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Review of Literature

Drought is a natural phenomenon in the global weather system. However, climate change induced erratic rainfall pattern and extreme weather events resulted in alteration in hydrological processes, increasing their frequency and intensity. One of the major impact of drought can be seen in the agricultural sector where many studies are reported over the years revealed deleterious impact of drought in the crops by hampering plant turgidity, nutrient uptake, leaf gas exchange, and carbon assimilation, etc. [1]. Processes governing soil nutrient availability to plants such as physical diffusion, chemical form transformation, and ecosystem functions are significantly hampered by drought. It significantly impairs not only plant processes but also ecosystem processes carried out by microorganisms, such as the structure and conversion of soil organic matter, nutrient biogeochemical cycles, and greenhouse gas emissions.

N and P nutrition under water stress in legumes

Drought can directly affect plant nutrient availability by limiting its uptake or indirectly affect soil nutrient supply by inhibiting the majority of nutrient cycling processes. Nitrogen is an essential macronutrient required for crop growth and productivity. As a vital complement of chlorophyll, enzymes, proteins, etc., it is required in larger quantities to the plant system as compared to other nutrients. According to Jones et al. [2], plants can directly absorb NH_4^+-N, NO_3-N, and low molecular weight organic N from soils. These nutrients are then assimilated and converted into proteins for use in the development of plant tissues. The soil nitrogen uptake in plants is mostly in the form of NO_3^- or NH_4^+. Nitrogen is one of the most abundant elements on earth, however only a small portion is directly available to the plants. Hofman et al. (2004)[3] reported that the normal range of total N content in surface mineral soils (in the plough layer) as 0.05% to 0.2%, or roughly 1750 to 7000 kg N ha^{-1}. The remaining organic nitrate gradually becomes accessible to plants through mineralization. Booth et al. (2005), and Schimel and Bennett, (2004)[4,5] documented that microbial processing primarily regulates the amount of nitrogen (N) in soils through the fixation of atmospheric N, the breakdown of organic N sources, and the uptake and release of ammonium (NH_4^+) and nitrate (NO_3-) during the mineralization and nitrification processes.

Minucci et al. (2017)[6] and Tenhunen et al. (1990)[7] reported that seasonal droughts and water restrictions have an impact on various processes, including vegetation structure, ecosystem functioning, and plant physiology. In faba bean cultivation, Katerji et al. in 2011[8] delineated that the symbiotic N fixation affected more by exposure to drought as compared to salinity. In a study with soya beans (*Glycin max* Merr.), Fenta et al. (2012)[9] reported that water withholding at trifoliate stage, significantly reduce symbiotic nitrogen fixation along with photosynthesis, nodule biomass and nodule number. Neugschwandter et al in 2015[10] demonstrated that grain N yield and impaired N fixation occurred under drought stress in faba beans (*Vicia faba*). Polania et al. in 2016[11] studied the quantification of symbiotic N fixation under drought in 36 common bean genotypes using ^{15}N nitrogen derived from atmosphere (%Ndfa) method. They observed significant reduction in plant symbiotic N fixation under drought. In the subsequent year, Polania et al. (2017)[12] observed the symbiotic N fixation in common beans and found that it was positively related to the mean root diameter when exposure to drought. Parvin et al. (2019)[13] documented that even under elevated CO_2, N_2 fixation and seed N content was significantly reduced in faba beans (*Vicia faba* L.) when exposed to drought, which otherwise improved N fixation of the crop in earlier stage. Similarly, when berseem clover (*Trifolium alexandrinum*) were subjected to water deficit stress, Saia et al., (2014)[14] observed a sharp decline in N content and N fixation of the crop. Kunrath et al., (2018)[15] studied perennial forage species and observed that water scarcity lowers crop N status, regardless of the crop's primary source of N (mineral N or N_2 fixation). He also noted that a decrease in transpiration efficiency caused by a water shortage is inversely proportional to a decrease in crop N status.

Dovrat (2015)[16] reported that water scarcity creates a stark trade-off between a plant's resources allocated to fixation maintenance, drought tolerance and survival (such as a deep root system, root:shoot partitioning, and leaf traits). Gonzalez-Dugo et al. (2005)[17] documented that even in the presence of mineral N in the soil, drought conditions automatically reduces the amount of nitrogen that crops can absorb. According to Khasanova et al. (2013)[18], drought reduced plant growth and physiological function, which had a negative effect on plant N resorption proficiency and efficiency. The study also revealed that over the course of the growing season, this impact on resorption arose. Lambers et al. (2008) [19] observed that N uptake by roots may be constrained due to decreased N supply from mass flow, diffusion under drought, and root N interception because of slower root elongation rates. However, a connection between N intake and the ability to withstand drought exist with more external N supply that enhance the physiological status and growth under water limitation[20,21].

Since nitrogen (N), an essential nutrient element, is the most frequently limiting nutrient for growth of plants, maintenance, and reproduction in terrestrial ecosystems, nitrogen cycling is at the center of ecosystem functioning[22]. Ammonium (NH_4) is converted during nitrification into nitrite (NO_2^-) and nitrate (NO_3^-), with the release of N_2O as a byproduct. NO_3^- is sequentially reduced to N_2O and N_2 during denitrification. Denitrification is dependent on O_2 and the availability of NO_3^- and organic substrates, while nitrification is directly influenced by the availability of NH_4 and O_2. N mineralization and immobilization rates, plant N uptake, and factors affecting soil diffusion rates like structure, temperature, aggregation, and cation exchange capacity are all factors that affect nitrification and denitrification at a more distal level. These processes also control the availability of mineral N. In the terrestrial N cycle, nitrification is a crucial process. Prosser et al. (2012)[23] reported that the first step being the oxidation of ammonia to NO_2 by ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA), and the second being the oxidation of NO_2 to NO_3^- by nitrite-oxidizing bacteria. Kuypers et al. (2018)[24] documented plants take up N in the form of NO_3^- and NH_4^+ and *Rhizobium* spp., a specific type of symbiotic N-fixing bacteria are found in legume crops. They interact mutualistically with the roots of the legume crop, transforming atmospheric N into a form of N that is readily available by inducing the expansion of root cells to form nodules. According to Wang et al. (2019)[25] the rhizosphere can be significantly acidified by legumes, which have a greater capacity for proton release than cereals. This helps to activate and absorb soil insoluble phosphorus, as well as to provide the adenosine triphosphate (ATP) needed for legumes to fix nitrogen and maintain a stable nitrogen and phosphorus stoichiometric relationship[25]. Francisquini et al. (2020)[26] documented that legumes can substitute for nitrogen application in situations where there is low phosphate capacity and no external nitrogen application[26]. Kumar et al. (2020)[27] reported that depending on the species of legumes, their variety, crop duration, climatic conditions, soil type, agronomic interventions, etc., a significant variation in the total amount of N fixed by this bacterial-legume symbiosis can be observed.

Likwise, P is another macronutrient which plays a vital role in growth, development and overall functioning of the plant system. Rouphael et al., (2012)[28] observed that reduced P uptake, transport, and redistribution can inhibit plant growth under drought as numerous significant energy transfer and photosynthetic oxidation-reduction reactions involve phosphorus[29]. Additionally, phosphorus is a component of a wide variety of biochemical components such as nucleic acids, structural proteins, enzymes, and signal transductions[30,31]. P is frequently unavailable to plants due to its strong binding in insoluble forms[32,33]. According to the studies by Cramer et al. (2009)[34] and Sardans and Peuelas, (2012)[35], plants reduce P uptake as soil moisture decreases.

Egamberdieva et al. [37] documented 6% reduction in phosphate uptake by lupin (*Lupinus angustifolius* L.) when exposed to drought. Impaired P uptake and accumulation was also reported by Hao et al. (2019)[38] when the *Glycyrrhiza uralensis* Fisch. seedlings were exposed to water deficit stress. Jin et al. (2015)[39] documented increased P concentration by 16% and 7% in shoots and roots respectively under drought. However, it reduced total P uptake by 17% when compared to well-watered field pea plants. Bista et al. (2018)[40] documented drought-related decrease in nutrient concentration, particularly %P. This was most likely caused by decrease in the concentration of root nutrient-uptake proteins in both drought sensitive (*Hordeum vulgare*, *Zea mays*) and tolerant species (*Andropogon gerardii*). Meisser et al. (2019)[41] reported that soil moisture and time of drought appearance had a significant effect on soil P, microbial P, and plant P uptake.

Belnap, (2011)[42] reported the sensitivity of P desorption and dissolution from inorganic source to soil moisture. In order to combat P deficiency, plants have developed a variety of strategies such as increased organic acid efflux, modified root architecture, and increased acid phosphatase activity. All of these mechanisms help plants to undergo P-deficient conditions and increase their P intake[31,43–45]. Though a plethora of studies have been done to study the P uptake in plants under water stressed conditions, in-depth studies of the form and transformation of fractions under limited water availability are still scarce.

Walker and Syers, (1976)[46] and Tiessen et al., (1984)[47] reported the natural entry of P through weathering of major sources of P i.e. the phosphorus-bearing minerals. Once released into the soil, P is changed by intricate geochemical and biological processes into a variety of coexisting inorganic and organic forms. According to Hansen et al. (2004)[48] inorganic P (*Pi*) and organic P (*Po*) are two chemical forms of soil phosphorus and they behave differently in soil where inorganic P (*Pi*) typically makes up 35% to 70% of the total soil P. The release of available P from primary P minerals like apatites, strengite, and variscite by weathering is typically too slow to meet the crop demand. Therefore, direct application of phosphate rocks (i.e., apatites) has shown to be relatively effective for crop growth in acidic soils. Contrarily, the dissolution rates of secondary P minerals, such as calcium (Ca), iron (Fe), and aluminium (Al) phosphate depend on the size of the mineral particles[49].

Plant roots absorb P as either $H_2PO_4^-$ or HPO_4^{2-} under neutral to alkaline environments (pH 6.0-7.0). Geelhoed et al. (1999)[50] reported that P can rapidly diminish in the rhizosphere by root uptake because of its low solubility and mobility in soil. This causes a gradient of P content in a radial direction away from the root surface. Merbach et al. (2009)[56] reported that soil contain a high concentration of total P, which are highly stable and poorly soluble, rendering them unavailable to plants. Shen et al. (2011)[51] also documented that lower P mobility under drought limits plants' access to it despite presence of higher total P content in soil. Fearnside (1998)[52] and Richardson (2001)[53], observed aluminum and iron-free oxide and hydroxides form complexes with Fe and Al. This formation of the complexes is a result of increased concentration of Fe and Al in soil solution due to pH decline. A study by Fankem et al. (2006)[54] documented that soil acidity initiates and speeds up P fixation and immobilisation. Fearnside (1998)[52], Richardson, (2001)[53] and Bashan et al. (2012)[55] documented that in acidic soil, phosphate is primarily present as variscite and strengite. However, higher solubility of vivianite leads to its deposition at lower soil profiles. Mitran and Mani (2017)[57] documented that primary P minerals (apatite) and secondary clay minerals, such as calcium (Ca), iron (Fe), and aluminium (Al), are the native sources of phosphorus (P) in soil. These minerals also play a key role in maintaining the accumulation of available P in soil through the dissolution and desorption processes. Mineralization of organic matter (OM) to inorganic forms of phosphate with the help of soil bacteria helps plants to access organic forms of phosphate.

Effect of soil amendment on N and P nutrition

A plethora of work has been done to study the N and P relations under manual fertilizer applications in crop fields. Studies by Rosenstock et al. (2013)[59] revealed that to increase plant nutrition and produce higher yields N fertilizers (up to 400 kg N/ha/year) have been added to soils all over the world. Associated soil damage from the prolonged use of inorganic fertilizers damage soil apart from polluting the environment. Therefore, use of organic amendments is becoming an integral part for soil nutrient management in sustainable crop production. For instance, Biau et al. (2012)[60] demonstrated that sole use of mineral fertilizer over a 10-year period resulted in higher soil residual nitrate content with associated risk of leaching. Numerous studies conducted under drought have confirmed that soil-conditioning tools like biochar enhance soil qualities by enhancing soil characteristics related to water in various crops and are beneficial for plant nitrogen uptake.

Ma et al. (1999)[61] reported that applications of stockpiled and rotted dairy manure (50 and 100 Mg ha^{-1}) resulted in increasing total amount of nitrogen absorption by maize crop that was comparable to treatment 200 kg N ha^{-1}. Helgason et al. (2007)[62] in a study with *Brassica napus* L. documented that when compared to the control, the addition of compost increased N uptake by 27–99%. The study also delineated the amount of nitrogen that plants were able to absorb from compost was directly correlated to its inorganic N content ($r^2 = 0.98$; P 0.0001). In a study with barley crops, Miller et al. (2009)[63] reported that fresh manure and composted manure were applied annually for nine years at three different rates (13, 39, and 77 Mg/ha dry wt.), and obtained comparable results with those of inorganic fertilizer in terms of aboveground dry matter yield, total N and total P uptake. In a study by Weber et al. (2014)[64], it was reported that the yields produced by spring triticale (18, 36, and 72 t/ha dry mass) under the application of composts from two different municipal solid wastes were comparable to those of plots fertilised with mineral NPK. Huang et al. (2018)[65] reported that the impact of biochar on fertilizer N uptake was not significant in three of the first four seasons of a study carried out for six consecutive seasons with biochar application at a rate of 20 t/ha. The application of biochar led to increased (14–26%) soil N uptake in the fifth and sixth seasons.

Ahmad et al. (2021)[66] observed increased soil available N under the application of soil amendments such as poultry manure, farmyard manure and biochar when cotton crops exposed to drought. Hafez et al. (2021)[67] reported enhanced accumulation of N and

P in wheat crop when soil were amended with vermicompost and biochar under drought. Bayu et al. (2006)[68] reported an increase in soil total N in sorghum cultivated soils when amended with FYM under drought. Ample studies have looked into how soil microbial communities react to the application of N fertilizer, however, the findings were inconsistent and varies on the type of ecosystem[69–71]. Wang et al. 2011; Zhou et al. 2014 [72,73] documented that the addition of N fertilizer frequently increases the rates of nitrification and denitrification. The transformation of soil N fractions under application of soil amendment under drought is still rare, despite the abundance of reports regarding the effects of various soil amendments on the N status of soil and plants in crops.

As an essential mineral nutrient, phosphorus (P) is needed in relatively high concentrations to maintain growth and is crucial for energy transfer and storage during cell metabolism[74]. Lack of phosphorus affects root development, plant establishment, and seedling vigour. P is also a reasonably mobile element in plants[75]. Snapp and Lynch (1996)[76] and Fujita et al. (2003)[77] reported that P deficiency alters the way that P is distributed among different parts of the tomato (*Lycopersicon esculentum* L.) and bean (*Phaseolus vulgaris* L.) with higher translocation towards the reproductive parts at the expense of the P contents of the vegetative parts.

Waldrip et al. (2011)[78] documented higher content of root P (37%) and total P uptake (59%) compared to control in cultivation of ryegrass (*Lolium perenne*) when poultry manure was applied at a rate of 42.6 Mg manure/ha. According to Bah et al. (2007)[79], green manure alone or in combination with P fertilizers contributed less than 5% to the total P in soil. However, total P uptake by Setaria plants under application of green manure treatments was three to four times higher than that of the inorganic P fertilizers, as the green manure mobilised more soil P. Sikora and Enkiri (2005)[80] observed when plant available P was amended with poultry litter compost (PLC) at the rates of 0, 25, 50, 100, and 150 kg P/ha in Codorus silt loam soil, it provided the same amount of fertilizer equivalents as triple superphosphate (TSP). Peirce et al. (2013)[81] in his study using fast-growing wheat (*Triticum aestivum* cv. Axe) under addition of fresh manure documented largest labile P pool, manure P uptake, and manure P recovery. However, use of manure that was stockpiled for 12 months produced the lowest manure P uptake and manure P recovery. According to Ramphisa et al. (2019)[82], when composted chicken manure, anaerobically digested dairy manure (organic amendments), and mono ammonium phosphate (inorganic fertilizer) were applied at rates of 10, 20, 30, and 40 kg

P/ha, plant P concentrations in the plots receiving organic amendments were at par to the inorganic fertilizer. According to studies by Paredes et al. (2022)[83], addition of combined cattle manure and lemon peel led to a significant increase in phosphorus uptake (43% and 44%, respectively) and yield of ryegrass compared to treatments using synthetic supertriple phosphate fertilizer.

Jian Jin et al. (2007)[84] observed alleviation of drought stress in crops and enhancement of P uptake due to P fertilization in soya beans. Studies on spinach by Zemanová et al. (2017)[85] and chickpeas by Hashem et al. (2019)[86], delineated high phosphorus uptake, transport, and accumulation in plant parts due to use of biochar as soil amendment. Ding et al. (2020)[87] reported an enhancement in P fractions as a result of organic fertilization (farmyard manure and sewage sludge) in wheat crops under exposure to water deficit conditions. However, no additional research has been done to ascertain the effect of P fertilizers on soil P fractionations at field scale, especially in arid and semi-arid ecosystems Ding et al. (2020)[87].

Soil biological properties and effect of drought

Transformation of nutrients from their organic forms in detritus (dead biomass) into less complex, soluble forms that can be reabsorbed by microbes and plants is a crucial step in any nutrient cycle. Microbes and other soil organisms perform this conversion by releasing or mineralizing nutrients as a by-product of their consumption of detritus. When the detritus contains enough N to fulfil the microbial requirement under that condition, any excess N released (mineralized) into the soil solution on consumption of C by the microbes. However, the reverse situation happens when detritus does not contain enough N to meet microbial needs. The additional N must be immobilized from the soil solution as C is consumed. It has been demonstrated that when decomposing low-quality substrates, microbes expend more energy on enzyme synthesis (e.g., amidases to acquire N and phosphatases to acquire P).

Microbial transformation of nitrogen are frequently represented as a cycle made up of six distinct processes that move along in a systematic way. The theory of the nitrogen cycle states that a molecule of dinitrogen gas is first fixed to ammonia before being assimilated into organic nitrogen (that is, biomass). According to Kuypers et al. (2018)[24] ammonification, the breakdown of organic nitrogen, releases a molecule of ammonia, which is then oxidised to nitrate through nitrification (NH_4^+ ->NO_2 -> NO_3) and ultimately converted back to a molecule of dinitrogen gas through denitrification (NO_3 -> NO_2 -> NO -> N_2O -> N_2) or anaerobic ammonium oxidation (anammox; NO_2 + NH_4). Though the process is overly simplified here, the actual reactions are much more complex and yet to be discovered up to some extent.

As a primary agent in the transformation and circulation of soil organic matter, soil microorganisms play important role in the nitrogen cycling of ecosystems. While bacteria are crucial to the underground decomposition of organic matter, fungi contribute more to the degradation of organic matter on the surface layers. Therefore, it is common practice to regard the numbers of bacteria, fungi, and actinomycete as key indicators of the levels of soil biological activity. Protein and its derivatives are broken down by numerous microbial species. Ammonification process can be accessed by the majority of soil bacteria, fungi, and actinomycete. The capacity for decomposition varies among different microorganisms. Thus, microbial abundance, composition, and purpose affect the decomposition of soil organic matter and influence the mineralization of organic nitrogen.

Sardans et al. in 2008 [88] documented that soil enzyme activities serve as indicators of soil microbial health and physicochemical conditions and act as sensors in soil fertility research. Song et al. (2012)[89] in a study with corn hybrids documented a reduced alkaline phosphatase activity when the drought was imposed at the grain filling stage. However, catalase activity was significantly enhanced under the same treatment. Bogati et al. (2022)[90] observed a reduction in oxidoreductases, hydrolases, dehydrogenase, catalase, urease, phosphatases, β-glucosidase under the exposure of drought. Baldrian et al., (2020)[91] reported that soils with low water content (0.30-0.40 g g1) significantly decrease soil microbial communities and reduce (more than 50%) activities of laccase, Mn-peroxidase, endo-1,4-β-glucanase, endo-1,4-β-xylanase, cellobiohydrolase, β-glucosidase, β-xylosidase, chitinase, and acid phosphatase compared to control samples with higher water content (0.60-0.70 g g1) in a hardwood forest soil. However, Hueso et al. (2012)[92] discovered that adding different types of organic matter to the arid soil, such as compost (COM), sewage sludge (SS), and municipal solid waste (MSW) increased the activities of soil enzymes such as oxidoreductases, hydrolases, dehydrogenase, catalase, urease, phosphatases, β-glucosidase, casein- and N-α-benzoyl-L-argininamide (BAA)-hydrolyzing proteases. Ahmed et al. (2018)[66] in a study with enzymatic and priming response to root mucilage under drought documented that maximum enzymatic activity (Vmax) of P and N-cycle enzymes was influenced by soil moisture. Lower soil moisture resulted decrease in the V_{max} of acid phosphatase and T-aminopeptidase in the control plots. However, Km (Michaelis-Menten constant) values at 80% WHC were found to be reduced under mucilage addition. Sanaullah et al. (2011) [93]documented increased soil enzyme activity under *L. perenne* cultivation (β-cellobiosidase, chitinase, and leucine amino peptidase) and *M. sativa* (β-cellobiosidase, leucine amino peptidase) cultivation when exposed to drought. Sardans and penulas (2005)[35] recorded that 21% moisture reduction in *Quercus ilex* L. forest decreased urease activity by 42–60%, protease activity by 35–45%, β-glucosidase activity by 35-83%, and acid phosphatase activity by 31-40%.

Impact of soil amendments on soil biological properties

Secure flow of water is necessary for microbial mobility in the soil environment and the extraction of nutrients[94]. As a result, it is anticipated that microorganisms will be more affected by changes in water content. Numerous studies have shown that climate extremes, such as drought, can have a significant impact on soil microbial communities, frequently with repercussions for ecosystem functions and plant community dynamics[95–97]. Additionally, Vries et al. (2013)[95], and Barnard et al. (2013)[98] demonstrated that different elements of the microbial community react to drought in various ways. Soil fungi typically more resilient to change in soil water status than bacteria.

Franco-Andreu et al. (2017)[99] reported that application of soil amendments viz. sheep manure (52.55 Mg ha^{-1}), cow manure (67.41 Mg ha^{-1}), and municipal solid waste (30 Mg ha^{-1}) showed higher dehydrogenase activity (71.3%, 60.9% and 38.6% respectively) and urease activity (60.6%, 51.5% and 37% correspondingly). According to Egamberdieva et al. (2019)[100], application of hydrothermal char significantly increased plant root and shoot biomass in chickpea cultivated soil over high temperature pyrolyzed char. It also increased soil alkaline and acid phosphomonoesterases, and soil proteases under drought conditions along with the uptake of soil nutrients such as N, P, K, and Mg.

Carlson et al. (2015)[101] observed that addition of bio-solids or composted vegetative yard waste to soils (202 Mg/ha or 403 Mg/ha, respectively) was the most efficient way to boost soil enzyme activities (viz. arylsulfatase, β-glucosaminidase, β-glucosidase, acid phosphatase, fluorescein diacetate, and urease). The bio-solids treatment also increased fungal biomass more than the other treatments and reduce microbial stress. In a study with sugarcane, Lopes et al. (2021)[102] found that applying biochar from eucalyptus residues up to 30 Mg/ha increased the activity of the enzymes such as ßglucosidase, acid phosphatase, arylsulfatase, urease, and the total microbial quality of the soil. However, higher doses decreased the activity of these enzymes and the total microbial quality of the soil over a longer period. Tejada et al. (2010)[103] reported that as compared to green forage (6 Mg/ha) amended soils, the soil microbial biomass C, dehydrogenase, urease, β-glucosidase, phosphatase, and arylsulfatase values were documented to be 28.3, 25.9%, 12.6%, 26%, 12%, and 14.2% (respectively) higher in cow dung (3 Mg/ha) amended soils. Tejada et al. (2010)[104] revealed that animal vermicompost amended soils had the largest hike in (86.4, 85.8, 94.5, 99.3, 70.1 and 63.8%, respectively) soil microbial biomass and enzyme activities compared to the control soil under maize (*Zea mays* cv. Tundra) cultivation. This is followed by the vegetal amended (84.8, 80.6, 92.7, 99.1, 68.3 and 61.6%, respectively) and cotton gin compost amended soils (80.5, 75.9, 89.7, 99, 65.7 and 59.9%, respectively). Differential response of the soil amendments have been clearly delineated by Albiach et al. (2000)[105] in a study with five different soil amendments viz. 24 t/ha/yr of MSW compost, sewage sludge, and bovine manure, 2.4 t/ha/yr of vermicompost, and 100 l/ha/yr using commercial humic acids solution on a horticultural soil. They studied various soil enzymes such as dehydrogenase, alkaline phosphomonoesterase, phosphodiesterase, arylsulphatase, and urease. The study revealed that application of MSW compost increased soil enzymatic activity the most, with lower but roughly equivalent results coming from bovine manure and sewage sludge.

Francioli et al. (2016)[106] in a study with organic amendments observed that in addition to stimulating microbial communities (*Firmicutes*, *Proteobacteria*, and *Zygomycota*) that are known to prefer nutrient-rich environments and are involved in the degradation of complex organic compounds, organic fertilisation increased bacterial diversity. Lazcano et al. (2012)[107] in a study with organic and inorganic fertilization observed that in comparison to inorganic fertilisation, the integrated fertilizer regimes promoted microbial growth, changed soil microbial community composition, and increased enzyme activity. While fungal growth only responded to the amount of fertilizer provided and the bacterial growth was particularly influenced by the type of fertilizer regime. Heikkinen et al. (2021)[108] reported that in an agricultural soil the treatment using composted pulp mill sludge had the most bacterial operational taxonomic units, but it differed significantly only from the treatments using clover roots, which had the least diversity. Organic modifications significantly altered the bacterial communities and accounted for 69% variation in the composition of bacterial operational taxonomic units.

Abubaker et al. (2013)[109] in an incubation study with biogas residue and cattle slurry as soil amendment reported that after 120 days of incubation, there were notable differences between the non-amended (control) and amended soils with regard to bacterial community composition particularly in sandy soil where cattle slurry caused a more noticeable shift than biogas residues. The findings of Li et al. (2015)[110] showed that, compared to controls, long-term fertilizer treatments significantly increased the structure of the soil bacterial community. Long-term inorganic fertilizer applications with organic amendments caused significantly enhanced soil bacterial structure compared to inorganic fertilizer applications alone. In a similar study by Gu et al. (2009)[111] with rice-wheat cultivations, showed that mixed applications of N, P, and K with supplemental farmyard manure as amendment improved soil microbial biomass, transformation of bacterial communities, and sustained crop production. Lin et al. (2019)[112] documented that organic fertilizers regulate the composition of microbial communities, controlling the variance in prokaryotic and fungus communities by 41% and 29%, respectively. The study also delineated that pig manure had greater impact than plant residues on SOM content, soil aggregation as well as microbial community structure.

Effect of drought on grain quality of the crops

Drought is one of the limiting factors of crop production that affects the quality of the produce and consequently the fulfilment of the nutritional demand of increasing global population becomes a challenge. Crops have to face frequent drought owing to erratic pattern of rainfall under changing climatic scenario [113]. Legumes are the major sources of protein to humans as they satisfy around 33% of dietary protein nitrogen [114]. Minerals like Fe, Zn, P, Ca, K and Mg along with vitamins and complex carbohydrates make them more important next to cereals. Moreover, persistent water limitations in the semi-arid areas of South Asia significantly affect the legume productivity [115] and deteriorates its grain quality.

In a study on durum wheat (*Triticum aestivum*), Houshmand et al. (2012)[116] found that significant increases in grain protein content, wet and dry gluten contents, and sodium dodecyl sulphate (SDS) sedimentation volume were all brought on by drought stress. Hu et al. (2012)[117] found that drought stress during the reproductive stages of the soybean crop decreases carbon dioxide exchange rate (CER), photosynthesis, sugar production, and flow of metabolites to the expanding cells, increasing flower and pod abortion and reducing vegetative growth, duration of the seed filling stage, seed number, and seed size. Lu et al. (2014)[118] observed deleterious effect of drought on fresh waxy maize crops where the effects of drought on grain springiness, paste and gelatinization temperatures, trough, final, and setback viscosities, as well as gelatinization enthalpy, were minimal. The study also revealed that drought increased hardness while decreasing peak viscosity, breakdown viscosity, and adhesiveness (absolute value). In a study with sorghum crops, Yi et al. (2014)[119] found that drought stress during the flowering stage of sorghum crops, the total starch, amylase, and amylopectin concentration all lessened at the mid-late stage of grain filling. The study also documented differential impact of drought on starch branching enzyme (SBE), starch debranching enzyme (DBE), soluble starch synthase (SSS), and granule-bound starch synthase (GBSS) activities. Dawood et al. (2014)[120] in a study with *Brassica napus* observed that drought stress reduced seed yield/plant, oil and carbohydrate, total phenolic content, tannins, flavonoids, and antioxidant activity while significantly increasing the protein content of the seeds produced at 75% and 50% field capacity. According to Nam et al. (2014)[121], drought treatment had a significant impact on the amounts of some grain nutritional components in both transgenic and wild type of rice crops. In particular, the levels of grain copper and lignoceric acid decreased by 12.6% and 39.5%, respectively in wild type rice.

According to Nakagawa et al. (2018)[122], the contents of lipid and protein in soybean seed at 24 and 29 days after treatment were noticeably lower than control levels when drought stress was present during the grain filling stage of the crop. However, the same treatment increased the amount of soluble sugar in seeds. Alghabari et al. (2018)[123] reported uneven grain size caused by drought stress in barley (*Hordeum vulgare* L.) led to a lower grain yield (42%), especially at 30% field capacity. In a study with cottonseed, Li et al. (2022)[124] found that drought significantly increased protein concentration while significantly decreasing oil concentration (%/dry weight). Under extreme drought, concentrations of both total essential amino acids (EAA) and total unsaturated fatty acids (UFA) decreased significantly. The study also showed a decline in the ratio of polyunsaturated to saturated fatty acids (PUFA/SFA), health-promoting index (HPI), unsaturation index (UI) with the increased atherogenicity index (AI) under drought stress. They also noted less than optimal amount of unsaturated fatty acids in the oil due to drought exposure.

Effect of soil amendment on grain quality of the crops

In a study with wheat and rapeseed crops, Sharma et al. (2011)[125] found that after applying chicken manure and sugar cane press mud, the quality of wheat grains significantly improved in terms of total soluble sugars, reducing sugars, starch, lipids, and sulphur content. According to Ewais et al. (2015)[126], different compost treatments combined with inorganic fertilizers significantly increased maize plant height, ear characteristics (length, diameter, and weight), grain yield/fed, and grain quality and nutrition when compared to control and compost alone.

In combination with nitrogen fertilizer, Wang et al. (2012)[127] found that adding biochar increased grain yield and production of rice and wheat by 12% and 17%, respectively. Hu and Qi (2013)[128] in an eleven years study with wheat reported that in comparison to untreated soil, soils with effective microorganism compost showed significantly higher biomass, grain yields, straw, and grain nutrition. According to Liu et al. (2016)[129], application of rice straw biochar at a rate of 4.5 t/ha led to increase in grain yield (8.5–10.7%) of rice crops compared to the control, which may be attributed to better nutrient availability (mainly P and K). In a study with *Eragrostis abyssinica* Zucc. and *Triticum aestivum* L., Dessalew et al. (2017)[130] found that application of brewery spent diatomite sludge led to two times higher grain yields than the control and 50% increases over farmyard manure. Agegnehu et al. (2016)[131] reported that interaction of organic amendment and N fertilizer significantly affected the grain yield of barley crops at two cultivation sites in the central Ethiopian highlands. They documented highest grain yield (5381 kg/ha) at Holetta due to application of compost plus biochar and an addition of 69 kg inorganic Nitrogen per hectare, whereas the highest grain yield (4598 kg/ha) at Robgebeya was produced by compost and 92 kg inorganic Nitrogen per hectare. The use of compost in rice crops as investigated by Halim et al. (2018)[132], documented highest number of grains per panicle (121), filled grain percent (83.40%), weight of a thousand grains (23.30 g), and the harvest index (88.71%). Xiao et al. (2018)[133] observed that addition of biochar to a maize field at rates of 0, 10, 20, and 30 t/ha increased growth rates, cob biomass, grain yields, and the uptake of nitrogen, phosphorus, and potassium with the increased rate of soil amendment application. As per studies done in 2012 by Elrahmann et al. (2012)[134] application of 50% gypsum + 50% FYM as soil amendments significantly increased wheat plant productivity in terms of grain yield, weight of 1000 grains, and NPK concentration.

The findings of The et al. (2006)[135] delineated application of poultry manure to maize crops increased grain yield by 38% as compared to the application of senna leaves and was linked to increases in Ca, Mg, and P as well as a decrease in Al. According to an investigation by Banik and Nandi (2004)[136], rice straw supplemented with biogas residual slurry manure in a 1:1 ratio led to a significant increase in protein content with a decrease in carbohydrate content, and an increase in vital mineral nutrients in mushroom sporophores. Guibali (2016)[137] revealed that application of compost to wheat crops at a rate of 10 m/fed significantly increased wheat grain yield and grain protein and N, P, and K content. According to Lyson et al. (2015)[138], grain derived from organic amendment applied field had 27% lower crude protein levels than those derived from inorganic N application at the rate of 210 kg ha^{-1} ($p<0.05$). It was also found that adding organic amendments to winter wheat produced higher levels of total carbohydrates and crude fibre. In a study using aromatic rice, Sumon et al. (2018)[139] found that the maximum fat content (3.1%) and minimum carbohydrate content (76.53%) were obtained from using 60% of the NPKSZn + green manure at recommended doses (7 t ha^{-1}). Additionally, the highest moisture content (10.43%) and lowest protein content (8.26%) in rice grain were produced by applying 20 and 40% recommended doses of NPKSZn + green manure (14 and 10.5 t ha^{-1}). Addition of green manure (17.5 t ha^{-1}) produced the highest ash (1.79%), protein content (9.06%), and lowest fat content (2.51%) in grains. The findings of a study by Gao et al. (2020)[140] demonstrated that the application of a biofertilizer mixture, which included *Azotobacter chrocoocum*, AMF, and *Bacillus circulans*, along with liquid biogas slurry improved the amount of soluble sugars, starch, carbohydrates, protein, and amino acids in maize seeds. In a study with *Zea mays* L., Tabatabai et al. (2020)[141] found that the application of various organic fertilizers, such as fresh farmyard manure (20 t/ha), composted cattle manure (10 t/ha), and vermicompost (10 t/ha) resulted in the highest grain yields, oleic acid percentages, and linoleic acid percentages.

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