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Revitalizing maize production through managing biological N fixation, soil acidification and nitrous oxide emission from legumes in tropics

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Legume associations address challenges related to soil fertility and land degradation commonly encountered in maize monocultures. However, it's important to note that legumes contribute to the production of both nitrous oxide (N₂O) and hydrogen ions (H⁺). In our examination of 693 manuscripts published between 1941 and 2023 to document the benefits of legumes in maize-based cropping systems, we identified and included 195 credible journal publications in our analysis. The findings revealed that, apart from fixing 50 to 320 kg nitrogen (N) ha⁻¹, legumes offer various non-N advantages. When compared to maize grown after maize, a 2.4 to 173% greater yield of maize was recorded, corresponding to a 9 to 96.7% increase in biomass when maize is grown after legumes. The most substantial increases were observed in farms employing reduced tillage, residue retention, and suitable legumes. Intercropping maize with legumes, as opposed to solitary maize production, resulted in 4.3 to 80% higher biomass, 5 to 14.8% higher grain yield, and 5 to 29.5% higher profit. However, it's important to acknowledge that acid and N₂O production ranged from 0.2 to 2.7 mol H⁺kg⁻¹ biomass produced and 5.6 kg N₂O ha⁻¹, respectively. Implementing compatible cropping systems, increasing soil N mineralization, and recycling crop residues can enhance biological N₂ fixation, reduce acid buildup in soils, mitigate N₂O emissions, and simultaneously improve maize yield. In conclusion, the review underscores the necessity for location-specific cropping system standards and regulations to ensure the sustainability of maize-legume cropping systems.

Key words: Cropping system, legumes, nitrous oxide, residue management, soil acidification.

INTRODUCTION

According to van Dijk et al. (2021), there is projected to be a 35 to 56% increase in global food demand from the agricultural sector between 2010 and 2050 to

accommodate an additional 3.5 billion people (Borlaug, 2007). Muhie (2022) suggests that by 2050, the production of maize, wheat, and rice alone should rise by 70% to meet

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the demands of the world's rapidly expanding population. This necessitates an increase in maize yields while simultaneously reducing greenhouse gas emissions globally. Low soil fertility has consistently posed a significant challenge to maize production, historically limited by the lack of varieties adaptable to environmental shocks such as heat, drought, salinity, and acidity.

Additionally, nutrient exhaustion and declining soil fertility have been linked to the practice of growing maize after maize (Thierfelder et al., 2013). Therefore, improving soil fertility and establishing sustainable cropping systems are crucial for increasing maize yields for smallholder farmers in the tropics (Stoorvogel et al., 1993).

In such circumstances, increasing the adoption of legume technology is a well-considered initial step toward addressing unsustainable cropping systems. Intensifying cropping systems in developing nations could yield significant increases in productivity. Nitrogen, a vital element for soil and plant systems, is cycled from the environment. Approximately 78% of the nitrogen available for cycling is present in the atmosphere in a form that most organisms cannot utilize. In terrestrial and aquatic ecosystems, nitrogen continues to be the limiting factor for growth (Dalton and Krammer, 2006). This limitation is primarily due to the fact that, aside from N-fixing bacteria, most living organisms find the gaseous form of N_2 unavailable for use. The atmospheric nitrogen must be converted from its N_2 form to ammonia (NH_3) and nitrate by energy-releasing biotic processes, such as the Nitrogenase enzyme complex, which has iron or nickel catalysts, to become biologically accessible (Unkovich et al., 2008; Lasaletta, 2014).

It is worth noting that the addition of N_2 -fixation from non-biological sources, such as meteor streaks, cosmic radiations, forest fires, volcanic eruptions, and thunderstorms, contributes as much as 10 to 20 million metric tons of nitrogen. However, this nitrogen is not directly available to plants (Bezdicsek and Kennedy, 1998; Table 1).

Terrestrial plants require between 150 and 200 million tons of mineral nitrogen (N) annually (Unkovich et al., 2008). To meet this demand, the industrial Haber-Bosch process produces over 100 million tons of fertilizer nitrogen, constituting only 20% of the world's total nitrogen requirement (Table 1). An example is the necessity for nitrogen (N) in cereal cropping systems, which is addressed by applying N fertilizers produced through industrial processes involving high temperatures (400 to 450°C) and high pressures (200 atm) in the presence of iron or nickel catalysts. These processes also annually consume 3 to 5% of the world's natural gas (Bezdicsek and Kennedy, 1998; Myrold and Bottomley, 2007). However, the industrial production of inorganic nitrogen releases 2.25 to 10 kg of CO_2 for every kilogram produced (Ecoinvent). Despite the energy costs, rising manufacturing expenses, and environmental concerns associated with

industrial nitrogen production, biological N_2 -fixation has been advocated as a solution since the 1970s (Phillips, 1980).

Further research has shown that symbiotic and non-symbiotic relationships mediated by Rhizobium, BradyRhizobium, and free-living bacteria in soils produce between 100 and 175 million metric tons of nitrogen annually, saving approximately US\$10 billion on fertilizer nitrogen annually (Freiberg et al., 1997; Chafi and Bensoltane, 2003). The effects of legumes for nitrogen fixation go beyond improving soil fertility. Legumes reduce reliance on nitrogen derived from industrial methods that use significant amounts of fossil fuels by fixing nitrogen from N_2 (Herridge and Rose, 2000). Thus far, biofertilizers have improved the yield of legumes and reduced the need for synthetic nitrogen fertilizer required in most parts of the world, benefiting many cropping systems through this biological process.

Legumes directly contribute to daily nutritional uses, providing food or feed values, health benefits, or protein supplements. They serve as sources of proteins, amino acids, chlorophyll, or urea, all essential for life on earth (Buren and Rubio, 2017). Additionally, most legumes offer several non-nitrogen benefits, such as being sources of carbon, phosphorus, and other nutrients.

In the simplest terms, biological nitrogen fixation (BNF) by legumes has been described as the second most important biological process on Earth, following photosynthesis (Cheng, 2008). However, it's important to note that energy is required for both photosynthesis and the nitrogen fixation process. The triple-bonded nitrogen atoms constituting gaseous N_2 must be separated to reduce 1 mole of N_2 to ammonia, a process requiring 147 kCal, 16 moles of ATP, or 20 kg CO_2 kg⁻¹ N fixed (Herridge and Brock, 2016). The symbiotic nitrogen fixation process in legumes is considered "greenhouse-gas neutral" since they acquire all the required carbon directly from the atmosphere through photosynthesis (Ecoinvent Centre, 2010). Therefore, developing optimal legume management scenarios under various genetic and environmental conditions is essential to minimize N_2O emissions and soil acidification.

While fixation by legume-cereal cropping systems may reduce nitrogen (N) and carbon (C) losses, effective management practices play a crucial role in achieving this outcome (Gregorich et al., 2005; Li et al., 2015). Several scientists (Starling et al., 1998; Ohyama et al., 2009) have observed inconclusive or negative BNF results in various field investigations when starter-N applications were applied for legumes. Consequently, the use of biofertilizers is becoming increasingly necessary for legumes or their symbiotic relationships with cereals.

The adoption of the sustainable crop production technique involving biological nitrogen fixation by legumes within well-designed cropping systems should be standardized across various agro-ecologies (Lasaletta,

Table 1. Estimated proportion of industrial, biological and non-biological N fixation (Bezdicsek and Kennedy, 1998; Lasaletta, 2014).

Type of fixation	N ₂ fixed (10 ¹² g per year, or 10 ⁶ metric tons per year)
Industrial N fixation	About 50 to 100
Non-biological N fixation	
Combustion	About 20
Lightning	About 10 to 12
Sub-total	- 30-32
Biological N fixation	
Agricultural land	About 90
Forest and non-agricultural land	About 50
Sea	About 35
Sub-total	About 175

2014). This is because the cultivation of legumes stores nitrogen, enhances biodiversity, and sequesters carbon, all of which can benefit partner crops planted alongside legumes in intercropping or rotation systems (Ecoinvent Centre, 2010). The inclusion of legumes in cropping systems contributes to a reduction in the carbon footprints of agricultural products, promoting sustainability (Peoples et al., 2009a; Gan et al., 2011). Historical data from the 1950s indicated that leguminous foods, fodder, and green manures provided approximately half of the necessary nitrogen in several European nations (Gan et al., 2011). Therefore, leveraging leguminous biological nitrogen fixation presents both an opportunity and a necessity to reduce reliance on synthetic nitrogen fertilizer, mitigate environmental impact, and address the negative consequences of climate change on agricultural productivity.

However, there has been a lack of examination and documentation for grassroots utilization in tropical regions regarding how much nitrogen can be fixed by specific legumes in cropping systems under different conditions and how much of this fixed nitrogen can be utilized by subsequent or companion maize crops. In order to establish productive maize-based legume cropping systems, the purpose of this paper is to evaluate and explore quantifications in nitrogen fixation, acidification, and nitrous oxide (N₂O) production resulting from diverse legume species. The aim is also to identify key characteristics for further investigation.

MATERIALS AND METHODS

The selection of documents for review was conducted through a literature search using keywords such as "legumes," "N fixation," "soil acidification," "formation of nitrous oxide," and "cropping systems," with a specific focus on quantifying the benefits. Additionally, references from papers published in internationally renowned journals, the international legume database, progress reports,

journals, and websites spanning the period from 1941 to 2023 were consulted. Following the removal of articles of a more general nature and eliminating obvious duplicates that were less relevant to tropical agriculture, the number of remaining publications (693) was reduced (Figure 1). The identified papers, such as those by Ellert and Janzen (2008), Peoples et al. (2009b), Njira (2016), Kermaha et al. (2018), were prioritized, and approximately 86 special journal issues addressing the topic were considered. The review revealed complexities in nitrogen fixation and its quantification, soil acidification, and the formation of nitrous oxide from legumes. It also brought to light some emerging realities and trends in the field.

FINDINGS AND DISCUSSION

Production of nitrogen by legumes

There is intense competition among crops growing in the same environment for limited nutrients, moisture, sunlight, and space. This competition highlights the effects of cropping systems on related legume crops and their biological nitrogen fixation (BNF) production. While legumes are capable of fixing atmospheric nitrogen for their own benefit, they can also transfer nitrogen to companion crops in the same growing season or to subsequent crops in the following season. This capability allows for planning and utilizing legume-derived nitrogen for non-legume crops, presenting a sustainable agricultural production method with significant potential for reducing the use of chemical pesticides and fertilizers. Incorporating legumes into cropping systems focused on maize, whether as fallows, green manures, rotations, intercrops, or alley crops, has been demonstrated as a viable approach (Peterson and Russelle, 1991; Smil, 1999; Giller, 2001).

Legume sole crops

The atmosphere contains between 79 to 80% nitrogen,

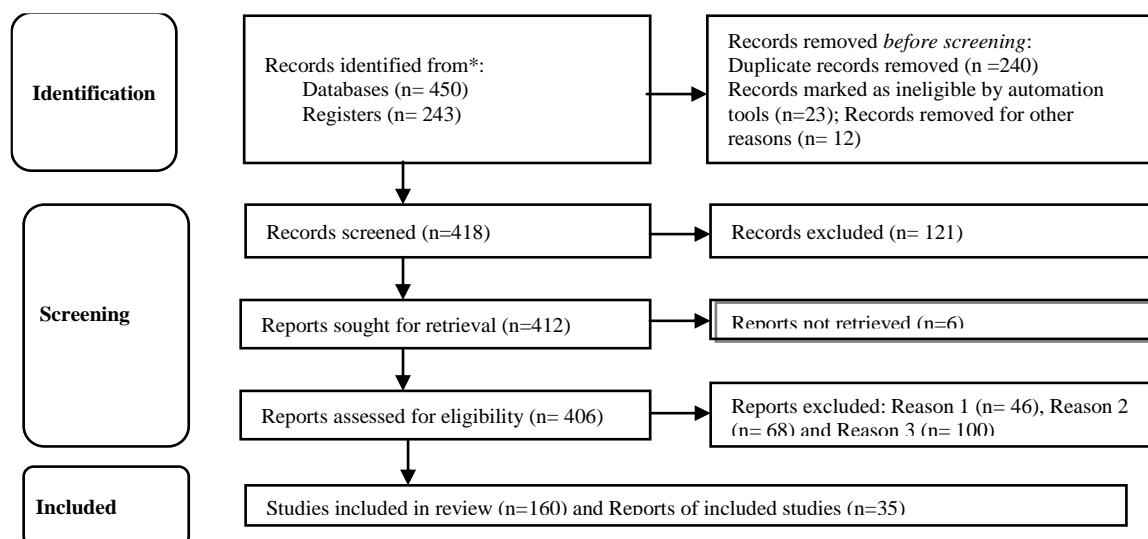


Figure 1. Screening of studies via databases and registers between 1941 to 2023.

meaning that most legumes obtain more than 70% of their nitrogen needs from the atmosphere (Ahmed et al., 2005). After seed harvests, legumes such as cowpea, pigeon pea, green gram, and groundnuts generated positive net nitrogen balances of up to 136 kg N ha⁻¹ (Peoples and Craswell, 1992). Recently, it was discovered that biological nitrogen fixation (BNF) accounted for between 50 and 60% of the nitrogen requirement in legumes (Salvagiotti et al., 2008). The amount of nitrogen fixed varied widely depending on crop management conditions, with the percentage of transfer to related crops ranging from 0 to 70%, as noted by several writers (Anglade et al., 2015). The net nitrogen balance would decrease even more from 28 to 104 kg N ha⁻¹ if residues were removed from the field (People and Craswell, 1992). These differences are explained by the legume's variety, maturity period, and biomass production (Rao and Dart, 1987; Seymour et al., 2015; Table 2). Rhizobium inoculation could enhance this process by increasing N₂ fixation, plant yield, and seed quality (Bambara and Ndakidemi, 2010).

Productivity and quality benefits following Rhizobium inoculation were attributed to increased soil pH, nitrogen, calcium, and salt levels (Bambara and Ndakidemi, 2010). For staple cereal crops, BNF serves as a necessary and affordable substitute for industrially produced nitrogen fertilizers (Brockwell and Bottomley, 1995; Bezdicek and Kennedy, 1998; Carlsson and Huss-Danell, 2003; Galloway et al., 2008; IAASTD, 2008; Weil and Brady, 2017). According to Buchi and his associates, biological fixation allowed *Lathyrus sativus*, *Pisum sativum*, *Vicia sativa*, *Vicia villosa*, or *Vicia faba* to fix more than 100 kg ha⁻¹ of nitrogen (Buchi et al., 2015). They found that the percentage of nitrogen obtained from atmospheric N₂ varied from 0 to 100% both between and among species

in a brief growing season, providing valuable data for application in later cropping systems. The amount of nitrogen fixed in single crops was also higher than in legume-cereal combinations, according to the results, due to higher biomass accumulation in sole crops compared to mixed cropping systems (Anglade et al., 2015). *Trifolium pratense* L., white clover (*Trifolium repens* L.), and alfalfa (*Medicago sativa* L.) produced total BNF values of 465, 252, and 102 kg N ha⁻¹, respectively. Faba bean (*Vicia faba* L.), field pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medik.) produced total BNF values of 165, 111, and 52 kg N ha⁻¹ year⁻¹, respectively (Table 2).

Due to their limited access to land, manpower, and capital, small-holder farmers are attracted to dual-purpose legumes that can be utilized for both food and feed (Giller, 2001). Forage legumes, mucuna, and long-duration pigeon pea are a few examples of dual-purpose legumes with low harvest indices (Giller, 2001). Therefore, to increase the biomass available for fodder, weed suppression, and soil fertility enrichment, it would be preferable to cultivate dual-purpose genotypes with early maturity duration rather than developing new varieties of cowpea and pigeon pea with a high harvest index trait or with extra-early or extra-short maturity duration (Giller, 2001).

Crop rotation

Many nations have standardized the rotation of grains with legumes through rules and regulations, such as the states (PCO, 2021), Uzbekistan (InforMEA, 2007), and Brazil (Sparovek et al., 2012). This is likely due to the fact that, as highlighted by Zablotowicz et al. (2011), legumes

Table 2. Biological nitrogen fixation (kg N ha⁻¹) by legume species grown as sole crops.

Crop	N fixed	Reference
Alfalfa	90 - 220	Bell and Nutman (1971)
Beans	20 - 80	Havlin et al. (2014)
Lupins	60 - 100	-----do-----
Black gram	100	Mugwe et al. (2011)
Cowpea	90	----- do-----
Fenugreek	45	----- do-----
Lentil	40 – 68	----- do-----
Chickpea	40 – 50	Seymour et al. (2015)
Faba bean	130	----- do -----
Mung bean	112	----- do -----
Groundnut	150	----- do -----
Clover	100 -150	Aranjuelo et al. (2009)
Cluster bean	60 – 150	Meena et al. (2017)
Soybean	100–150	----- do-----
Cowpea	47 – 105	Giller (2001)
Pigeon pea	13 – 167	----- do-----
Cowpea	90	Wetselaar et al. (1973)
Field pea	65 -100	Peoples et al. (2009)
Groundnuts	33 – 124	Nyemba and Dakora (2010)
Mung bean	60	Shaha et al. (2003)
Field pea	30 – 140	Nutman (1965)
Pigeon pea	20 – 124	Njira et al. (2012)
Pigeon pea-groundnuts	42 - 82.8	Mhango (2011)
Pigeon peas	133	Sen (1958)

constitute a significant source of protein for both human and animal nutrition. In addition to providing plants with nitrogen from the atmosphere, rotating cereals with legumes helps prevent the accumulation of weeds, pests, and crop diseases. Legumes contribute to improved soil structure and are therefore preferred for rotational cropping due to their large tap roots, which can extend deep into the soil profile (Ofori and Stern, 1987). The benefit of grain legumes to the yield of the companion crop is greater than the benefit brought through the carryover of nitrogen in the soil (Zablotowicz et al., 2011). Grain legumes can boost yields in subsequent cereal crops by up to 1.6 t ha⁻¹ (Ofori and Stern, 1987; Preissel et al., 2015).

According to writers such as Berg (1997), wheat (*Triticum aestivum*) yielded 3,070 kg ha⁻¹ year⁻¹ after five years of alfalfa, 2,580 kg ha⁻¹ year⁻¹ after milk vetch, and 950 kg ha⁻¹ year⁻¹ after grass. Reports from other authors indicate that the productivity of maize increased by 46% when soybeans were grown following maize (Yusuf et al., 2009). Another study found that the production of maize increased by 28 and 21%, respectively, in the year

following the planting of soybean and cowpea compared to growing maize again (Kureh et al., 2006). Following two rotational years after soybean and cowpea, maize yield increased by 85 and 62%, respectively, compared to sole maize cropping (Kureh et al., 2006). Conversely, in another maize-soybean rotation experiment, maize crops adversely affected soybean nodulation in the subsequent seasons (Charles, 1990).

In plots treated with uniform residue, rotating maize with velvet bean, cowpea, and soybean produced advantages in biomass production of 41, 18 and 9%, respectively, in sandy soils of Moniya area at Oyo state in Nigeria (Uzoh et al., 2019). Even in plots untreated with residue mulch in the same area, rotating maize with velvet bean, cowpea, and soybean resulted in biomass production advantages of 96.7, 55.5 and 23.9%, respectively. These authors attributed the advantages to significantly increased total soil nitrogen, exchangeable potassium, magnesium, and cation exchange capacity arising from legume-cereal rotations. In plots treated with residue, a yield advantage of 122.4, 3.7 and 2.4% was measured due to rotating maize with velvet bean, cowpea, and soybean; in plots

untreated with residue, there was a yield advantage of 173, 61.8 and 71% in respective order in sandy soils of Moniya area at Oyo state in Nigeria (Uzoh et al., 2019).

The study by Lengwati et al. (2020) showed that the symbiotic nitrogen contribution from groundnut, black gram, cowpea, mung bean, or bambara groundnut was about 20 kg N ha⁻¹ for the succeeding maize crop. Eaglesham et al. (1981) reported that 24.9% of nitrogen fixed by cowpea was transferred to the succeeding maize crop. Up to 35% of nitrogen in maize grown after pigeon pea was obtained from nitrogen fixation, and part of the fixed nitrogen was due to root excretion, nitrogen leached from leaves, and leaf fall (Eaglesham et al., 1981). In some environments, faba bean has shown a greater effect than other legumes on the yield of subsequent cereal grain crops (Hauggaard-Nielsen et al., 2012). In another maize-soybean rotation experiment, Gomez (1968) observed maize yields similar to those of sequential maize fertilized with nitrogen. Caldwell (1982) also obtained a 14% yield increase over nitrogen treatments for maize following soybean. These differences in nitrogen transferred to the succeeding maize crop could be attributed to inherent differences in the potential of legume species and varieties to fix atmospheric nitrogen.

One of the essential prerequisites for biological nitrogen fixation is the prevalence of Rhizobia in great numbers in the surrounding area of legume roots. In this regard, Brockwell et al. (1988) showed that the actual densities of nodule bacteria are in the order of 10⁶ to 10⁹ organisms per milliliter of soil solution in the rhizosphere. Such large amounts are because Rhizobia originating from nodule disintegration of the previous legume crop are likely to form an important component of the Rhizobial populations and act as a source of molybdenum, phosphorus, cobalt, iron, zinc, sulfur, and nitrogen for subsequent legume crops (Brockwell et al., 1988).

An intercrop of maize and soybean rotated after wheat resulted in nitrogen uptake of 100 kg N ha⁻¹, which is twice that following maize alone (Searle et al., 1981). Such high nitrogen uptake was due to the suppression of Rhizobial multiplication during the non-legume cropping season, resulting in poor survival of introduced Rhizobia. This manifested that residual nitrogen input and the nitrogen fixation capacity of the preceding legume crops have a direct effect on the total nitrogen uptake of the following maize crop. Other authors also showed that nitrogen recovery by the succeeding crops may reach as high as 12% of the residual nitrogen at the maturity of the cropping season (Mayer et al., 2003). Soils may be devoid of Rhizobium to form an effective symbiosis with a legume when the legume succeeds a non-leguminous crop like maize, which requires planning inoculations for subsequent legume crops. Hence, supporting high yields of the succeeding legume becomes impracticable without re-inoculation, largely because the Rhizobia have to live saprophytically.

Relay cropping

Relay cropping is a common practice in industrial agriculture where intercropping falls short due to difficulties associated with machinery use for weeding, fertilizer application, and harvesting of intercrops (Peoples et al., 2009b). The advantages from legumes relay cropping are due to the addition of organic carbon and mineralization of nitrogen from residual legume biomass that could, in turn, support the growth of subsequent non-legume crops (Zablotowicz et al., 2011).

In Australia, non-legume crops required nearly 60% less nitrogen (N) fertilizer when planted with relay-cropped legumes, which yielded an average of 225 kg N ha⁻¹ (Zablotowicz et al., 2011). Legume crops frequently contribute to yields of cereal crops that are comparable to those obtained from applying 30 to 80 kg of N fertilizer ha⁻¹ (Peoples et al., 2009a).

Additionally, the authors estimated that root biomass contains 16 to 77% of total plant N, a percentage that is not typically included in calculations of N fixation (Peoples et al., 2009a). Grain legumes could provide a minor positive N balance even with significant grain N exports if estimates of root biomass are included in the N estimation process (Figure 2). Nevertheless, the majority of this nitrogen is exported from the farm as protein-rich seeds, which causes poor or negative net nitrogen balances in the soil (Peoples et al., 2009b). Due to their greater root: shoot ratios than annual species, perennial legumes typically have higher below-ground nitrogen (N) as a percentage of total plant N (average of 43%) than do annual grain legumes (average of 32%) (Antos and Halpern, 1997). But as plant allocation to roots rises during drought, environmental factors may also have an impact on root biomass and root architecture (Zablotowicz et al., 2011).

Intercropping systems

Smallholder farmers in the tropics intercrop leguminous and non-leguminous crops to mitigate the risks of crop failures associated with monocultures and ensure stable income and nutrition (Francis, 1986). Examples of intercropping systems include maize-pigeon pea, maize-common beans, maize-cowpea, sorghum-cowpea, maize-groundnuts, maize-lablab, millet-groundnuts, and rice-pulses (Matusso et al., 2012). Researchers in the tropics have reported yield advantages of 7.5 and 5% from intercropping maize with common beans and cowpea, respectively, compared to sole maize cropping, corresponding to 29.5 and 5.9% profit in that order (Hidoto and Markos, 2019). In other studies, maize production improved by 25 and 88% after intercropping mucuna-maize and cowpea-maize, respectively (Whitbread and Pengelly, 2004). Franzluebbers et al. (2016) also observed 30% more efficient productivity of millet due to millet-

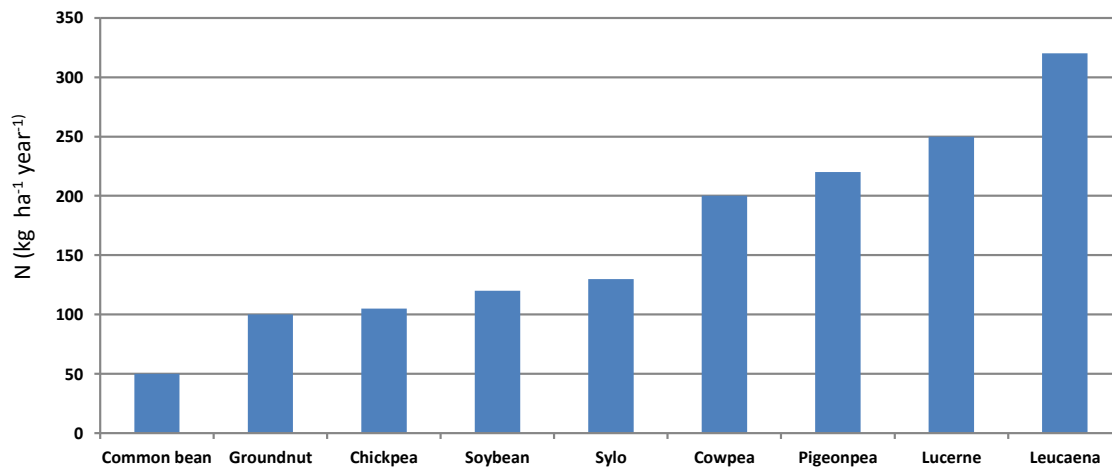


Figure 2. Average amount of N fixed by legumes under relay cropping (Zablotowicz *et al.*, 2011).

Table 3. Leaf litter and nutrient released from selected legumes (Addo-Quaye *et al.*, 2011).

Crop	Leaf litter (t ha ⁻¹)	Nitrogen (kg ha ⁻¹)	Phosphorus (kg ha ⁻¹)	Potassium (kg ha ⁻¹)
Chickpea	1.1 - 1.7	7 - 14	3 - 5.5	8 - 20.0
Lentil	1.2 - 1.6	8 - 10	3.5 - 4.5	12.5 - 19
Pigeon pea	1.3 - 2.8	8 - 16	2.5 - 5	13.5 - 24

cowpea intercropping compared to sole millet planting. Thus, the nitrogen (N) nutrition of cereals is improved due to the transfer of biologically fixed N from associated legumes when cereals and legumes are grown in an intercropping system (Willey *et al.*, 1983; Meena *et al.*, 2015). This brings the possibility of minimizing the present-year N demand by about 25 to 50%, possibly due to the transfer of N from legumes to non-legumes through excretion by plant roots, release from decaying roots and falling leaves, and leaching of N from leaves of component legumes, which is a better way to reduce environmental damage from nitrate (NO₃) leaching and nitrous oxide (N₂O) emission (Table 3). The process involves rhizodeposition of low and high molecular weight N and C compounds, which are later used by non-legume crops like maize (Wichern *et al.*, 2007). Indeed, intercropping contributes fresh organic matter to the rhizospheres, enhancing nutrient mineralization due to changes in organic matter decomposition rates (Mobasser *et al.*, 2014). However, limited information is available on the effect of Rhizobia inoculation on the chemical composition of the rhizosphere of intercropped plants (Mobasser *et al.*, 2014). The yield advantage of intercropping maize and common beans under conservation agriculture was 14.8% higher compared to intercropping under conventional agriculture, corresponding to a 39.4% profit (Hidoto and Markos, 2019). Intercropping maize with pigeon pea

resulted in 52.6, 4.3 and 80% higher biomass, grain yield, and land equivalent ratio, respectively, in the southern central rift valley of Ethiopia (Hidoto and Daniel, 2019). This could be attributed to the moisture-conserving and microclimate-modifying attributes of conservation agriculture, along with the biological nitrogen fixed and transferred from pigeon peas. The quantity of nitrogen fixed by legumes in cereal-legume intercrops depends on plant species, plant morphology, density, and growth habit of the component crops (Stern and Ofori, 1987). Intercropping sorghum with groundnut, green gram, and cowpea reduced the mineral nitrogen requirement by 61, 83, and 38 kg ha⁻¹, respectively, for the subsequent crop (Nair *et al.*, 1979).

The partial soil nitrogen balance study conducted by Kermaha and his colleagues indicated that intercrops produced 14 to 21 kg N ha⁻¹, and sole legumes yielded 8 to 23 kg N ha⁻¹, but these values were smaller than those of sole maize receiving nitrogen fertilizer, which ranged from +7 to +34 kg N ha⁻¹ (Kermaha *et al.*, 2018). Another study by Li and his colleagues reported a production contribution of 15% nitrogen for the intercropped cereal (Li *et al.*, 2009). Cowpea, mung bean, or groundnuts were reported to accumulate nitrogen in the range of 80 to 350 kg N ha⁻¹ year⁻¹ (Table 3).

Some authors suggested that 40% of nitrogen could be fixed by legumes biologically without nitrogen fertilizer in

Table 4. N₂ fixation by grain legumes grown in monoculture or intercropped with non-legumes (van Kessel and Hartley, 2000).

Crop	N ₂ fixed (%)		N ₂ fixed (kg/ha)	
	Mono crop	Intercrop	Mono crop	Intercrop
Soybean/non-nodulating	42	23	71	17
Pea/barley	62	84	115	81
Cowpea/maize	28	34	22	10
Pea/mustard	48	50	71	62
Pigeon pea/sorghum	74	55	169	124
Pea/oat	27	52	22	30
Lentil/flax	77	85	14	8
Pea/rape	38	33	41	27
Pea/mustard	28	34	20	18
Pea/oat	80	86	50	16
Pea/rape	78	88	20	27
Rice/bean/maize	32	75	30	39
Cowpea/rice	32	30	35	32
Faba bean/barley	74	92	79	71
Pea/barley	68	84	213	74

intercropping systems of soybean with cereals and 30% in monocrops (Osunde et al., 2004). Mucuna harvested in 12 weeks supplied about 160 kg N ha⁻¹ when intercropped with maize (Sanginga et al., 1996). Eaglesham et al. (1981) recorded that cowpea fixed about 41 kg N ha⁻¹ when intercropped with maize, and approximately 24.9% of the nitrogen fixed by cowpea was transferred to intercropped maize (Eaglesham et al., 1981).

The contribution of nitrogen from groundnut to the growth of maize in intercropping systems is equivalent to the application of 96 kg N ha⁻¹ at a ratio of plant population densities of one maize plant to four groundnut plants (Mandimba, 1995). Osunde et al. (2004) found that without the addition of fertilizer, the proportion of nitrogen derived from N₂-fixation was about 40% in the intercropped soybean and 30% in the sole crop. These contributions result from root excretion, nitrogen leached from leaves, and leaf fall. In another study, the nitrogen input from groundnut to the growth and yield of maize in an intercropping system was equivalent to the fertilization of 96 kg of nitrogen/ha at a proportion of plant population densities of individual maize plants to four groundnuts plants (Mandimba, 1995). However, there is an opportunity cost of space or time when legumes are integrated with other crops in the cropping system, which has been considered a major constraint to the adoption of legumes in cropping systems. Successful adoptions are more likely when legumes serve multiple purposes of producing a net positive nitrogen balance while still producing feed or food (Ghosh et al., 2007). The total amount of nitrogen fixed per unit area in maize-legume cropping systems is often lower than in sole legume cropping due to decreased legume

population densities and increased competition for light, moisture, and nutrients among leguminous and non-leguminous crop components (Table 4). An intercropping system could also produce higher nitrogen fixation at times when limited resources are used effectively among companion crops (Table 4). In another study, intercropping pigeon pea with other legumes suppressed biological nitrogen fixation (BNF) (Njira et al., 2012). However, when pigeon peas were intercropped with maize, the slow growth of pigeon pea offered little competition, allowing the BNF released from the legume component to be efficiently used by intercropped maize, resulting in better system productivity (Giller, 2001; Hidoto and Markos, 2019).

While intercropping generally results in a reduction in the amount of nitrogen fixed relative to a legume monocrop, it represents an agronomically important input of nitrogen compared to a sole cereal crop and enhances the use of available nutrients and water (Hauggaard-Nielsen et al., 2003). Hence, a properly designed maize-legume intercropping system can be considered productive and sustainable, making an invaluable contribution to food and nutrition security. Besides improved soil fertility, the intercropping system offers benefits such as resource facilitation, enhanced crop productivity, increased soil and water conservation, and protection against crop pests and diseases (Dahmardeh et al., 2010; Lemlem, 2013). Furthermore, intercropping reduces soil erosion and nutrient leaching, suppresses weeds and pathogens, and provides food and shelter for beneficial insects (Dahmardeh et al., 2010; Lemlem, 2013). However, intercropping with perennials like *Leucaena leucocephala* resulted in a respective decrease of 38%, 34%, and 29%

in maize, black gram, and cluster bean yields compared to pure crops (Ghosh et al., 2007), highlighting the need for the selection of an appropriate legume-maize cropping pattern.

Green manures

Green manures are cover crops incorporated into the soil at the maximal stage of biomass production of legumes (Ahmed et al., 2005). These manures are primarily meant to improve soil fertility. Tropical green manures, such as *Canavalia*, *Crotalaria*, and *Mucuna*, commonly fix over 100 kg N ha⁻¹ per year, all of which are known to produce a more positive N balance than grain legumes (Ahmed et al., 2005). Green manures are more commonly used in temperate systems because of lower land pressures and because they could be grown during the colder winter months when crop production is not possible. In tropical systems, relay green manures are less common due to high land pressures, labor shortage, the inability to produce crops year-round in some regions, or the lack of moisture to support green manure growth during the dry seasons (Giller, 2001; Choudhury and Kennedy, 2004). The intercropping of green manure crops to supply nitrogen to simultaneously growing cash crops has also been adopted in some systems (Yoneyama et al., 1987). The aquatic fern, *Azolla*, and its symbiotic association with the cyanobacteria *Anabaena* provide an example of a green manure that is used exclusively as a source of nitrogen when intercropped in lowland rice systems. With 80–95% of *Azolla*, *rice–Azolla* green manures could fix approximately 30 kg N ha⁻¹ (Yoneyama et al., 1987; Choudhury and Kennedy, 2004). Some constraints to more widespread adoption of *Azolla* are pest pressures, phosphorus limitation, and limited irrigation availability in some regions (Giller, 2001).

Alley cropping

Alley cropping involves the use of perennial woody or shrub legumes between "alleys" of non-legume crops (Ghosh et al., 2007), where pruning from the legumes has been used as livestock forage or incorporated into the soil as a source of nitrogen for non-legume crops. Inclusion of perennials in cropping systems provides additional ecological benefits due to their extensive rooting systems that persist across multiple cropping seasons (Ghosh et al., 2007). Perennials could lessen soil erosion, access nutrients and water from deeper soil pools, provide critical microbial habitat between annual cropping seasons, and increase soil organic matter (Giller, 2001). *Leucaena* and *Gliricidia* are two common leguminous alley crop species practiced in sub-humid environments. Ghosh et al. (2007) also reported that the highest earnings can be achieved

when *Leucaena* is grown in alley cropping with cluster bean and black gram than growing of sole maize or *Leucaena*. *Leucaena* intercropped with sorghum increased sorghum yields by 73%, as compared to sorghum grown without N fertilizer, and yields were 43% greater than with a low rate of N fertilizer application (Ghosh et al., 2007). Phiri and Snapp (1999) reported that maize production was enhanced by 24.4% after *Sesbania sesban-maize* cropping system. Alley-cropped legumes could fix between 200 and 300 kg N ha⁻¹ per year (Giller, 2001). A 1-year *Sesbania sesban alley* crop increased the yields of succeeding maize crops by 50–80%, and a 2-year alley crop showed yield increases of 150 to 270% (Nair et al., 1999). The residual benefits of different legumes were observed for 4 years after alley cropping, and yields were three times greater than monocropped maize. Some of the challenges in the adoption of alley cropping systems include the competition of the legume with the cash crop for moisture in dry years, the labor required for pruning, and the use of land by a non-cash crop (Ghosh et al., 2007). Selection of species that have complementary rooting systems with cash crops (that is, a deep-rooted perennial legume cropped with a shallow-rooted annual), and species that grow at a manageable pace to supply nitrogen while not requiring excessive pruning inputs, are important considerations in the selection of legume species for alley cropping (Ghosh et al., 2007). Lastly, while reliable data on the contributions of non-symbiotic diazotrophs is limited, there are circumstances where it may be possible to increase nitrogen fixed by these microbes (Giller, 2001).

Forage legume – grass mixtures

In grass-legume mixture systems, choosing appropriate cultivars and species may enhance nitrogen fixation (N₂ fixation) and nitrogen transmission (N₂ transmission) (Jørgensen et al., 1999). For instance, in white clover monoculture, the percentage of nitrogen derived from biological nitrogen fixation (BNF) ranged from 75 to 94%, while in combinations of white clover and ryegrass; it was between 85–97%. Compared to legume monocultures, grass-legume combinations exhibit comparatively higher nitrogen fixation, which may be explained by increased competition from non-nitrogen-fixing plants for soil nitrogen. Nitrogen losses into the environment could occur even while the ecosystem had high nitrogen inputs (from relationships) (Scherer-Lorenzen et al., 2003). An abundance of grasses in the feed combination could enable a highly competitive uptake of mineral nitrogen from the soil, preventing such nitrogen losses (Scherer-Lorenzen et al., 2003). Forage legume BNF can differ based on species, cultivar, soil nutrient content, climate, and prevailing environmental factors. Legumes fix different amounts of nitrogen, which can be explained by the

Table 5. Soil pH prior and after legume growth without lime application.

Crop	pH (a) (before legume)	pH (b) (after legume)	% Change	Source
<i>Vicia faba</i>	6.00	5.64	-6.0	Yan et al. (1996)
White clover	4.97	4.27	-14.1	Monaghan et al. (1998)
Lotus	4.97	4.34	-12.7	
Lucerne	4.97	4.44	-10.7	
Caucasian clover	4.97	4.41	-11.3	

multitude of factors controlling BNF (Jørgensen et al., 1999).

Production of acids by legumes

Legumes have been shown to acidify their rooting medium through field tests, solution cultures, and greenhouse investigations (Table 5). Although several nutrient cycles can produce acids, the carbon and nitrogen cycles are thought to generate the most acids in pasture and agricultural ecosystems (Helyar and Porter, 1989). McLay et al. (1997) tested ten legume species (*pilosus*, yellow, white, and narrow-leafed lupins, faba beans, field peas, grass peas, chickpeas, common vetch, and lentils) for their ability to produce acid. They found that the species' ability to do so varied greatly, with proton production ranging from 77 to 136 cmol kg⁻¹ dry matter (McLay, 1997). Additionally, their research revealed that field peas had the least potential for acidification, while chickpea and narrow-leafed lupin had the largest acidification potential. It was also recognized that acid production by nitrogen-fixing legumes ranges from 0.2 to 2.7 mol H⁺ kg⁻¹ biomass produced. The condition is worsened in continuous legume cultivation, sole cropping of legumes with high nitrogen fixation potential, and in conditions where no residue is incorporated back (Yan et al., 1996; Monaghan et al., 1998) (Table 5).

Due to the excess uptake of nutrient cations over anions from the soil solution, the net efflux of hydronium (H₃O⁺) ions from plant roots into the rhizosphere, and the leaching of nitrate (NO₃⁻ N), perennial legumes acidify the rooting zone more than annuals (Jarvis and Robson, 1983; Helyar and Porter, 1989; Loss, 1992). When the pH of the soil falls below 4.5, most plant nutrients become less available, making it harder to grow food crops. In humid tropical locations, aluminum and certain micronutrients become more soluble and harmful to plants that have acute issues (Harter, 2007).

It takes 15 to 36 kg of calcium carbonate (CaCO₃) to neutralize the acidity produced by 1,000 kg of grain legumes, but it takes 53 to 100 kg of CaCO₃ to neutralize the acidity produced by 1,000 kg of bean shoots (McLay et al., 1997).

According to Helyar (1991), preventing nitrate leaching

is a crucial step in reducing soil acidity. Therefore, some corrective measures to prevent the accumulation of soil acidity in legume fields include growing acid-tolerant crops, applying lime, burning crop residue and leftovers, limiting the amount of ammonium-based nitrogen fertilizer to what plants actually need, following recommended tillage intervals, using cover crops during the off-season, rotating with cereals, and incorporating residue, which are important.

Production of nitrous oxides by legumes

Two-thirds of all anthropogenic N₂O emissions are caused by agricultural operations. N₂O has 300 times the potential to cause global warming than carbon dioxide. Legume cultivation produces more N₂O emissions than it can reduce CO₂ emissions from (Lugato et al., 2018), hence the role of legumes shouldn't be undervalued. The addition of fertilizer N (the largest magnitude), the development of legumes that fix atmospheric N, and the inoculation of legume residue into the soil through the microbiological processes of ammonification, nitrification, and denitrification have all contributed to an increase in nitrous oxide emissions from agricultural soils (Chafi and Bensoltane, 2003). Rather than the actual process of N fixation, the impact of legumes on N₂O emissions is due to the release of excess N through the rhizodeposition of soluble N compounds and the breakdown of nodules (Rochette and Janzen, 2005). Up to 5.6 kg N₂O-N ha⁻¹ of nitrous oxide was released by *vetch*, *alfalfa*, and *lupin* (Pattey et al., 2008), 4.9 N₂O-N ha⁻¹ by Ellert et al. (2008), and 0.5-2.4 N₂O-N ha⁻¹ by Barton et al. (2011). Variations in these amounts were attributed to factors such as temperature, pH, soil water-holding capacity, irrigation techniques, fertilizer rate, tillage techniques, soil type, and oxygen concentration, availability of carbon, vegetation, land-use practices, and chemical use. But the amounts of nitrous oxide that legumes produce are less than those released in industrial processes, fuel combustion, synthetic fertilizers, N-leaching, and runoff in magnitude. Indeed, if appropriate management was implemented, biological N fixation might be regarded as one of the biological ways to minimize the usage of fertilizers and perhaps reduce N₂O emissions (Shah, 2014). Lower N

Table 6. Nitrous oxide (N₂O) annual emissions measured based on year-round estimate N (N) ha⁻¹ over 3 yr (Ellert and Janzen, 2006).

Cropping system						N ₂ O-N (kg/ha)	% change
Alfalfa	Alfalfa	Alfalfa	Wheat	Barley	0 N	4.90	315.3
Alfalfa	Alfalfa	Alfalfa	Wheat	Barley	Manure	8.66	633.9
Alfalfa	Alfalfa	Alfalfa	Wheat	Barley	N	7.11	502.5
Alfalfa	Alfalfa	Alfalfa	Wheat	Barley	N and manure	12.13	928.0
Corn	Wheat	Corn	Wheat	Barley	0 N	1.39	17.8
Corn	Wheat	Corn	Wheat	Barley	Manure	2.08	76.3
Corn	Wheat	Corn	Wheat	Barley	N	6.54	454.2
Corn	Wheat	Corn	Wheat	Barley	N and manure	8.67	634.7
Faba bean	Wheat	Faba bean	Wheat	Barley	0 N	1.18	0.0

fertilizer rates combined with legume intercropping with sugarcane decreased N losses (N₂O emissions), but did not increase sugar yields in the first year (Smith and Conen, 2004).

Regardless of the presence of legumes, N₂O emissions decreased by 50 to 70% in the second year with a 67% N treatment (Elizabeth et al., 2016). Comparing N₂O emissions between mono-cropped faba bean and unfertilized wheat, authors found that faba bean fields had three times greater N₂O emissions than unfertilized wheat plots (441 vs. 152 g N₂O ha⁻¹, respectively); in contrast, when faba bean was mixed with wheat, cumulative N₂O emissions fluxes were 31% lower than that of N-fertilized wheat (Senbayram et al., 2016).

If mineral N inputs to intercropping or rotation could be decreased, or if N mineralization from legume residues is synced with the N need of the cereal crop, then N₂O emissions from intercropping might be minimized. The release of nitrous oxides from fertilizers combined with manure was greater than that from N fertilizer applied alone. On the other hand, alfalfa released twice as much nitrous oxide than cereal single crops. In a similar vein, Table 6 shows that nitrous oxide output was highest from N fertilizer compared to manure, but lowest from the control. Thus, intercropped legumes can influence N₂O emissions in two ways: either by directly supplying organic N or by adjusting the degree to which plants and microorganisms compete for soil N, for instance by serving as extra N sinks before nodulation. However, adding synthetic N to readily degradable crop wastes may increase N₂O emissions (Baggs et al., 2000). Therefore, adding grain and legume residue aids in reducing the amount of N₂O released. It is commonly recognized that the quantity and quality of crop residues (C: N ratio, lignin and cellulose content), soil texture, mulch location (surface mulching or integration), soil moisture, and temperature regimes all affect how much N₂O is released from the soil (Li et al., 2016). Therefore, the management of the agroecosystems in which legumes are grown determines the

impact of legumes in lowering GHG. Anyway, when economically relevant rates of N fertilizer are applied, the benefits of introducing legumes into crop rotations become noteworthy. Low-land rice cultivation techniques that flood their fields create anaerobic conditions that may lead to gaseous N losses (Havelin et al., 2014).

Bottlenecks in biological nitrogen fixation

Numerous agricultural techniques, including tillage, crop rotation, residue retention, and continuous cropping, alter the microbial communities in the soil; however, various microbial groups may react in different ways (Lindstrom and Mousavi, 2019). Ineffective strains, low populations of microorganisms, high levels of contaminants, exposure to high temperatures, storage in unfavorable conditions, use of suboptimal doses, poor adhesive quality, negative effects of plant protection chemicals, exposure to low soil moisture, acidity or alkalinity, low availability of phosphorous and molybdenum, presence of high native populations, or the presence of bacteriophages could all be reasons for a lack of response from the application of biofertilizers.

Nitrogen in the soil

For the majority of legumes, 5–15 kg N from different fertilizer sources are utilized during planting as starter N. This initial N promotes quick nodule production, strong growth, and subsequent N fixation. On the other hand, N fixation is decreased by high residual or additional N levels. This is because there is rivalry for photosynthate between NO₃⁻ reduction and N₂ fixation reactions when there is excess NO₃⁻ availability, which lowers nitrogenase activity and inhibits N₂ fixation (Havlin et al., 2014). For leguminous crops, N fertilization is typically not advised due to this negative effect.

However, there can be circumstances in which N must be applied, such as to cereals in rotations or mixed cropping, and fertilizer might then have an impact on the legume crop's ability to fix N. The corrective measures, which comprise the development of grain legumes that are less sensitive to mineral N or apply small amounts of soil or foliar N fertilizer, may increase yield without reducing the amount of N fixed are promoted (Hardarson et al., 1991; Boote et al., 1978).

Other soil nutrients

Compared to legumes in fertile fields (-0.8 to $+2.2\text{‰}$; 23 to 85%), those in poorly fertile fields exhibited considerably reduced shoot $\delta^{15}\text{N}$ enrichment (-2.8 to $+0.7\text{‰}$) and a higher %Ndfa (55 to 94%). However, due to higher shoot dry matter and N yields, the N_2 fixed was higher in fertile fields (16 to 145 kg N ha⁻¹) than in poorly fertile fields (15 to 123 kg N ha⁻¹) (Kermaha et al., 2018). Similar environmental conditions that are required for the host plant's healthy growth, vigor, and production of dry matter promote N_2 fixation by Rhizobium bacteria in leguminous plants. Dependent on biological N_2 fixation, plants require extra P for signal transduction and membrane production, as well as ATP for nodule formation and function. The concentration of phosphorus in the nodule is frequently much higher than in the tissue of the shoot or root. Additionally, Al-Niemi et al. (1997) proposed that even in cases where plants have received ordinarily sufficient P levels, bacteroids may be P limited. Considering this necessity for symbiosis, strategies that increase legumes' uptake and utilization of P are crucial. According to Israel (1987), there was a considerable reduction in host plant growth and biological N_2 fixation when there was a severe phosphorus deficiency. This suggests that N_2 fixation requires more phosphorus for efficient functioning than host plant growth and nitrate assimilation. Reduced N_2 fixation would arise from shortages in molybdenum, iron, phosphorus, magnesium, and sulfur since these elements are components of the Nitrogenase complex, which facilitates N_2 fixation. Molybdenum is a major component of nitrogenase since N fixation requires more of it than the host plant can provide (Verma et al., 2015).

Soil acidity

Acidic soils hinder N fixation and agricultural productivity. Low levels of soil-available P and some micronutrients in acidic soils inhibit the growth of the related N-fixing Rhizobium, which lowers the BNF in the soil (Vincent, 1990; Giller, 2001). Rhizobia can thrive best at a pH of 6 to 7 (Giller, 2001). Nonetheless, species that grow slowly and produce alkali, like *Bradyrhizobium japonicum*, are more tolerant of lower pH values, whereas species that grow quickly and produce acid, like *R. leguminosarum*, are

more tolerant of higher pH values (Krieg and Holt, 1984). Certain Rhizobia may, in fact, withstand large quantities of aluminum (Al) at low pH in both solution media and soil, according to certain research. On the other hand, vulnerable species, low phosphorus levels, high levels of acidity, and high amounts of aluminum caused a 40% decline in population, retarded growth, and frequently prolonged the lag period (Munns and Keyser, 1979). Low pH prevented the development of nodules, and nodulation failure in these soils is typically ascribed to Rhizobia's low survivability or inability to proliferate in the rhizospheres (Munns, 1978). This is due to the fact that low soil pH is typically linked to mineral toxicity for Rhizobia and nutritional deficiencies. For instance, toxicity results from low molybdenum levels or excessive iron solubility in acidic environments (Munns, 1978). Therefore, some environmental factors are detrimental to *Rhizohium* life (for example, if the pH of the soil is higher than 7 for *R. lupini* or less than 5.5 for *R. meliloti*). Soil amendments were necessary in these cases to guarantee Rhizobia establishment. Using Rhizobium species and acid-tolerant legume cultivars are among the necessary management alternatives; also, soil liming should be restricted to reaching a pH where accessible manganese or aluminum levels are no longer harmful (Vincent, 1990; Giller, 2001).

Unsuitable microbial factors

Poor quality inoculants, inability to compete with local Rhizobia, suppression by native microbial flora, or inoculants' inability to thrive in low pH and dry soils are some possible reasons for BNF failure (Graham, 1981). Certain *Rhizobia* are promiscuous (able to nodulate with native Rhizobium species), while others are non-promiscuous (could only nodulate with the variety-specific bacteria). Therefore, in non-promiscuous legume cultivars, the biological N fixation would be reduced in the absence of a particular *Rhizobial* strain. Microbes such as parasites like bacteriophages and belliovibrios and predators like protozoa and amoebae may control the amount of Rhizobia in tropical soils (Keya and Alexander, 1975). Consequently, inoculation is required whenever new leguminous crops are brought to a region in order for host-specific *Rhizobia* to regularly develop for the development of new cultivars (Montanez, 2000).

Furthermore, many soils have a high concentration of inefficient Rhizobia that might cause nodulation without benefiting the host. In these circumstances, it becomes necessary to replace the ineffective native *Rhizobia* with very large inoculums of a very effective and competitive strain. In order to decrease inorganic N inputs and increase legume production, research institutes (such as IITA) appropriately began dispersing promiscuous legume germplasms (nodulated by broad host-range Rhizobia strains) (Schulze, 2004; Ndakidemi et al., 2006; Li et al.,

2015; Arreseigor et al., 1997). Accordingly, the amount of Rhizobia already present in the soil, the availability of soil N, and the crop's need for N all influenced how the legumes responded to inoculation (Montanez, 2000).

Tillage

Nodulation and BNF are positively impacted by reduced tillage. This is because tillage promotes the soil's organic matter to become more mineralized, which makes a lot more nitrate available and may inhibit nodulation and N fixation.

According to Alves et al. (2002), it indicates that, in terms of BNF, no-tillage circumstances are favored over frequent tillage operations.

In comparison to findings in conventional tillage without residue retention, Kihara et al. (2011) showed increased nodule numbers, nodule dry weights, and percent of N derived from the air in legumes under decreased tillage with residue retention. The study was conducted in Kenya. Reduced tillage will result in reduced rates of nitrification and mineralization, as well as greater N immobilization and a greater potential for denitrification, which will reduce the amount of accessible N. Remedial actions such as reducing tillage may thereby increase N requirement and N₂ fixation.

Therefore, until a new equilibrium between residue input and the rate of decomposition is attained, conservation and zero tillage management strategies will stimulate N₂ fixation (Table 7).

Residues from cereal crops

It took until recently to identify soil organic carbon (SOC) limits, above or below which crop output could be negatively impacted or at which no or strong response to nitrogen treatment could be realized (Dobberman, 2005). However, it seems that when N application rates rise, so do the N fertilizer replacement values for organic inputs. According to Pikula et al. (2016), all organic residues, whether it comes from legumes or not, has a N fertilizer replacement value (NFRV). According to Mrabet et al. (2003), the amount of N, organic carbon, and particulate organic matter varies with the residue level. According to some recent estimates, increasing soil organic carbon (SOC) concentrations may help narrow worldwide output gaps and lessen the need for N fertilizer (Oldfield et al., 2019). Meki et al. (2012) found that in the Upper Mississippi River Basin, removing maize residue decreased soybean yield, N fixation, uptake, losses, and soil storage by 8, 6, 7 and 5%, respectively. This ultimately decreased the amount of nutrients available for loss, leading to a 9% decrease in N losses compared to leaving the residue in place. When *diazotrophs* used the carbon in

the straw from wheat crop with a yield of 2 t/ha, they produced 50–150 kg N/ha, which drove N fixation (Kennedy and Islam, 2001).

This is because these resources are used by the tiniest and most prevalent N-fixing microorganisms in the soil, which include bacteria, *actinomycetes*, *fungi*, *algae*, and *protozoa*. Because they actively participate in the nutrition cycle, the decomposition of organic materials, N fixing, and *P solubilization*, they are crucial to the fertility of the soil. According to some research, adding organic wastes (bio-solids, slurry), synthetic fertilizers, and bettering soil biological processes involving BNF and *mycorrhizae* can all improve soil fertility. This is one method of doing this. The retention of soil carbon and nitrogen is enhanced by the use of organic residues with a high C to N ratio, such as grain residues and during integrated nutrient management (INM).

Residues from legume crops

Legume residues can be used as a source of carbon and nitrogen for companion non-legume crops because they have a low carbon-to-nitrogen ratio and a large amount of nitrogen. This allows them to release nitrogen more quickly than cereal residues with lower nitrogen content (Hestermann et al., 1986; Bruulsema and Christie, 1987; Yano et al., 1994; Mubarak et al., 2002). According to other writers, 44% of the nitrogen fixed by legumes was still present in the soil (Sawatsky and Soper, 1991). Additionally, the authors demonstrated that 8.6 to 12.1% of N is recovered by the next cereal crop from legume shoot residue, and 8.2 to 10.6% is recovered from microbial biomass (Sawatsky and Soper, 1991). Hence, increased release from low carbon/N shoot and root led to increased N availability for crops that came after legumes. It was documented that the residue from peanuts contributed approximately 11.2% nitrogen for subsequent wheat (Yano et al., 1994); the residue from red clover and alfalfa contributed approximately 22.7 kg N ha⁻¹ for subsequent maize (Bruulsema and Christie, 1987); the residue from crimson clover contributed approximately 19.4 kg N ha⁻¹ of nitrogen (Hestermann et al., 1986); and the residue from peanuts contributed approximately 7.9 kg N ha⁻¹ (Mubarak et al., 2002). Compared to cereal crops grown in the same environment, the amount of mineral N in the root zone after legumes is frequently 30–60 kg N ha⁻¹ higher (Dalal et al., 1998). Using a 15N label to include the residue from legumes revealed that 10 to 34% of the legume N could be recovered in the next crop of rye or wheat, 42% in rice, and 24% recovered from velvet beans by the corn crop (Ambrosano et al., 2005). Legumes' deep root systems, which accessed nutrients from lower soil layers, are to blame for this. When fed to the soil in the short term, soybean residues at harvest are lignified (10% lignin) with C/N ratios of approximately 45:1,

Table 7. Influence of conventional tillage (CT) and zero tillage/minimum tillage (ZT/MT) practices on N₂ fixation by grain legumes (van Kessel and Hartley, 2000).

Crop	N ₂ fixed (%)			N ₂ fixed (kg/ha)		
	CT	ZT	% change	CT	ZT	% change
Chickpea	34	28	-17.6	32	27	-18.5
Soybean	73	88	20.5	180	232	22.4
Soybean	73	88	20.5	91	156	41.7
Chickpea (1994)	31	40	29.0	9	11	18.2
Chickpea (1995)	12	17	41.7	4	5	20.0
Pea	48	79	64.6	ND*	ND	ND
Lentil	62	72	16.1	ND	ND	ND
Soybean cv S12	87	91	4.6	33	47	29.8
Soybean cv S15	86	88	2.3	39	44	11.4

*Not determined.

which tends to immobilize N and release it for plant uptake in the long run (Toomsan et al., 1995). As active N₂ fixation peaks between growth stages V2-V3 and R5-R6, residue inclusion for improved N should be carried out during the legume flowering period. Grain legume residues collected during flowering phases have a narrow C/N ratio, which speeds up decomposition and increases SOM. This affects soil aggregations and reduces soil bulk density. This is because of N fixation, deep rooting, leaf shedding ability, and mobilization of insoluble soil nutrients (Ofori and Stern 1987). Straw application dramatically boosts N₂-fixing activity of photosynthetic bacteria and *Rhizobial* populations, according to several field and greenhouse investigations.

Nonetheless, N increases of 2 - 4 mg N g⁻¹ straw added were observed in marijuana trials (Santiago et al., 1986). Furthermore, even when the residues are returned to the soil, there is typically a net removal of N from the field (Giller et al., 1994). Legumes like soybeans are very effective at translocating their N into the grain, ranging from 50-150 kg N ha⁻¹ (Matusso et al., 2014).

Temperatures

Temperatures outside of the ideal range may impact *Rhizobia*'s ability to nodulate, fix nitrogen, and survive in soil, potentially hindering N fixation. Many bacteria that develop in root nodules prefer temperatures between 25 and 30 degrees Celsius. The majority of *Bradyrhizobium* strains, however, are said to withstand high soil temperatures, with a maximum growth range of 30 to 40 degrees Celsius. Thus, variations in soil temperature can affect *Rhizobia*'s ability to survive and persist in soil. Nodulation might not occur below 15 degrees Celsius (Elkan, 1987). The fact that these conditions arise during

the dry off-season when crop hosts may not be growing in the field exacerbates the effects of high soil temperatures. The recommended management choice is to place the inoculum in deeper soil layers when topsoil temperatures are high and use surface mulches to conserve moisture and reduce soil temperature (Roughley, 1980).

Soil moisture

For N fixation, both high and low moisture stress are detrimental. Low moisture stress inhibits nodulation by affecting *Rhizobia* colonization and infection of root hair, as well as nodule activity and function, and *Rhizobia* survival in soil (Davey and Simpson, 1990; Graham, 1992). Two common bean (*Phaseolus vulgaris* L.) cultivars, Carioca and EMGOPA-201, were used to investigate the effects of water stress on N₂ fixation and nodule structure. The results showed lower nodule dry weight, lower shoot dry weight, host cell vacuolation, loss of the peribacteroidal membrane, degradation of cytoplasm host cells, and senescence of bacterioids with their release into intercellular spaces. According to Lucrecia et al. (2003), water stress changed the structure of cultivars' nodules, inhibited Nitrogenase function, and decreased the amount of intercellular glycoprotein.

Rhizobia's growth and activity are impacted by flooding the soil because it decreases the gas exchange between the soil and bacteria or plant nodules. *Rhizobial* strains are aerobic heterotrophs, which explain why. Furthermore, in water, *Rhizobium* spp. quickly lose vitality. According to Osa-Afiana and Alexander (1979), when soils were flooded, the population of soybean *Rhizobia* decreased by a factor of 150 (from 6.0 x 10⁸ to 4.0 x 10⁶ cells per gram of soil), while the population of *R. trifolii* was reduced by a factor of 300 (from 1.3 x 10⁸ to 4.2 x 10⁴ cells per gram of

soil). Nitrate absorption is impacted by the *rhizosphere's* decreased O₂ content after floods. First, nitrate might be utilized in hypoxic roots as an electron acceptor instead of O₂. Second, compared to nitrate absorption and assimilation, the respiratory energy requirements for N₂ fixation and assimilation are greater (Bacanamwo and Purcell, 1999). As a result, plants that rely on N₂ fixation and have hypoxic roots are severely impacted. According to Reyna et al. (2003), waterlogging in soybean root nodules decreased nitrogenase activity and permanently changed the ultrastructure of the cells. According to Oosterhuis et al. (1990), soybeans typically do not fully recover from flooding injury. This can result in a reduction in soybean yield of 17 to 43% during the vegetative growth stage and 50 to 56% during the reproductive stage. Reduced root and shoot growth, nodulation, N fixation, photosynthesis, biomass buildup, stomatal conductance, and plant death from diseases and physiological stress are the main causes of yield losses (vanToai et al., 2003).

Salinity

According to Munns (2002), salinity inhibits plants' capacity to absorb water, which lowers the growth rate and results in a number of metabolic changes similar to those brought on by water stress. It requires a combination of stress-tolerant *Rhizobia* and cultivars to maximize biological nitrogen fixation (BNF) under salinity circumstances.

Enhancing biological N fixation while reducing acidification and n₂o production

Legume crop productivity and biological N₂ fixation would be improved by using appropriate agronomic and plant protection practices, enhancing soil N mineralization, and recycling crop residues. Legume-supported crop systems have the potential to reduce N and C losses, but overall management plays a significant role in achieving this.

- 1) Finding the germplasm that has the highest potential for this trait, this necessitates addressing BNF's low heritability and comparable characteristics' evidence that BNF traits are quantitatively inherited and environment-influenced (Schulze, 2004).
- 2) Finding the best possible balance between crop management, biological inoculant, and variety (Ndakidemi et al., 2006).
- 3) N in the cropping system should be optimized (Ndakidemi et al., 2006), since excessive N fertilizer application above crop needs has deteriorated soil, water, and air quality.
- 4) The use of cover crops would lower N₂O emissions and soil acidification, and cropping systems might be

intensified by optimizing tillage, using residue or fertilizer, and designing appropriate cropping systems (Gregorich et al., 2005; Li et al., 2015).

- 5) *Rhizobia's* survival would have been decreased by the negative effects of temperature, which can be mitigated by surface mulching, inserting inoculum in deeper soil layers, and choosing heat-tolerant strains (Michiels et al., 1994).
- 6) *Rhizobial* populations and nitrogen fixation were protected from the negative effects of moisture stress by choosing strains of bacteria that can withstand moisture stress, mulching the soil, and irrigation (Hunt et al., 1981).
- 7) By reducing calcium deficiency and aluminum toxicity, liming the soil, adding compost, or using acid-tolerant legume cultivars all contribute to improving *Rhizobia* survival in the soil and enhancing nodulation and N₂-fixation in acidic soils (Giller, 2001).
- 8) To prevent P deficit and promote nodulation, N₂ fixation, and *Rhizobial* growth, P fertilizers should be added, effective mycorrhiza should be inoculated, and P-efficient cultivars should be used (Cassman et al., 1981).
- 9) Choosing salt-tolerant strains improves nodule activity, respiration by *Rhizobial* bacteria, and nodulation while lowering salt stress (Delgado et al., 1994).
- 10) Increasing root infection, nodulation, and nodule activity by the breeding of cultivars less sensitive to the mineral N (Arreseigor et al., 1997).
- 11) *Rhizobia* and agrochemicals placed separately reduce the negative effects of fungicides, insecticides, and herbicides while promoting nodulation, N₂ fixation, and *Rhizobial* growth, as well as plant growth (Mallik and Tesfai, 1993).
- 12) Research focused on particular strains of *Rhizobial* lowers natural *Rhizobia's* competitiveness and its ability to prevent inoculation (Dowlig and Broughton, 1986).

Silent features

A synthesis of the existing knowledge and identification of knowledge gaps has led to the determination of research requirements for the following areas of future study:

- 1) Is it possible to quantitatively divide a specific legume's contribution to subcomponents in various agro-ecologies for sustainable farming?
- 2) Due to the sensitivity of microorganisms, research on nodulation and N₂ fixation in conditions of salt or drought has not advanced significantly. What may significantly increase its impact?
- 3) If under-sowing, intercropping, catch cropping, cover cropping, crop rotation, and double cropping on both tilled and untilled soils are taken into consideration, what would be the outcome of quantifying BNF throughout multi-cropping and various locations?
- 4) Rhizosphere acidification, acid phosphatase secretion, altered architecture at low P, increased P transport and

use-efficiency, and functional variations in mycorrhizal symbioses are all factors contributing to legumes' improved uptake and utilization of P. Which procedure has greater significance than the others?

5) Different native *Rhizobia* can be found in a range of global habitats. Developing effective inoculation tactics requires an understanding of local populations and *Rhizobia* biodiversity. The diversity of *Rhizobia* is not, however, completely understood.

6) There is little quantitative data on the mineralization patterns of crop residues from intercrops of legumes and cereals (Njira, 2016). How may we optimize use and mineralization?

7) The discharge of greenhouse gases from agricultural land adds to global warming. Legume fields emit less N₂O when managed differently (Mania *et al.*, 2019). The amount of the emission reduction, though, has not yet been measured across maize based legume cultures.

8) Is it possible to create post-emergence herbicides that effectively control weeds in grain legumes without suppressing BNF?

9) How can we improve the N economy by postponing nodule degeneration?

10) Should we improve brown manuring or add green manure pulse crops for tropical Africa?

CONCLUSION AND RECOMMENDATIONS

This review aimed to incorporate the advantages of legume-based cropping systems for maize production while highlighting their drawbacks. The analysis then suggested cropping system techniques needed to address the drawbacks of monoculture. Allowing farmers to plant whatever they want whenever they want and letting nature choose what works best will simply worsen the already degraded soils and broken agricultural systems. Therefore, in mid- to highland locations, it is possible to reduce nitrous oxide emissions and soil acidification while improving N fixation by rotating maize with grain legumes, forage legumes, green manures, or cover crops every year. Maize can be relayed, double cropped, or simultaneously interplanted with legumes that complement it in moist mid-lands. Compatible legumes could be interplanted with maize in arid midlands. But legumes should be cycled in lowland areas where one crop may be grown in a season. In this final section, we propose a cropping system act (tillage act, rotation act, intercropping act, double cropping act, and cover cropping standards) relevant to each locality in maize-based production systems. This will enforce the practices needed to lower production costs and achieve sustainable maize production, which suppresses resource abuse and environmental degradation. This is because each recommended cropping system had its own recommendation domain. The legislations and practices

can be utilized for grassroots land planning as well as for regulatory purposes at the local government level.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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