier: Amsterdam, The Netherlands, 2006; pp. 138–147.

193. Beauchemin, K.; Colombatto, D.; Morgavi, D.; Yang, W.Z. Use of exogenous fibrolytic enzymes to improve feed utilization by ruminants. J. Anim. Sci. 2003, 81, E37–E47.

194. Eun, J.-S.; Beauchemin, K.A. Assessment of the efficacy of varying experimental exogenous fibrolytic enzymes using in vitro fermentation characteristics. Anim. Feed. Sci. Technol. 2007, 132, 298–315.

195. Hook, S.E.; Northwood, K.S.; Wright, A.D.; McBride, B.W. Long-term monensin supplementation does not significantly affect the quantity or diversity of methanogens in the rumen of the lactating dairy cow. Appl. Environ. Microbiol. 2009, 75, 374–380.

196. Patra, A.K. Enteric methane mitigation technologies for ruminant livestock: A synthesis of current research and future directions. Environ. Monit. Assess. 2012, 184, 1929–1952.

197. McGinn, S.; Beauchemin, K.; Coates, T.; Colombatto, D. Methane emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. J. Anim. Sci. 2004, 82, 3346–3356.

198. Guan, H.; Wittenberg, K.; Ominski, K.; Krause, D.O. Efficacy of ionophores in cattle diets for mitigation of enteric methane. J. Anim. Sci. 2006, 84, 1896–1906.

199. Clark, H.; Pinares-Patiño, C.; De Klein, C. Methane and nitrous oxide emissions from grazed grasslands. Grassland. A Glob. Resour. 2005, 279, 293.

200. Madsen, J.; Lassen, J.; Hvelplund, T.; Weisbjerg, M.R. A fast, easy, reliable and cheap method to measure the methane production from ruminants. Eaap Publ. 2010, 127, 121–122.

201. Eckard, R.; Grainger, C.; De Klein, C.A.M. Options for the abatement of methane and nitrous oxide from ruminant production: A review. Livest. Sci. 2010, 130, 47–56.

202. Sherman, R. Large-Scale Organic Materials Composting. North Carolina Cooperative Extension Service. 2005; North Carolina State Extension Publications: Raleigh, NC, USA, 2011.

203. Kelly, F.; Michael, L. Storing Manure on Small Horse and Livestock Farms; The State University of New Jersey: Rutgers, NJ, USA, 2014.

204. Ghaly, A.; MacDonald, K.N. An effective passive solar dryer for thin layer drying of poultry manure. Am. J. Eng. Appl. Sci. 2012, 5, 136–150.

205. Endres, M.I.; Janni, K.A. Compost bedded pack barns for dairy cows. Univ. Neb.-Linc. 2008, 1, 1–9.

206. Bewley, J.; Taraba, J.; Day, G.; Black, R.; Damasceno, F.A. Compost Bedded Pack Barn Design Features and Management Considerations; Cooperative Extension Publ. ID-206, Cooperative Extension Service; University of Kentucky College of Agriculture: Lexington, KY, USA, 2012.

207. Aguirre-Villegas, H.; Larson, R.A.; Ruark, M.D. Solid-Liquid Separation of Manure and Effects on Greenhouse Gas and Ammonia Emissions; University of Wisconsin-Extension, Cooperative Extension: Madison, WI, USA, 2017; Available online: https://learningstore.extension.wisc.edu/products/solid-liquid-separation-of-manure-and-effects-on-greenhouse-gas-and-ammonia-emissions-p1844 (accessed on 23 October 2023).