



Sustainable Intensification of Maize in the Industrial Revolution: Potential of Nitrifying Bacteria and Archaea

Oluwatobi Esther Ayiti[†] and Olubukola Oluranti Babalola^{*†}

Food Security and Safety Focus Area, Faculty of Natural and Agricultural Sciences, North-West University, Mmabatho, South Africa

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*Correspondence:

Olubukola Oluranti Babalola
olubukola.babalola@nwu.ac.za

†ORCID:

Olubukola Oluranti Babalola
orcid.org/0000-0003-4344-1909
Oluwatobi Esther Ayiti
orcid.org/0000-0002-6164-8965

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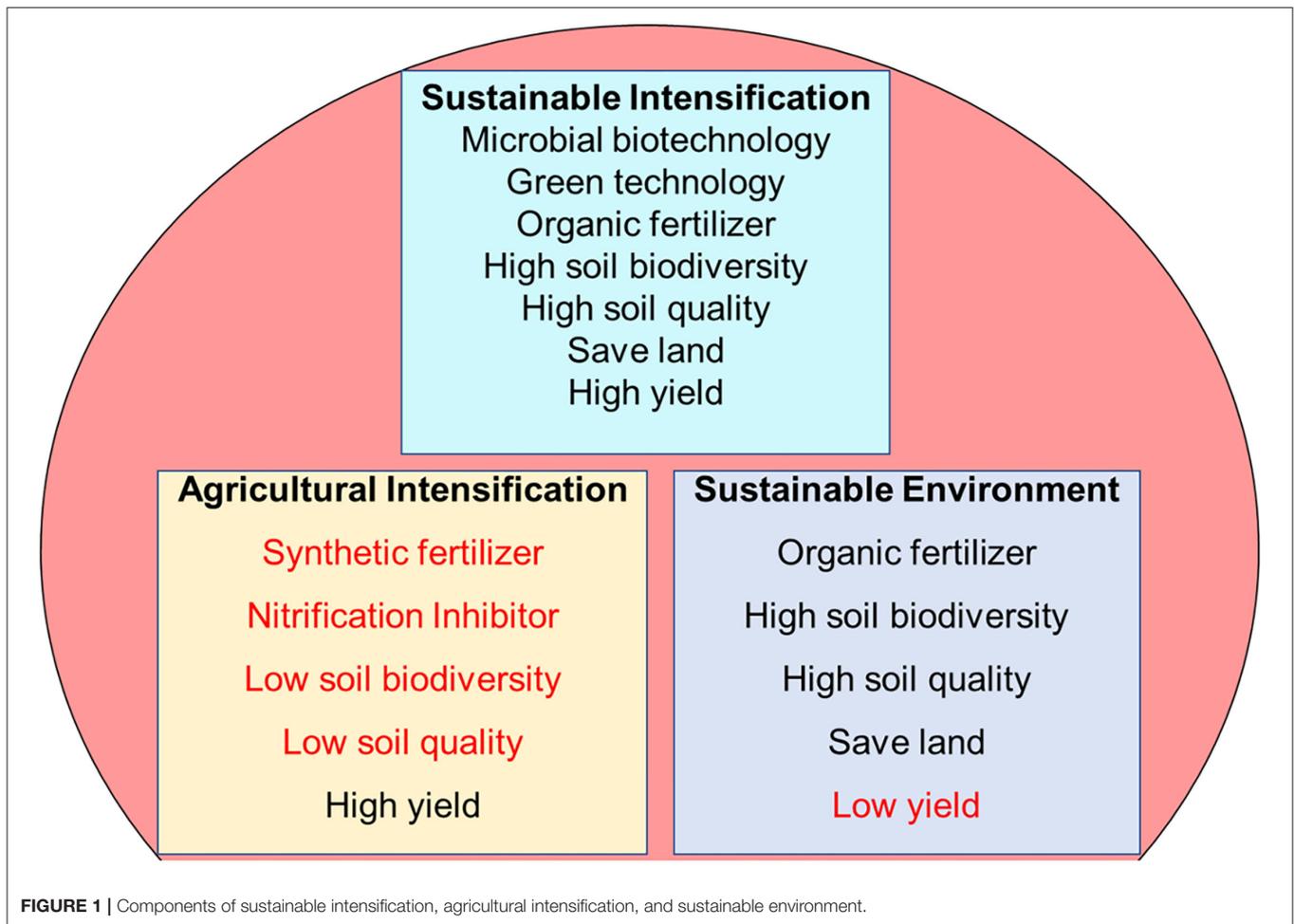
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Sustainable intensification is a means that proffer a solution to the increasing demand for food without degrading agricultural land. Maize is one of the most important crops in the industrial revolution era, there is a need for its sustainable intensification. This review discusses the role of maize in the industrial revolution, progress toward sustainable production, and the potential of nitrifying bacteria and archaea to achieve sustainable intensification. The era of the industrial revolution (IR) uses biotechnology which has proven to be the most environmentally friendly choice to improve crop yield and nutrients. Scientific research and the global economy have benefited from maize and maize products which are vast. Research on plant growth-promoting microorganisms is on the increase. One of the ways they carry out their function is by assisting in the cycling of geochemical, thus making nutrients available for plant growth. Nitrifying bacteria and archaea are the engineers of the nitrification process that produce nitrogen in forms accessible to plants. They have been identified in the rhizosphere of many crops, including maize, and have been used as biofertilizers. This study's findings could help in the development of microbial inoculum, which could be used to replace synthetic fertilizer and achieve sustainable intensification of maize production during the industrial revolution.

Keywords: biotechnology, food security, bacteria, archaea, sustainable agriculture

INTRODUCTION

An agroecosystem where yields are increased without an adverse effect on the environment and a need for additional non-agricultural land is referred to as sustainable intensification (SI) (Pretty and Bharucha, 2014). The focus on agricultural intensification to increase yield for the growing population has escalated environmental degradation (Armstrong Mckay et al., 2019). Furthermore, many agriculturists have yet to adopt environmental sustainability because the problem of low yields has not been addressed (**Figure 1**). Sustainable intensification can concurrently address environmental security and food security. This is because as agricultural production would be increased, environmental degradation would be reduced simultaneously without acquiring more land for farm use (Hunt et al., 2019). The components of SI (**Figure 1**) protect the process of an ecosystem and biological diversity while achieving an increase in food production. However, to achieve this aim, the development of suitable techniques for estimating both the



sustainability and intensification of agriculture is needed (Hunt et al., 2019). Therefore, studying the interaction of microorganisms and the ecosystem would help maximize their services to ensure a better ecosystem.

Industrial revolution (IR) connotes industrialization that began way back in the seventeenth century (More and More, 2002). The industrial revolution brought about the expansion of farm crop yield and goods produced from them. Over the years IR has improved drastically as a result of mechanical production, electricity, electronics, telecommunication, computers, cyber-physical systems, genetic engineering, green revolution, and the internet (Prisecaru, 2016; Vu and Le, 2019). This has affected the agricultural sector also because the innovation of technology is crucial to the renovation and cultivation of food. Food security is part of the challenges the industrial revolution intends to resolve (Prisecaru, 2016). Expectations have been raised regarding using new technologies to conserve resources and improve food nutrients. People are malnourished because nutrient requirements are not being met. Therefore, there is a need for further global green revolution if the world needs to be fed. The industrial revolution could contribute to the security

of food by improving crops by artificially adjusting important microbes associated with crops.

Maize is an important staple crop in the industrial revolution and is still in high demand worldwide, considering its importance as food, additives in industrial products, scientific research, and economy. The necessity to intensify its production sustainably is of paramount importance. Modifications in the nitrogen cycle have acutely disturbed the structuring and functioning of the natural ecosystem. The suitable range of nitrogen levels has been altered within the ecospheres and has posed a challenge to the issue of nitrogen maintenance (Xu et al., 2016). The increasing nitrogen level is partly caused by the input of nitrogen-based synthetic fertilizers. Consequently, to avert the challenge with the use of synthetic fertilizers, the inoculation of plant growth-promoting microbes wholly or together with manures would be critical in improving maize productivity for industrial revolution. Nitrifying bacteria with traits that promote plant growth have the potential of achieving sustainable intensification. This review discusses the role of maize in the industrial revolution, progress toward sustainable production, and the potential of nitrifying bacteria and archaea to achieve sustainable intensification.

SIGNIFICANCE OF MAIZE IN THE INDUSTRIAL REVOLUTION

Maize accounts for a significant amount of daily food in most developing regions. It is referred to as yellow gold because of its usefulness as food, animal feeds, and manufacturing processed food and non-food materials. Several studies have been carried out on maize because of its economic importance. Maize is one of the few crops that have attracted the attention of researchers in the area of genetic enhancement (Badu-Apraku and Fakorede, 2017). Aside from its importance, researchers choose to work with maize because it is suitable to cultivate and easy to collect data from Chen et al. (2015). Considering the foresight of industrial revolution, it is necessary to elaborate its role and point out how it can be cultivated in an environmentally friendly way.

Maize Products

The IR has caused an increase in agricultural products, both raw materials and industrialized. The processing of food rapidly has created sufficient time for human liberation, labor market participation and children care (Reardon et al., 2019). This has resulted in a reduced death rate and increased birth rate, causing a sharp increase in population, and placing high demand on resources. According to Dowswell et al. (2019), 20 million tons of maize is used for starch, 10 million tons are used for ethanol fuel production, 3 million for cereal and baked products, 0.7 million for cereal and hybrid seed sales. As a result of its reduced price as compared to other crops, maize has been used as feed formulae in animal rearing.

Maize is of high nutritional value and has been considered raw material for many industrial productions (Adiaha et al., 2016). This includes biomethane production, bioplastic, paper making, packaging and many additives. The agricultural sector substantially contributes to job creation and international marketing (Rekha and Singh, 2018). The effect of any technology in agriculture should be weighed against product output, profits, health, and environmental effect (Reardon et al., 2019). Over processed food has led to obesity, diabetes, and several health problems, hence the need to ensure the fortification of foods with sufficient nutrients (Reardon et al., 2019).

Economic Importance of Maize

Since the transcend of IR, global economic growth has been increasing. The production of maize ranks first in Latin America and Africa, while in Asia it is ranked third after rice and wheat (Dowswell et al., 2019). The demand and supply for maize globally for food and non-food products are usually on the increase. Yearly, 15 million metric tons (MMT) are used for animal feed, 4.25 MMT for industrial use, 1.36 MMT is used as food (Yadav et al., 2016). Considering its value for domestic, industrial and economic use (Adiaha et al., 2016), investing in the increase in maize production is an opportunity for any country. Maize is grown in 170 countries using 184 M ha of land with a production of about 1016 MMT (Food Agricultural Organization of the United Nations, 2017)). Various countries have benefited from the exportation and importation of maize.

In India maize has an annual production of 24.26 million metric tons (MMT) (Yadav et al., 2016). There was a rapid increase in the production of maize from 1950 to 1980, while 1983 marked a sharp decrease in maize production (Dowswell et al., 2019). It generates income for the government as it is used by countries as a commercialized product (Adiaha et al., 2016). Companies and individual entrepreneurs are collaborating with large-scale farmers to produce high-quality maize seeds. This helps mitigate their high demand and insufficient supply (Jonga et al., 2018). Seed quality determines crop yield and productivity. Jonga et al. (2018) advised that a quality management system should be put in place by the companies and entrepreneurs to ensure better products continuously.

Scientific Research on Maize

The role of maize in scientific research for the industrial revolution cannot be overemphasized (Table 1). Some upcoming scientists wonder why there is intensive research on maize when compared to other cereals. Aside from its importance as food and uses in industrial products, maize is easy to cultivate and manage, thus the results are observed easily and juxtaposed occasionally to other plants. Notable of its use in genetic studies, Jiao et al. (2017) referred to it as a model species for agricultural and genetic research. Maize plant has been used to check the quality of soil (Adiaha et al., 2016). The cob is useful in the treatment of waste. Okoya et al. (2015) reported the efficiency of maize cob in the removal of lead and chromium from waste.

Food Security

The quantity and quality of food have been threatened by unfavorable environmental conditions. To meet the needs of the high population, the quantity of food must be increased without jeopardizing the quality. In search of a solution, maize has been a choice crop by researchers (Adiaha et al., 2016; Otsuka and Muraoka, 2017). According to Abate et al. (2015), after considering factors that can be used to combat food security, maize was chosen as the best cereal to be cultivated in Ethiopia. He further explained that in terms of calorie intake, maize is the most important staple food. Otsuka and Muraoka (2017) acknowledged maize to be the most important cereal, considering its production and consumption. The development of the agricultural sector is necessary to reduce poverty and secure food. The need to secure food should be reinforced with green revolution that would drastically increase the yield of crops in a sustainable way. Therefore, maize which is easily cultivated and possess lots of nutrient has the potential to combat food insecurity globally. Maize cultivation has dropped the rate of poverty and improved the lives of local farmers, especially in developing countries Adiaha et al. (2016).

INDUSTRIAL REVOLUTION OF MAIZE

The agricultural sector, in general, has benefitted from industrial revolution using green and microbial biotechnology. Presently, green revolution has been anchored on genetically modified food and agrochemicals alongside several other inventions and technology (Llewellyn, 2018). Otsuka and Muraoka (2017)

TABLE 1 | Significant research findings related to the study of maize.

Scientific research on maize	Result	References
Agronomic assessment of a Controlled-Release Polymer-Coated Urea-Based Fertilizer in Maize	20% significant increase in maize yield compared to traditional fertilizer. Soil property was improved, and nitrogen loss was reduced	Gil-Ortiz et al., 2021
Evidence for phloem loading via the abaxial bundle sheath cells in maize leaves	The transfer of sucrose toward phloem was carried out by abaxial bundle sheath cell and it is subject to dorsoventral pattern	Bezruczyk et al., 2021
How to increase maize production without extra nitrogen input	Increasing the density of plant increase the yield of maize by 5.59% Greenhouse gas reduced	Hou et al., 2020
Early isotopic evidence for maize as a staple grain in the Americas	Maize consumption started 4,000 calendar years before present	Kennett et al., 2020
Comparison between organic and inorganic fertilizer	The cost of production using organic fertilizer is one fourth cheaper than inorganic Significant increase in broadness and number of leaves in the plants with organic fertilizer	Deba et al., 2019
The function of ZmUBP15, ZmUBP16, and ZmUBP17	Help plant tolerate cadmium and salt stress They are mostly found in the plasma membrane	Kong et al., 2019
The role of cytoplasmic diversification on plant agronomic productivity and trait	A significant influence on the yield component of plants as a result of interaction between cytoplasm, nucleus, and testers	Calugar et al., 2018
Determination on how cells and tissues rely on autophagy	The evident alteration was seen in plants missing the core autophagy component ATG12 Autophagy influences eukaryotic membrane under nutrient stress	Mcloughlin et al., 2018
Effect of climate change on maize cultivation	Yield loss majorly as a result of drought stress Elevated CO ₂ and heat had no effect on the crop	Webber et al., 2018
Assemble and annotation of maize genome using single molecule real-time sequencing and high-resolution optical mapping	Contig length was significantly increased and there was a deletion in the low gene density region	Jiao et al., 2017
Effect of heat and drought on rubisco activity which is associated with photosynthetic limitation	Rubisco activities was most affected at high temperature, but it was unrelated to the amount of rubisco activities The reduced rubisco affected CO ₂ assimilation rate Rubisco can be used to improve plant photosynthetic performance in warm climate	Perdomo et al., 2017
Molecular basis of carpel fusion in ovary development	Certain miRNAs influence incomplete carpel fusion which code for auxin response factor and growth regulating factor	Li et al., 2017
Cadmium stress tolerance of plant using dark septate endophyte	Cadmium phytotoxicity reduced significantly while maize growth increased This was done by triggering the antioxidant system, altering cadmium and partitioning the subcellular cadmium into the cell wall.	Wang et al., 2016

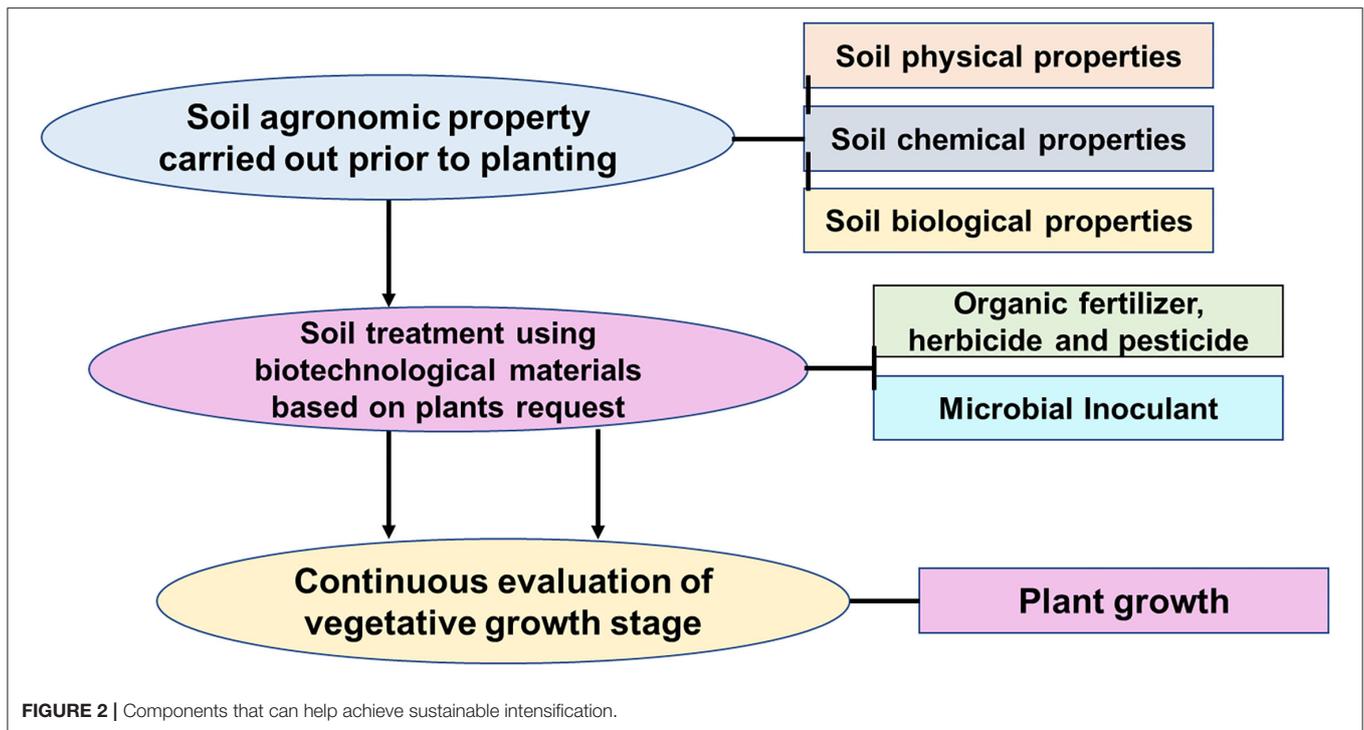
stated that the green revolution has helped resolve food crisis however, some countries are yet to meet the global standard of maize yield and attributed this to low soil quality. Also, food insecurity is rising, crop yields are lower than expected when compared to farmers' input, many crop plants are susceptible to disease and the environment is being depleted. An improvement in the present green revolution is necessary, this could be achieved by scientific and biotechnological research toward agricultural production.

The focus is now on sustainably feeding the growing population. Increasing land productivity is a crucial requirement in meeting the growing demand for food in every region. Implementing technology in agriculture can cause a global transformation. Brill (1981) suggested the possibility of getting a hybrid plant with foreign genetic material that would make it possible for the plant to efficiently use atmospheric nitrogen. The possibility of using recombinant DNA techniques in microbial breeding for agriculture is still at a primitive stage, while engineering of beneficial soil microorganisms associated with the specific crop is ongoing. The inoculation of bacteria into soil

has been seen to have a positive effect on plant growth (Ndeddy Aka and Babalola, 2016). The beneficial microorganisms can be cultured, grown in fermentation tanks and isolated for use. This can be taken practically to revolutionize industrial maize production.

ACHIEVING SUSTAINABLE INTENSIFICATION

In-depth knowledge of the dynamism of nitrogen would require research on the distribution, function, structure, and contribution of Bacteria and Archaea associated with its cycling process (He et al., 2012). Inoculation of microorganisms is a biotechnological environmentally safe alternative to increase crop production (Alori et al., 2017; Olanrewaju et al., 2017). The microorganism with the highest benefit could be useful for biotechnology breeding (Walters et al., 2018). Integration of microbes with organic material can also be considered Enebe and Babalola (2018). This would reduce the need for synthetic



fertilizer and achieve SI. A new system incorporating different components that can boost maize production can be put in place (Figure 2).

PLANT GROWTH PROMOTING MICROORGANISMS

Unavailability of nutrients, pest infestation, and drought are some of the challenges to plant growth. Some microorganisms referred to as plant growth promoters have been observed to have traits that could help combat these challenges. One of the ways to address these challenges is to assist in the cycling of geochemical making nutrients available for plant growth (Etesami and Adl, 2020). Inoculation of microorganisms is a biotechnological alternative to increase crop productivity, increase the availability of nutrients, reduce the use of synthetic fertilizer, and achieve SI (Table 2). *Bacillus subtilis* was reported by Zheng et al. (2018) to be able to influence the physical, chemical and hydrological characteristics of the rhizosphere, thus improving drought tolerance of plants in the long run. They ascribed this attribute of *Bacillus subtilis* to their production of extracellular polymeric substances. Using genomic information, Wang et al. (2018) ascertained the usefulness of *Streptomyces albireticul* and *Streptomyces alboflavus* as a biocontrol agent.

NITRIFYING BACTERIA AND ARCHAEA

Surprisingly, nitrifying bacteria and archaea (Table 3) have not been focused on as plant growth-promoting bacteria. Considering their importance in nitrate production and

oxidizing ammonia in soils and substrates, this calls for attention in scientific research. Aside from their major function of nitrification, they could have other plant growth-promoting traits. They can be classified into three distinct groups depending on the key enzymes possessed. The first group is the ammonia-oxidizing bacteria and archaea, second is the nitrite-oxidizing bacteria (Table 3) and the third is comammox bacteria (oxidation of ammonia to nitrate) (Stein and Klotz, 2016). Key enzymes used by these organisms are ammonia monooxygenase (AmoA), hydroxylamine oxidoreductase (HAO), and nitrite oxidoreductase (NXR) (Kuypers et al., 2018).

Based on nutrition, the nitrifying bacteria and archaea could be divided into heterotrophs and autotrophs (Liu et al., 2015). The heterotrophs depend on other organisms or dead organic matter for food while the autotrophs can synthesize their food. The autotrophs could further be divided into photoautotrophs (possess bacteriochlorophyll and use solar energy to produce food) and chemoautotrophs (using the oxidation of certain chemicals to produce food). Cellular respiration of nitrifying bacteria and archaea could either be aerobic (with oxygen) or anaerobic (without oxygen) (Muck et al., 2019). The group of organisms involved in anaerobic ammonium nitrification is known as anammox, they carry out nitrification in oxygen-depleted zones (Rich et al., 2018).

Nitrifying microbes include chemolithotrophic members, members of Betaproteobacteria, Gammaproteobacteria, and members of the Thaumarchaeota (Stein, 2019). The reactions occur under varying soil characteristics with some abiotic components contributing to it (Heil et al., 2016). Also, there are heterotrophic and methanotrophic bacteria that oxidize ammonium to nitrite efficiently (Stein and Klotz, 2016). High

TABLE 2 | Microorganism with plant growth-promoting traits that have been used on maize.

Microorganism inoculate used in maize	Type of experiment	Plant growth promoting trait	Result	References
<i>Aspergillus niger</i>	Field	Zinc and phosphate solubilization at a wider temperature and pH range	Inhibit production of aflatoxin Increase harvest index and yield Improves maize nutrient content	Naeem et al., 2021
<i>Rhizophagus Irregularis</i> , <i>Glomus mosseae</i> , <i>Paraglomus occultum</i>	Greenhouse	Increase soil fertility and enhance plant growth	Significant increase in root colonization and maize growth	Fasusi et al., 2021
<i>Anabaena-Nostoc consortium</i> , <i>Anabaena-Trichoderma biofilm</i>	Field	Carbon Nitrogen mobilization	Higher efficiency was recorded in terms of economic, energy and environmental use Increased cob yield	Sharma et al., 2021
<i>Azospirillum brasilense</i>	Field	Increase chlorophyll content of plant	Increased yield and productivity	Cardozo et al., 2021
<i>Metarhizium sp</i>	Greenhouse	Possess entomopathogenic properties	Antagonistic effect on maize pathogen <i>Spodoptera frugiperda</i>	Silva, 2021
<i>Azospirillum brasilense</i> and <i>Bacillus subtilis</i>	Greenhouse	Zinc solubilization	Modified root system which efficiently improves water and nutrient use	Moreno et al., 2021
<i>Trichoderma harzianum</i>	Field	Induce resistance of plant against herbivorous attack	Alter and reduce the community and abundance of pests	Contreras-Cornejo et al., 2021
<i>Bacillus sp.</i> and <i>Paenibacillus</i>	Field	Auxin production	Improve maize yield	De Carvalho Nascimento et al., 2021
<i>Bacillus subtilis</i> and <i>Pseudomonas koreensis</i>	Greenhouse	Siderophore production	Reduces infectious disease caused by <i>cephalosporium maydis</i>	Ghazy and El-Nahrawy, 2021
<i>Burkholderia cepacia</i> and <i>Acinetobacter baumannii</i>	Net house	Zinc solubilization	Improve the level of protein and sugar accumulation	Upadhyay et al., 2021
<i>Claroideoglomus etunicatum</i>	Greenhouse	Facilitate revegetation of contaminated soil	Enhance plant growth in lanthanum contaminated soil	Hao et al., 2021
<i>Azotobacter chroococcum</i>	Field	Promotes absorption of plant nutrients	Increase total nitrogen and phosphorus content in plant	Song et al., 2021
<i>Anabaena cylindrical</i> and <i>Azospirillum brasilense</i>	Field	Nitrogen-fixing bacteria	Higher nitrogen content of maize	Gavilanes et al., 2020
<i>Arthrobacter arilaitensis</i> and <i>Streptomyces Pseudovenezuelae</i>	Greenhouse	Ammonia, Indole-3-acetic acid, and Siderophore activity	Plants tolerated drought better Physiological parameters show significant increase	Chukwuneme et al., 2020
<i>Trichoderma harzianum</i> , <i>Bacillus amyloliquefaciens</i>	Greenhouse	Phosphate solubilization	Stimulate root growth which promotes the absorption of nutrients in the soil	Mpanga et al., 2019

temperature changes soil nitrifying communities as a result of an increase in the rate of chemical production (Nguyen et al., 2019). pH between 7 and 9 is best for the activity of ammonia oxidizing bacteria and nitrite-oxidizing bacteria, as higher than that disrupts their activity (Heil et al., 2016). Environmental factors determine the group of nitrifying microorganisms that would be prevalent in a habitat or substrate.

Nitrifying bacteria are widely used in aquaculture management (Ruiz et al., 2020; Ajijah et al., 2021) and waste management (Sepahri et al., 2020; Zhao et al., 2020). It is rarely used in cropping. *Nitrobacter*, on the other hand, has been used as a biofertilizer both alone (Doost et al., 2019) and in groups of micro-consortiums (Vatandoost et al., 2019). Doost et al. (2019) discovered that the protein content of Canola improved when compared to the control. Beyond aquaculture and waste management, there is still a need to expand the use of nitrifying bacteria in cropping systems. Nitrifire 5x, MicrobeLift Nite-out II, Scape bac up, Nitrobacter multi-probiotic, Nbc1, and Nbc2 are some of the commercially available application-based nitrifying bacteria. Although these products were intended for

use in aquaculture, their novel application in crop management can be investigated.

Excess ammonia in the soil as a result of synthetic ammonium-based fertilizer affects the environment negatively (Lehtovirta-Morley, 2018). The presence of nitrifying bacteria in the soil reduces ammonia. This makes the soil less acidic and, as such, other beneficial microorganisms can proliferate, thus promoting soil quality. Also, nitrate, which is eventually produced from the nitrification process, elongates lateral roots (Mantelin and Touraine, 2004), mediates signaling pathways of phytohormones, expands leaves, and induces flowers in plants (Hachiya and Sakakibara, 2016). Furthermore, plants' yields and growth are increased and there is little or no dependence on synthetic fertilizer and other agrochemicals that degrade the soil.

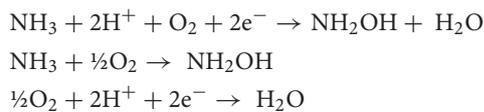
ELECTRON TRANSPORT CHAIN

The enzymatic process of nitrification can be divided into three pathways: NH₃ oxidation pathway, NH₂OH oxidation pathway, and NO₂ oxidation pathway. The enzymatic process is carried

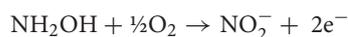
TABLE 3 | Well-identified nitrifying bacteria and archaea genera and their physiological group.

Domain	Phylum	Class	Order	Family	Genera	Physiological group	References
Bacteria	Proteobacteria	Betaproteobacteria	Nitrosomonadales	Nitrosomonadaceae	<i>Nitrosospira</i>	Ammonia oxidation	Schaechter, 2009
	Proteobacteria	Gammaproteobacteria	Chromatiales	Chromatiaceae	<i>Nirosococcus</i>	Ammonia oxidation	Gerardi, 2003
	Proteobacteria	Betaproteobacteria	Nitrosomonadales	Nitrosomonadaceae	<i>Nitrosomonas</i>	Ammonia oxidation	Koops and Stehr, 1991
	Proteobacteria	Deltaproteobacteria	Nitrospinales	Nitrospinaceae	<i>Nitrospina</i>	Nitrite oxidation	Gerardi, 2003
	Proteobacteria	Alphaproteobacteria	Rhizobiales	Bradyrhizobiaceae	<i>Nitrobacter</i>	Nitrite oxidation	Brenner et al., 2005
	Proteobacteria	Gammaproteobacteria	Chromatiales	Ectothiorhodospiraceae	<i>Nitrococcus</i>	Nitrite oxidation	Schaechter, 2009
Archaea	Nitrospirae	Nitrospira	Nitrospirales	Nitrospiraceae	<i>Nitrospira</i>	Nitrite oxidation	Schaechter, 2009
	Thaumarchaeota	Nitrososphaeria	Nitrososphaerales	Nitrososphaeraceae	<i>Candidatus Nitrososphaera</i>	Ammonia oxidation	Tourna et al., 2011
	Thaumarchaeota	Nitrososphaeria	Nitrosopumilus	Nitrosopumilaceae	<i>Candidatus Nitrosopumilus</i>	Ammonia oxidation	Qin et al., 2017

out by an electron transport chain and the reaction is exergonic (a biochemical reaction that releases energy) (Wendeborn, 2019). Ammonia monooxygenase (AMO) turns ammonia into NH_2OH with the gain of two electrons (Daims et al., 2015). The electron is obtained from subsequent oxidation of hydroxylamine, and the energy liberated is obtained from the linked reaction of oxygen reduced to water (Wendeborn, 2019). AMO exists in an integral membrane protein and is a member of the copper membrane monooxygenase (CuMMO) family. The mechanism by which CuMMO carries out its oxidation could help in the development of monitored synthetic oxidation (Lancaster et al., 2018).

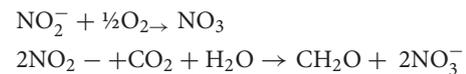


Four electrons are used by hydroxylamine oxidoreductase (HAO), a multiheme enzyme used to oxidize NH_2OH to NO_2^- . Two of the electrons used in oxidizing hydroxylamine return to AMO while the remaining two enter the respiratory electron transport chain, terminating the electron acceptor using O_2 (Daims et al., 2015). This reaction is also exergonic and the energy produced is higher if coupled with a reduction of water (Wendeborn, 2019). According to Lancaster et al. (2018), oxygen is not required for HAO activity, and NO is the product of NH_2OH oxidation and not NO_2 . He further explained that NO is a reactive molecule, as its transformation to other forms of nitrous oxide could be a non-enzymatic reaction. This might be true, however (Wendeborn, 2019), reported some organisms that can oxidize NO_2 to NO_3 .



Nitrite oxidoreductase possessed by some NOB oxidizes nitrite to nitrate with the use of electrons donated from oxygen. However, it can also be produced when nitrite donates electrons to reduce CO_2 to glucose by some photosynthetic

bacteria (Wendeborn, 2019).



Comammox (complete ammonia oxidizer) was predicted by Costa et al. (2006) and discovered in *Nitrospira* by Daims et al. (2015) and Van Kessel et al. (2015). They can utilize eight electrons to oxidize NH_3 to NO_3^- (Lancaster et al., 2018). Broda (1977) predicted two chemolithotrophic organisms that can carry out anammox (Anaerobic ammonia oxidation). One of the bacteria responsible for anammox was identified as Planctomycetales in 1999 (Strous et al., 1999). Anammox microorganisms in an environment where oxygen is depleted can make use of nitrite instead of oxygen as the electron acceptor producing dinitrogen (Wendeborn, 2019). Considering the complex metabolic pathway in the nitrification process, there might be more discoveries to be made to manage the process efficiently.

AVAILABILITY OF AMMONIA IN THE SOIL AND ORGANIC WASTE

Ammonia-based substance is the substrate used by AOA and AOB. They can obtain it from ammonia-based organic waste or soil organic matter. Organic waste improves the quality of soil because it positively affects the growth of soil microorganisms. The natural process of nitrification does not provide sufficient nitrate. Therefore, to strike a balance between the modern process and the natural process, it would be good to provide a technology that would mimic the natural process. Organic fertilizers have been made from composting of organic waste and vermicomposting (Caceres et al., 2018). Plant growth-promoting microorganisms can be used along with these organic materials (Domenico, 2020). One of the biological approaches suggested for SI is to increase biological diversity in the agricultural systems (Petersen and Snapp, 2015). Nitrate has been successfully produced from ammonium contained in vegetable waste using

Nitrosomonas sp. and *Nitrobacter* sp. by Naghdi et al. (2018). Synthetic fertilizer is the cause of excessive amounts of nitrate because it speeds up the rate of nitrification. The gradual and systematic production of nitrate is considered safe for the ecosystem and a better alternative to synthetic fertilizer.

IDENTIFICATION AND ISOLATION OF NITRIFYING BACTERIA AND ARCHAEA

Microorganisms are ubiquitous, however, their composition varies in different habitats as a result of varying environmental factors. In time past isolation and identifying of microorganisms are usually carried out after culturing. Recently, metagenomics survey has enabled the easy identification of microorganisms. Known and unknown nitrifying microorganism strain has been identified from different habitats *via* metagenomics analysis (Clark et al., 2021). The establishment of the presence of nitrifying bacteria and archaea provides a guide on what type is to be isolated and cultured. Although nitrifying bacteria and archaea have been difficult to culture, however, some researchers have been successful in that regard (Könneke et al., 2005; Mellbye et al., 2017). Könneke et al. (2005), isolated nitrifying archaea using serial dilution and incubated them with a medium enriched with ammonia at 21–23°C. The use of mineral salt media with varying formulations has been used by Mellbye et al. (2017). Furthermore, Fujitani et al. (2015), explained the possibility of isolating them from nitrifying granules in a wastewater plant and cultivating them in a liquid culture rich in ammonia. Molecular characterization of the nitrifying microorganisms can also be carried out using 16S rRNA gene sequencing after serial dilution, DNA extraction and PCR amplification (Hastuti et al., 2019). Cultivating nitrifier community unique to maize plant can be carried out and used to increase their population in maize rhizosphere. This would increase the bioavailability of nitrogen in the soil, thereby replacing nitrogen-based fertilizers.

CONCLUSION AND PERSPECTIVE

Sustainable intensification proffers the solution to the conflicts of meeting the increasing demand for food and ensuring a

sustainable environment. Industrial revolution merges trends in intelligent automation with artificial intelligence, this results in remarkable improvement in technology, growth in economy and unimaginable progress. Maize accounts for a significant amount of daily food in most developing regions and it is important to scientific and industrial use. Considering the need to increase maize production, microorganisms with growth-promoting properties can help achieve proper management, sustainable agriculture and sustainable environments. Agriculture has used large amounts of land globally, with major implications for reactive nitrogen from synthetic fertilizers and the use of nitrifying inhibitors to inefficiently manage the system. Nitrifying bacteria and archaea can transform ammonia locked up in soil organic matter and organic waste matter. They can be inoculated wholly or together with ammonium-based organic waste into the rhizosphere of maize. Although the biotechnological formulation and use are still in their primitive stage. Identifying and isolating nitrifying microorganism communities and structures associated with maize is a step toward achieving SI.

AUTHOR CONTRIBUTIONS

OEA reviewed and wrote the first draft of the paper, while OOB critiqued, proofread, and contributed substantially to the structure of the manuscript. Both authors contributed to the article and approved the submitted version.

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