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Original Research

Contribution of Legume-Derived Biological Nitrogen Fixation in Reducing Greenhouse Gas Emissions Originating from Agriculture in Türkiye

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Abstract

Nitrogen fertilizer production and use contribute to the increase in greenhouse gas (GHG) emissions. GHGs due to nitrogen (N) fertilizer use can be reduced to a certain extent with legume agriculture. This study was conducted to estimate the amount of N produced by biological N fixation (BNF) in legumes grown in Türkiye, the amount of synthetic N fertilizer corresponding to this amount of N, and the global GHG emission equivalent of the production, transport, and use of this fertilizer in the field. Firstly, the amount of N fixed by BNF in a year in legume cultivation areas in Türkiye was calculated. Then, the GHG equivalents emitted during the production, transport, and application in the field of synthetic N fertilizers, which is the equivalent of N fixed by BNF, were calculated. The total amount of N fixed with BNF in 2022 in Türkiye is 363,354 tons. The total GHGs emissions during the production, transport, and use of N fertilizer equivalent to 363354 t of N fixed by BNF is 2,631,043 tons CO_2-eq. In other words, in one year in Türkiye, 2,631,043 tons of CO_2-eq GHGs will be reduced thanks to legume agriculture. GHG emissions of the Turkish agricultural sector (total 72.1 Mt CO_2-eq) have been reduced by about 3.65% (2.63 Mt CO_2-eq). For an economically and environmentally sustainable agriculture, we need to give more importance to the cultivation of pulses.

Keywords: carbon footprint, fertilizers, greenhouse gases, nitrogen, rhizobium bacteria

Introduction

The continued rise in atmospheric GHG concentrations is a global concern [1]. In 2019, global GHG emissions reached 106 billion tons of carbon dioxide equivalent (CO_2-eq), of which 17 billion tons (16%) were accounted for by the agricultural food production system [2]. At the same time, agriculture is one of the most vulnerable to climate change and one of the most significant sources of carbon emissions [3-6]. The production and use of mineral fertilizers is necessary to provide sufficient plant nutrients for sustainable food production and our growing population [7, 8]. The production of mineral fertilizers, especially

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N, contributes significantly to the carbon footprint (CFP) of agricultural crops and food [9]. N fertilizers are very important for high productivity in today's agriculture, but they are also one of the most important sources of nitrous oxide (N_2O), a GHG that is about 300 times more than CO_2, with its potential impact on global warming from agricultural production [10]. N fertilizer production and use accounts for about 5% of global GHG emissions [11]. Ammonia production accounts for about 90% of the total energy consumption of the fertilizer industry and about 2% of total global energy consumption [12]. In addition, FAO [13] estimates that global use of synthetic N fertilizers will increase by 50% by 2050 compared to 2012 levels. Ammonia production is a carbon and energy-intensive process, relying mainly on natural gas and coal as feedstocks [12].

Synthetic N fertilizer production accounts for 35.2% of total synthetic N fertilizer-related emissions, transport 2.4% and field 62.4% [14]. Similarly, [11] found that about two-thirds of N fertilizer emissions occur after application to cropland, with one-third of emissions coming from production processes. When N fertilizer is applied to the soil, only part of it is taken up by plants. Another part is used by soil micro-organisms that produce N_2O as a by-product of their metabolism, while another part of the applied N may leak or evaporate from the application site [14]. When excessive N fertilizer is used in crop production, more than half of the applied N fertilizer is lost [15].

It is never possible to zero GHG emissions from fertilizer use, especially N_2O. However, measures can be taken to minimize them, such as applying the right nutrient source, at the right rate, at the right time and in the right place [12]. Mineral fertilization is the largest contributor to the CFP of crops [16]. Current production techniques are being challenged by the increasing global demand to produce more food with fewer inputs, less energy and lower GHG emissions [17]. BNF in legume production can reduce the demands for mineral N fertilizers [18]. The cultivation of legume crops has been proposed as a way to reduce GHG emissions due to their ability to fix N in the atmosphere and thus reduce the need for external N fertilizers [19]. In this way, great economic and environmental benefits are obtained.

Legume crops have a lower CFP than grain crops [20]. The impact of legumes on climate change is less than vegetables, grains, oilseeds and corn [21]. Legume crops contribute to the reduction of GHG emissions as they emit 5-7 times less GHGs per unit area compared to other crops and save fossil energy inputs in the system thanks to N fertilizer reduction corresponding to 277 kg ha^{-1} CO_2 per year [22]. A significant portion of the N assimilated by symbiotic bacteria feeds the soil in the form of plant and root residues [16] of the succeeding plant. In other words, it acts like slow-release N fertilizers [23]. Thanks to legume cultivation, the use of mineral N fertilizers in agriculture will decrease and the GHG emission values of agricultural products will also decrease [16].

Legume cultivation has an important place in field agriculture. Rhizobium bacteria, which live in symbiosis with legume plants, meet the needs of the plant by fixing free N in the air while obtaining nutrients from the plant. In many studies, the amount of N fixed by BNF has been determined according to plant species. There are also different studies on determining the amount of greenhouse gas emissions that occur during N fertilizer production, transportation and application in the field. However, there is a need to develop a method to estimate the total amount of N fixed by legume plants thanks to rhizobium bacteria for a certain area (world, country, region, etc.) and its equivalent GHG emissions. In order to make such a prediction, in this study, an attempt was made to develop a calculation-based prediction by using the research results obtained experimentally or through calculations by different researchers.

Many legume crops are cultivated in Türkiye, which has different climatic conditions. A significant amount of N fertilizer is saved with the legume crops grown in Türkiye. In this study, the amount of N fixed by legume cultivated areas in Türkiye, the synthetic N fertilizer equivalent of this N amount and the total direct and indirect GHG emissions resulting from the production, transport and use of this fertilizer were estimated.

Material and Methods

The amount of N fixed by legumes cultivated in Türkiye through BNF, the equivalent amount of N fertilizer and GHGs emission calculations were planned in stages (Fig. 1). The calculations are divided into 7 main parts. These stages are explained respectively.

1. Reviewing the results of the research conducted by the researchers and collecting the literatures to determine the amount of N fixed by BNF separately according to legume species. The results obtained for each legume species are given in Table 1. To determine the amount of N fixed by BNF in each legume species, as many research results as possible were considered. For each legume species, the arithmetic mean of N fixed per hectare determined by the researchers was calculated these mean values were used in subsequent calculations.

2. Legume cultivation areas in Türkiye were determined separately by species for the year 2022. The Turkish Statistical Institute (TUIK) [38] data were used to determine the sowing areas (Table 2).

3. The average amount of N per hectare fixed by BNF was multiplied by the area under cultivation for each legume species separately. The amount of pure N fixed by each legume species according to the cultivation area was determined (Fig. 1).

4. The amount of pure N fixed by each legume species was converted to ammonium sulphate (AS, 21%) fertilizer containing 21% N (Fig. 1).

Table 1. The amounts of N fixed by legume crops.

Legume crop*	Total N fixed (kg ha^{-1} $year^{-1}$)	Mean
Alfalfa	229-290 [24]; 153 [25]; 103 [26]; 500 [27]; 465 [28]	290.0
Bean	40-70 [24]; 16-94 [29]	55.0
Bitter vetch	110 [24]	110.0
Chickpea	103 [24]; 70 [26]	86.5
Clovers	215 [25]; 130 [26]; 128 [24]; 140 [26]; 207 [24]; 120 [26]	156.7
Cowpea	73-354 [24]	213.5
Faba bean	45-552 [24]; 110 [26]; 118.6-311 [30]; 165 [28]	216.9
Fenugreek	70-138 [31]	104.0
Grass pea	101-149 [30]	125.0
Kidney bean	40-70 [24]	55.0
Lentils	88-114 [24]; 58 [26]; 60 [32]; 52 [28]	74.4
Pea	52-77 [24]; 105 [32]; 111 [28]	86.3
Peanut	72-124 [24]; 95 [26]; 139-206 [33]; 17-450 [34]	157.6
Sainfoin	125 – 480 [35]; 138 [25]	247.7
Soybean	60-168 [24]; 180 [26]; 89.3-146.5 [36]; 117-237 [37]	142.5
Vetch	110 [24];107-131 [30]	116.0

*Listed alphabetically by plant name. In cases where the fixed N amount of the cultivated plant could not be found, the data of the closest species were used. For bitter vetch, vetch data were used

5. For each legume species, the amounts of AS fertilizer calculated according to the cultivation area were summed and the total amount of N fixed by legume cultivation areas in Türkiye was calculated in terms of AS fertilizer containing 21%N, which is the equivalent of the total amount of N fixed (Fig. 1).

6. The total amount of AS fertilizer equivalent to the N fixed by legume crops was multiplied by the GHGs emission value per unit ton during the production of 21% N AS fertilizer. In this way, the GHGs emission amounts during the production of synthetic N fertilizer (21%N AS) equivalent to

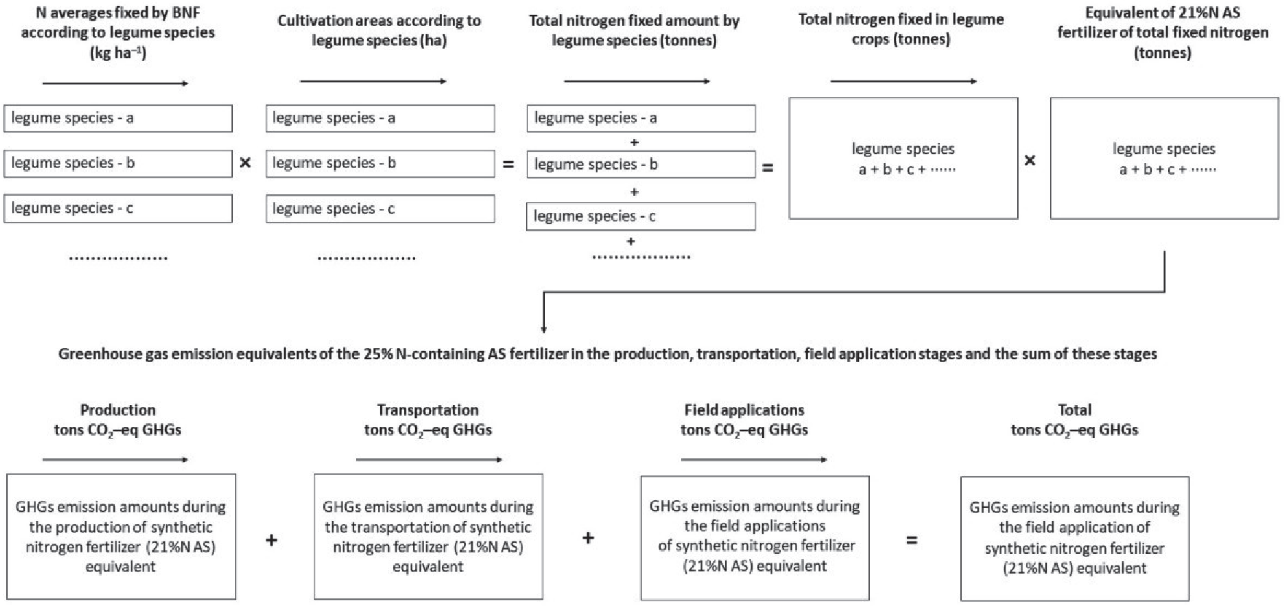

Fig. 1. Summary of the stages of calculation of GHG emissions equivalence of N fixed by BNF fixation of legume crops.

the N fixed by legume crops cultivated in Türkiye were calculated (Fig. 1).

In this calculation: [9] data were taken as reference carbon footprint (CFP) values. Since Türkiye is located in the Middle East, 0.59 kg CO_2-eq kg^{-1} product value was used in the calculation.

7. At this stage, the emission values during the transportation and application of the produced fertilizer to the field were added to the GHG emission values amount during production. [14] stated that synthetic N fertilizer production accounts for 38.8% of total synthetic N fertilizer-related emissions, while field emissions account for 58.6% and transportation for the remaining 2.6%. Using the percentages indicated by the researchers, total emission values were determined by calculating the emissions from production, transportation, and use of fertilizer in agriculture (Fig. 1).

In this way, the GHGs from the production, transportation, and use of synthetic N equivalent to the N produced by BNF in existing legume cultivated areas were calculated.

Results and Discussion

Nitrogen is the most abundant gas in the atmosphere. While plants cannot directly utilize this N in the atmosphere in molecular form, the amount of N in the soil that plants can utilize is generally very small. Legume plants utilize the N in the air thanks to the Rhizobium bacteria in their roots. In this way, there is no need to apply N fertilizer, grain and grass products with high protein content are obtained and a significant amount of N is provided for the plants planted after them. Many legume crops are cultivated in Türkiye, which has different climatic conditions. Thanks to the legume crops grown in Türkiye, a significant amount of N fertilizer is saved.

The amounts of N fixed per hectare used in this study are based on data obtained from experimental studies. Another method is to make calculations with reference to the N content of the resulting product (grain, hay, grain + hay). However, in such a calculation, especially in annual legumes (chickpea, lentils, beans, soybeans, peanuts, chickpeas, etc.), it is not possible to distinguish the amount of N formed by the residue of fertilizers given to the previous crop, the decomposition of plant residues of the previous crop, and non-symbiotic N fixation, from the amount of N provided by symbiotic means. In other words, it is not possible to distinguish how much of the N in the legume product obtained is provided by BNF and how much is taken from the soil. For these reasons, the determination of the amount of N obtained by BNF in this study was based on the amount of N determined by empirical methods. However, the amount of N fixed by the symbiotic life of legume plants and rhizobium bacteria varies according to many factors. These factors can be listed as the species of legume plant, the species and strain of rhizobium bacteria, the presence of bacteria in the soil and inoculation with rhizobium bacteria before sowing, vegetation period, whether rhizobium bacteria are active or not, the amount of N in the soil and N fertilizer application, soil temperature, soil moisture, soil pH, poor soil aeration, nutritional status of the plant, agricultural activities, and other factors affecting plant growth [23,39]. There are no empirical study results on the effects of each of these factors separately for each legume species in each region. For example, alfalfa is a highly adaptable plant that can grow in cold and hot climatic conditions. In Türkiye, clover is cultivated both in Sivas province with a very short vegetation period (annual average temperature 9.0 °C, [40]) and in Antalya province with a long vegetation period (annual average temperature 18.8 °C, [41]). In alfalfa trials carried out according to the same instruction, 8630 kg ha^{-1} hay yield was obtained with 3 mowing in Sivas [42] and 43510 hg da^{-1} hay yield was obtained with 6 mowing in Antalya [43] in 2020. This yield difference is due to the difference in climate, soil, presence and strain of rhizobium bacteria and the alfalfa cultivars used. In both studies, standard N fertilization was applied once during sowing to meet the needs of the plant in the seedling period. No N fertilization was applied in the yield years. Therefore, the plants supplied the N they needed with BNF. When we look at the yield difference of alfalfa by region, it can be easily understood that the amount of N fixed by BNF is also very different. However, there are not sufficient empirical results to determine the amount of N fixed according to every region and condition for both Türkiye and the world. For this reason, it was preferred to use the average of the studies carried out on species basis in the calculations within the scope of this study. Within the scope of the study, the average value was used as the GHG emission that occurred during the transportation of fertilizers. However, there are different distances both in the distribution of fertilizers produced in Türkiye from the factory and in the distribution of imported fertilizers from the ports. This affects the carbon emission during transport to a small extent. It is not possible to calculate GHG emissions during transportation separately for each region or field. For these reasons, in this study, some values were accepted as average, calculations were made, and estimates were formed. This study will contribute to the development of better forecasting methods by adding the knowledge and experience of different researchers with its methods and results. Additionally, this method may be useful in calculating national N budgets.

The main legume crops grown in Türkiye are alfalfa, chickpea, vetch, lentils, sainfoin, bean, pea, peanut and soybean (Table 4). When we examine Table 1, the average amount of N fixed by BNF per hectare in a year varies between 55 – 290 kg ha^{-1}. In 2022, the legume cultivation area in Türkiye was 2,267,784 ha [38]. Based on 2022 cultivation areas, the amount of N fixed by legume crops in Türkiye was estimated (Table 4). For this calculation, the average amount of N

Table 2. Legumes cultivation areas in Türkiye in 2022 [38].

Legume crop	Cultivation area 2022 (ha)	Legume crop	Cultivation area 2022 (ha)
Alfalfa (hay)	643,593	Grass pea (seed)	1,615
Alfalfa (seed)	3,422	Kidney bean (fresh)	6,826
Bean (grain)	97,052	Lentils (green seed)	42,825
Beans (fresh)	38,719	Lentils (red seed)	299,812
Bitter vetch (green)	2,043	Pea (fresh)	12,433
Bitter vetch (seed)	1,448	Pea (fodder) (green)	25,887
Chickpea (grain)	456,834	Pea (seed)	887
Clovers (hay)	7	Peanut (groundnuts)	45,702
Cowpea (fresh)	1,761	Sainfoin (hay)	161,825
Cowpea (seed)	1,152	Sainfoin (seed)	310
Faba bean (fresh)	4,505	Soybean (grain)	38,009
Faba bean (grain)	2,581	Vetch (hay)	342,176
Fenugreek (seed)	890	Vetch (seed)	28,772
Grass pea (green)	6,699	Total	2,267,784

fixed per hectare for each species from previous studies was used. In Türkiye, the average amount of N fixed per hectare was multiplied by the area cultivated per legume species. As a result of the calculation, a total of 363,254 tons of N will be synthesized by BNF in 2022 on legume cropped areas in Türkiye (Table 4). The total amount of N obtained from legume crops grown in Türkiye was calculated as the equivalent amount of AS fertilizer containing 21% N. According to the calculation, the equivalent amount of fixed N to 21%N AS fertilizer is 1,730,259 tons (Table 4). The total GHG emission equivalents of these 1,730,259 tons of AS fertilizer during the production, transportation, field application stages and the total GHG emission equivalents of these stages were calculated as 1,020,853 tons CO_2–eq, 68,397 tons CO_2–eq, 1,541,794 tons CO_2–eq and 2,631,043 tons CO_2–eq, respectively. In other words, areas where legume crops are grown mitigate an average of 1,160 kg CO_2–eq GHG emissions per hectare per year thanks to the N fixed by BNF. Turkish's agriculture sector GHG emissions are 72.1 Mt CO_2–eq in 2021 [44]. Thanks to legume cultivation in Türkiye, GHG emissions from the agricultural sector have been reduced by about 3.65% (2.63 Mt CO_2–eq).

The results obtained from this study are an estimate. Türkiye has different climatic zones. Depending on the climate, the yields of legume crops and the amount of N they fix vary. Again, there are significant differences in the yield and the amount of N fixed depending on the legume production technique. In this study, these differences were not taken into consideration. To take these differences into account, it is necessary to determine the amount of N fixed separately for all legume crops grown in each region and cultivation techniques. Some researchers have used more general estimates to calculate the amount of N fixed. [45] estimated biological N fixation as a function of land use, i.e. 25 kg ha^{-1} $year^{-1}$ for grassland, 15 kg ha^{-1} $year^{-1}$ for arable land and 8 kg ha^{-1} $year^{-1}$ for maize land. The estimate for maize is an average value for the fixation by free living N fixing bacteria in all land use types. Some researchers have used the percentage of N derived from the atmosphere (%NDFA) for legume species determined by different researchers to calculate the amount of N fixed by BNF [46]. In our study, the amount of N fixed per hectare was calculated based on legume species, using empirical test results of different researchers.

BNF reduces GHG emissions by saving N fertilizer, which is the main source of GHGs in agriculture [47]. One of the researchers, [48] indicates that legume crops and legume-based pastures use 35% to 60% less fossil energy than N-fertilized grains or pastures, and that when legumes are included in alternating cropping, average annual energy use in a rotation is reduced by 12% to 34%. Compared to chemical fertilizers, BNF is less expensive and has a lower carbon footprint [49]. Among the researchers on this issue, [20] found that the CFP varied between 18-03 kg CO_2-eq ha^{-1} $year^{-1}$ in different crops according to all farm and crop types and was estimated to be 351.7 kg CO_2-eq ha^{-1} $year^{-1}$ on average, and that the CFP of legume crops was lower than that of cereal crops.

The amount of N_2 fixed from the rhizobia-legume symbiosis is highly variable and depends on many factors [50]. According to [23], some of the recommended measures can be implemented. These

Table 3. Estimation of the amount of N fixed by BNF and the equivalent GHG emissions in the cultivated land of Türkiye in 2022.

Legume crop	Cultivation area 2022 (ha)	Average crop N fixed (kg ha^{-1} $year^{-1}$)	Total crop N fixed (tons)	21% N containing fertilizer equivalent (tons)	GHG emissions tons CO_2–eq			
					At plant gate	Trans-port.	Field emissions	Total
Alfalfa (hay)	643,593	290	186,642	888,771	524,375	35,133	791,963	1,351,471
Alfalfa (seed)	3,422	290	992	4,726	2,788	187	4,211	7,187
Bean (grain)	97,052	55	5,338	25,418	14,997	1,005	22,650	38,651
Beans (fresh)	38,719	55	2,130	10,141	5,983	401	9,036	15,420
Bitter vetch (hay)	2,043	110	225	1,070	631	42	954	1,627
Bitter vetch (seed)	1,448	110	159	758	447	30	676	1,153
Chickpea (grain)	456,834	87	39,516	188,172	111,022	7,438	16,7676	286,136
Clovers (hay)	7	157	1	5	3	0	5	8
Cowpea (fresh)	1,761	214	376	1,790	1,056	71	1,595	2,722
Cowpea (seed)	1,152	214	246	1,171	691	46	1,044	1,781
Faba bean (fresh)	4,505	217	977	4,653	2,745	184	4146	7,075
Faba bean (grain)	2,581	217	560	2,665	1,573	105	2,375	4,053
Fenugreek (seed)	890	104	93	441	260	17	393	670
Grass pea (hay)	6,699	125	837	3,988	2,353	158	3,553	6,064
Grass pea (seed)	1,615	125	202	961	567	38	856	1,461
Kidney bean (fresh)	6,826	55	375	1,788	1,055	71	1,593	2,718
Lentil (green seed)	42,825	74	3,186	15,172	8,952	600	13,520	23,071
Lentil (red seed)	299,812	74	22,306	106,219	62,669	4,199	94,649	161,517
Pea (fresh)	12,433	86	1,073	5,109	3,015	202	4,553	7,769
Pea (hay)	25,887	86	2,234	10,638	6277	421	9,479	16,177
Pea (seed)	887	86	77	365	215	14	325	554
Peanut (groundnuts)	45,702	158	7,203	34,298	20,236	1,356	30,562	52,154
Sainfoin (hay)	161,825	248	40,084	190,876	112,617	7,545	170,086	290,248
Sainfoin (seed)	310	248	77	365	215	14	325	555
Soybean (grain)	38,009	143	5,416	25,792	15,217	1,020	22,982	39,219
Vetch (hay)	342,176	116	39,692	189,012	111,517	7,472	168,424	287,412
Vetch (seed)	28,772	116	3,338	15,893	9,377	628	14,162	24,167
Total	2,267,784	-	363,354	1,730,259	1,020,853	68,397	1,541,794	2,631,043

are: increasing the yield of legumes and making their cultivation more profitable; increasing the resistance of legumes to adverse conditions such as salinity, drought, high and low temperatures, diseases and pests; making preplant bacterial inoculation standard practice; liming low pH soils; development of more N-fixing legume varieties and rhizobium strains; production and commercialization of rhizobium bacterial inoculants for each cultivated legume species; demonstration studies to explain the benefits of rhizobium bacterial inoculation to growers. With these applications in legume crops, the amount of fixed N per unit area will increase and a positive contribution will be made by reducing the equivalent greenhouse gas emissions. Among the researchers on this subject, [51] found that the substitution of conventional technology by inoculation technology in fava bean resulted in an average reduction in environmental impact of 19% per ha and 21% per ton; in pigeon pea, the average reduction was 12% per ha and 32% per ton. Similarly, [52] found that an in-situ abatement of 70% of soil N_2O emission using the strain nosZ+ G49 vs. nosZ− USDA138 in association with soybean. The development of elite rhizobacterial strains is necessary to maximize legume-specific symbiotic outcomes [51]. [53] state that the inoculation of rhizobia strains on leguminous crops is a promising area for mitigating N_2O emission by cultivated soils and that further research are required to best evaluate quantitative benefits.

Initially, easy access to synthetic N fertilizer and its direct impact on yield over-shadowed the importance of BNF. However, global warming, whose effects have been felt so strongly in recent years, has reminded us of the importance of BNF for the environment and sustainable agriculture. In this study, it was revealed that the high amount of N fixed by BNF in legume cultivation areas, the greenhouse gas emission equivalent of the fixed N is very important, cultural measures that can be taken to increase the amount of N fixed per unit area, increasing legume cultivation areas and breeding rhizobium bacterial strain and the attention of policy makers should be drawn to increase the amount of N fixed by BNF.

Conclusions

The production of N fertilizer requires a lot of fossil fuels. It is therefore costly, both economically and environmentally, to produce N fertilizer industrially. We need to find different ways to minimize the need for industrially produced N fertilizers. Thanks to the rhizobium bacteria found in the roots of legumes, they require little or no N fertilizer. This saves a significant amount of N fertilizer. In the study, based on current 2022 data, it was aimed to make the most accurate estimation possible of the amount of N fixed by BNF in legumes grown in Türkiye's cultivated areas and the amount of GHG emissions equivalent to this N amount, by using appropriate approaches, new assumptions, and coefficients developed by other researchers. Thanks to legume cultivation in Türkiye, the greenhouse gas emissions of the agricultural sector have been reduced by about 3.65% (2.63 Mt CO^2-eq). The values obtained in the calculations are only a rough estimate. The yield of legumes and the amount of N they fix vary greatly depending on the region and agricultural practices. Further studies are needed to calculate the amount of N fixed by BNF in legume crops for each region and agricultural practice. However, it is a fact that we need to give more importance to legume crops for economically and environmentally sustainable agriculture.

Conflict of Interest

The author declares no conflict of interest.

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