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Agriculture 4.0: An Implementation Framework for Food Security Attainment in Nigeria's Post-Covid-19 Era

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ABSTRACT The challenge of Nigeria's food insecurity in the era of the Covid-19 pandemic, insecurity, climate change, population growth, food wastage, etc., is a demanding task. This study addresses Nigeria's food insecurity challenges by adopting agriculture 4.0 and commercial farming. Using data from six digital libraries, the Nigerian Bureau of Statistics, and other internet sources, we conducted a Systematic Literature Review (SLR using PRISMA) on Nigeria's agriculture, food security, and agriculture 4.0. Our results show Nigeria's current agricultural state, threats to food security, and modern digital agriculture technologies. We adapted our SLR findings to develop an implementation framework for agriculture 4.0 in solving Nigeria's food insecurity challenge in the post-Covid-19 era. Our proposed framework integrates precision agriculture in Nigeria's food production and the necessary enabling digital technologies in the agri-food supply chain. We analyzed the critical implementation considerations during each agri-food supply chain stage of farming inputs, farming scale, farming approach, farming operation, food processing, food preservation/storage, distribution/logistics, and the final consumers. This study will help researchers, investors, and the government address food security in Nigeria. The implementation of agriculture 4.0 will substantially contribute to SDG 2 (zero hunger), SDG 3 (good health and well-being), and SDG 8 (decent work and economic growth) of #Envision 2030 of the United Nations, for the benefit of Nigeria, Africa, and the entire world.

INDEX TERMS Agriculture 4.0, agri-food 4.0, food security, sustainability, SDG goal 2, implementation framework, supply chain.

I. INTRODUCTION

The challenge of Nigeria's food security attainment in the era of the post-Covid-19, characterized by lockdown, restriction of movement, national insecurity, violence, corruption, energy crisis, etc. [1], is still an open research issue. The impact of Covid-19 on Nigeria's already poor food security condition is evident from the inflation, unemployment, protest/violence, hunger/poverty, political and economic instability witnessed in the country. There is the need for a drastic paradigm shift from our traditional small-scale farming to the adoption of digital technologies in large-scale commercial agriculture. It is time for Nigerians to effectively utilize the limited available resources in few information-driven commercial farms and not spread them across millions of small-scale farms that cannot address our current food security needs. According to the World Bank,[1] only 1% of the United States (US) total labor force (employment) are farmers, yet the US is the largest exporter of food globally. This is in sharp contrast to Nigeria, with almost 73% of the workforce (employment) being farmers, yet Nigeria is a net importer of food.

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[1]https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS

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According to the Internation Food Policy Research Institutes (IFPRI[2]), a country is food secure when all its citizens, at all times, have access to an adequate quantity of clean, safe, and nutritious food that meets their food choice and dietary needs for a healthy life. There are five critical aspects of food security in the above definition. They include availability (in terms of quantity and quality), affordability (not too costly), accessibility (should be within the physical, social and economic reach of citizens), alternatives (there should be a variety based on people preferences), and attainment of healthy dietary needs of citizens [2]. One can measure a country's food security by the level of hunger and malnutrition in that country. Nigeria's 2020 hunger index ranking is between $4 - 14.9\%$, along with other countries like Mexico, Colombia, India, Thailand, etc., according to the World Food Programme hunger map.[3] These statistics show that Nigeria is not on track to achieving zero hunger by 2030 [3]. There is a strong connection between food security, good health, and any country's economic growth [4]. Globally, about 690 million people (representing about 8.9% of the world's population) are hungry in 2019. Experts forecast that these statistics may increase by $80 - 132$ million due to the Covid-19 pandemic impact.

There are many existing studies on the impact of Covid-19 on Nigerian food security. Andam *et al.* [5], attributed the major impacts of Covid-19 to external shocks and domestic policies. These impacts include government revenue shortfalls, reduced foreign remittances, and the impacts of lockdown on household earnings. The impact of the loss of income and purchasing power was greater than actual death or health-related issues in Nigeria [6]. Nigerian food insecurity increased by 13%, while non-farming activities reduced by 11% [7], [8]. We must improve our food production resilience to deal with potential disasters that may result in a lockdown or lack of access to food importation. Sustainable mechanization of food production is a viable solution to this challenge [9].

Several studies have investigated the challenge of food security in Nigeria. Adebayo and Ojo [10] identified inadequate funding and government overdependence on oil as the leading causes of food insecurity. The authors warned that developed countries might use food as an instrument of exploitation in the future and recommended biotechnology adoption to solve food security challenges. Nwozor *et al.* [11] emphasized that food security would only be possible in an atmosphere of national security. The study identified insecurity challenges like Boko Haram and Herdsmen–farmers' clashes as the major threats to food security. Metu *et al.* [12] identified the problems of food security and proposed agricultural biodiversity, environmental management, and policy change as the way forward to food security. Eme *et al.* [13] enumerated the challenges of food security in Nigeria and proposed zero-duty on agricultural machinery, local content machine production through Ajaokuta Steel Company as the approach to food security. Fudjumdjum *et al.* [14], assessed the barriers to food security in north-eastern Nigerian and recommended improved financing, irrigation, soil fertility, and climate-smart agriculture as the way to food security.

Some studies investigated household food security measurement in terms of location and specific food types. Ike *et al.* [15] used questionnaires to study 450 household food security in Taraba State. The authors concluded that about 69% of the investigated households are food insecure. Manda *et al.* [16] investigated household food security in terms of cowpea (beans) in Kano State. The authors over-generalized a study in a single state with only one type of food for the whole of northern Nigeria. Liverpool-Tasie *et al.* [17] investigated the methods adopted by maize traders in mitigating spoilage due to climate change. The authors identified fumigation, application of pepper and ash as some measures adopted by maize traders. The study over-generalized the survey conducted in few locations in three states (Kaduna, Kastina, and Kano) for the whole of Nigerian food security. Fudjumdjum *et al.* [14] investigated the factors limiting the adoption of improved rice varieties, commercialization among rural rice farmers. This study was limited in scope to only rice farming among smallholder farmers without implementing other modern agri-food technologies.

There exist also several studies on agriculture 4.0, its enabling technologies [18]–[26], and agri-food supply chain [27]–[29]. Some studies examined it from the perspective of sustainability, collaboration with stakeholders in decision-making [30]–[33], smart factories energy management [34], and specific applications in animal husbandry [35]. Advocates for sustainable innovation and intensification emphasized the need for stakeholders collaboration in agri-food technological innovation to ensure general acceptance and sustainability [30]–[33]. Most of these studies are based on either a single technology, or an aspect of agriculture 4.0. We could not find any existing framework for implementing agriculture 4.0 in developing countries like Nigeria.

Most of the studies on Nigerian food security focus on a specific food type, location, smallholder farming, or emphasizes past administration agricultural policies, which do not reflect the current realities. The few studies that mentioned adopting technology focus on either one aspect of agriculture 4.0 or general technology with no specific blueprint on its implementation. Several authors blamed the government, our overdependence on crude oil, lack of insufficient financial aids to rural farmers for our present food insecurity condition. However, when rural farmers receive financial aids, they do not use them for their intended purpose. These farmers, who usually lack a viable business plan/model, use such financial aids for other pursuits like building residential houses, marrying more wives, or purchasing cars. Although such financial aids may improve the

[2]https://www.ifpri.org/topic/food-security
[3]https://www.wfp.org/publications/hunger-map-2020

lives of rural farmers, this approach will not solve our food insecurity challenge.

This study aims to present a roadmap to Nigeria's food security by implementing agriculture 4.0 in the agri-food supply chain; its specific objectives include identifying the current state of agriculture and threats to food security in Nigeria. It shall also highlight the sources of food wastage and the low adoption of commercial agriculture in Nigeria. It will present a good understanding of agriculture 4.0, including its precision agriculture components, digitization of agri-food supply chain, and modern disruptive enabling technologies. This study shall also demonstrate how agriculture 4.0 will mitigate the identified threats to food security and propose an implementation strategy for the Nigerian context.

The main contributions of the study include

- An up-to-date analysis of the current state (2020) of agricultural production in Nigeria.
- An up-to-date enumeration of government interventions and policies on agriculture in Nigeria.
- A proposed implementation framework for agriculture 4.0 in Nigeria.
- A refined view of the agri-food supply chain and each stakeholder's roles for successfully implementing agriculture 4.0.

The remainder of the work is as follows; Section II is on methodology. Section III is on the results obtained from our systematic literature review. Section IV gives the implementation framework for agriculture 4.0 in Nigeria. Section V discusses results, the limitations of our research, and how we mitigated threats to validity. Section VI is the conclusion and future works of this study.

II. RESEARCH METHODOLOGY

We adopted a two-fold methodology approach in this study. First, we conducted a systematic literature review (SLR) using the Preferred Reporting Item for Systematic Reviews and Meta-Analysis (PRISMA) on Nigeria's agriculture, Nigeria's food security, and recent advances in agriculture 4.0. Next, we proposed a framework for the implementation of agriculture 4.0, using our SLR. Fig.1 shows our research study structure. We obtained our primary source materials reviewed for this study from six electronic digital libraries; Sciencedirect, IEEE explore, SpringerLink, Taylor and Francis Online, Wiley Online Library, and other agricultural journals sourced from Google Scholar. We selected these databases because they include the top science and technology journals, conference proceedings, and business research. We began our search with existing systematic literature reviews on agriculture 4.0 [19], [20], [36], [37]. We modified the search process by Brocke et al. and Kitchenham et al. to suit our research objectives for this study [38], [39].

We constructed six research questions to guide our primary source materials' search, selection, and inclusion process.

1) **RQ1:** *What is the current state of agriculture (as of 2020) in Nigeria?* This will enable us to evaluate our current position towards food security.

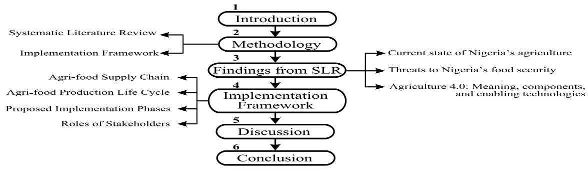

FIGURE 1. Research study structure.

2) **RQ2:** *What are the threats to food security in Nigeria?* This will enable us to determine the factors driving food insecurity in Nigeria and how to mitigate them.
3) **RQ3:** *What are the factors responsible for the low adoption of mechanized agriculture in Nigeria?* This will help us determine the hindrance to mechanized farming and the possible adoption of agriculture 4.0 in Nigeria.
4) **RQ4:** *What are the main components of agriculture 4.0?* This will make us understand the main components to address in our conceptual framework.
5) **RQ5:** *What disruptive technologies can ensure food security in Nigeria despite the existing threats?* This will give us a comprehensive list of disruptive technologies that will contribute to realizing the conceptual framework.
6) **RQ6:** *How can agriculture 4.0 be implemented in Nigeria to ensure food security?* Our motivation for this research question is to obtain implementation guidelines for our conceptual framework.

We constructed four search strings for our primary source material search and selection. We used each database's advanced search feature to limit our search scope to publications in the past five years (2015 – 2020). Our focus is on recent advances in agriculture 4.0 and Nigeria's current agricultural state.

- Search string 1 (SS#1): ((State of) OR (Advances in) OR (Statistics of)) AND (Agriculture in Nigeria)
- Search string 2 (SS#2): ((Threats to) OR (Problems of)) AND (Food Security in Nigeria)
- Search string 3 (SS#3): Agricultural Mechanization in Nigeria.
- Search string 4 (SS#4): ((component of) OR (technologies used in) OR (adoption of)) AND ((agriculture 4.0) OR (precision agriculture) OR (smart farming))

We modified the search strings using keywords in digital libraries where these search strings did not yield satisfactory results (e.g., IEEE Explore, Taylor and Francis, etc.). For search string #1, the modified searches became the State of Agriculture in Nigeria, Nigerian agriculture advances, and Nigerian agriculture statistics. The second search string became threats to Nigeria's food security and problems of Nigeria's food security. Similarly, precision agriculture components and technologies used in precision agriculture became the modified form of search string #4. Our literature search, selection, and inclusion policy are based on the Preferred Reporting Item for Systematic Reviews and Meta-Analysis (PRISMA) model; our search procedure involved four stages, as shown in the PRISMA chart of Fig. 2. The four stages are identification (information extraction), screening, eligibility, and inclusion. We used publication titles in the identification stage. For all publications identified in search string #2 and #3, keywords such as ''food security in Nigeria'' and ''agricultural mechanization in Nigeria'' must be present in the title of the identified articles. For search string #4, keywords such as agriculture 4.0, precision agriculture, smart farming were the basis for identification in the first stage. We identified a total of 691 studies for further analysis after the first stage. We used abstracts and conclusions during the screening stage to exclude 347 studies based on duplicate contents. Similarly, 221 studies were excluded based on irrelevancy, which resulted in 123 eligible studies for full-text analysis. Finally, 32 studies were excluded based on ambiguity and unexplained methodology, resulting in 91 studies included as our primary source materials. We used information from the National Bureau of Statistics and other media sources in addressing our first research question.

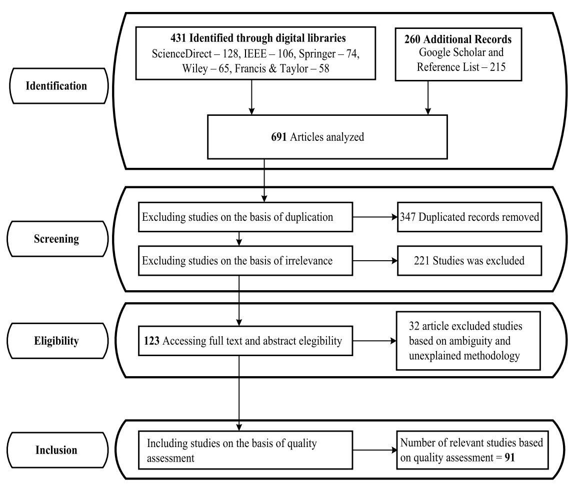

FIGURE 2. PRISMA flowchart for our search and selection procedure.

A. SEARCH STRATEGY

In this subsection, we shall discuss the search process adopted for each of our digital libraries. For Sciencedirect,[4] we entered each of the search strings into the keywords field. Next, we refined the search result using year (2015 – 2020), article types (research and review articles), and subject areas (agricultural and biological sciences). For IEEE Explore,[5] we inputted each search string and modified search strings filtered our results using year, journals, and conferences. For SpringerLink,[6] the search results were filtered using discipline (life sciences), English language, and subdiscipline (agriculture). We adopted similar approaches for other digital libraries. The initial results from this search process are shown in Table 1. We applied inclusion and exclusion criteria to identify some studies using titles (see Table 2). Our inclusion criteria are studies in the English language, Open Access, and the year range of 2015 – 2020. We tried the author's websites and their affiliations (University and Researchgate profiles) for articles with restricted access.

[4]https://www.sciencedirect.com/
[5]https://ieeexplore.ieee.org/Xplore/home.jsp
[6]https://link.springer.com/

TABLE 1. Initial Search Result.

S/No	Digital Library	SS#1	SS#2	SS#3	SS#4
1	Sciencedirect	1,799	561	140	5,030
2	IEEE Explore	42	-	-	1,425
3	SpringerLink	39	740	298	37,035
4	Wiley	214	169	1,283	15,142
5	Taylor and Francis	2	8	12	153
6	Google Scholar	76200	19300	16300	17500

TABLE 2. Number of studies from the indexed database for review.

S/No.	Digital Library	Number of Articles
1	Science Direct	24
2	IEEE Explore	15
3	SpringerLink	9
4	Wiley	7
5	Taylor and Francis	9
6	Others	27
	Total	**91**

Source: Authors

III. FINDINGS FROM SYSTEMATIC LITERATURE REVIEW

We reviewed 91 studies, of which 76 are journal publications, 12 conference proceedings, and 3 technical reports. Table 2 shows the distribution of our reviewed primary source studies according to the digital database source. Fig. 3 shows the distribution of our primary source studies according to the year of publication.

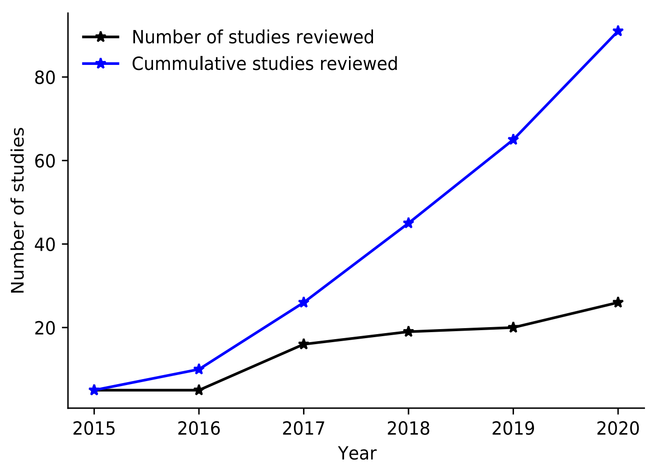

FIGURE 3. Distribution of reviewed studies by year.

We generated a word cloud from our reviewed primary studies' titles, as shown in Fig.4.

A. THE CURRENT STATE OF AGRICULTURE IN NIGERIA

This subsection shall highlight the agricultural sector's performance in production, importation, exportation, and efficiency. We shall also list some efforts made by

FIGURE 4. Generated word cloud from our reviewed article's title.

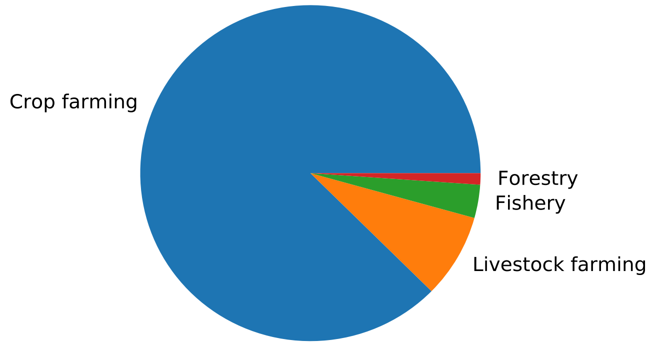

FIGURE 5. Agricultural production in Nigeria.

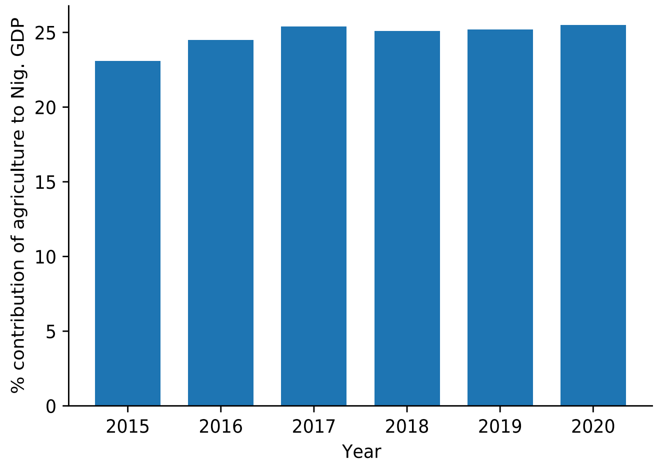

FIGURE 6. Percentage contribution of agriculture to Nigeria GDP for 2015 – 2020 (Q1 – Q3).

the Nigerian government to address the challenges facing agriculture in Nigeria as of 2020.

1) OVERVIEW OF AGRICULTURE IN NIGERIA

Agriculture in Nigeria comprises of four major categories: crop production (87.6%), livestock production (8.1%), fish production (3.2%), and forestry (1.1%), according to the National Bureau of Statistics [18], [40] (see fig. 5). The contribution of agriculture to Nigeria's GDP for 2015 – 2020 (Q3) is shown in fig. 6. Agriculture employs more than 36% (above 28.9 million) of Nigeria's labor force, with more than 80% of the agricultural workforce being smallholder farmers. These smallholder farmers account for more than 90% of Nigeria's agricultural produce. Tractor density in Nigeria is about 0.27 hp/hectare; this is far less than the minimum of 1.5hp/hectare recommended by FAO. In 2019, Agriculture accounted for less than 2% of total export, with crude oil contributing about 76.5%. The Government of Nigeria earmarks about ₦40 billion for agricultural research and development in 2019. The agricultural sector received about 1.8% (equivalent to ₦183 billion) of the total budget for 2020. Comparing the cumulative agricultural import to export for 2016 to 2019 revealed that our cumulative imports (about ₦803 billion) are nearly four times higher than exports (about ₦335 trillion) for the same period. Nigeria's top agricultural imports include wheat, sugar, fish, and milk, while the main agricultural exports include sesame seeds, cashew nuts, cocoa beans, ginger, frozen shrimp, and cotton. On consumption pattern, almost 56.65% of household expenditure is on food (NBS[7]). Table 3 shows the consumption pattern of primary food.

[7] https://www.nigerianstat.gov.ng/pdfuploads/Consumption%20 Expenditure%20Pattern%20in%20Nigeria%202019.pdf

The following infrastructural constraints hinder agricultural trade and exports in Nigeria [41].

1) **Poor land transportation infrastructure:** There are inadequate land transport infrastructures like good road and rail transport systems. This infrastructural shortage is more pronounced in rural areas where the majority of the food production takes place. This infrastructural shortage increases in the cost of food production, transportation, and distribution.
2) **Inadequate Distribution Cold Chain Logistics:** The lack of mobile cold room for the safe storage of perishable agricultural produce has resulted in heavy spoilage and food waste. Some rural farmers resort to drying to preserve food, which grossly affects the food's quality and nutrients.
3) **Insufficient ICT and e-commerce infrastructure:** Most rural settlements where food production takes place lack access to ICT and e-commerce infrastructure, which supposed to facilitate the rapid spread of market information in the supply value chain.
4) **Inadequate and aging seaports infrastructure:** Nigeria has six seaports. Two are located in Lagos

TABLE 3. Food Consumption pattern in Nigeria.

S/No	Food Category	Share of food expenditure	Share in total expenditure
1	Food Consumed Outside of Home	20.19	11.43
2	Starchy roots, tubers, and plantain	11.09	6.28
3	Rice	8.69	4.92
4	Vegetables	7.73	4.38
5	Fish and Seafood	5.86	3.32
6	Grains and Flours	5.64	3.19
7	Pulses, Nuts and Seeds	5.24	2.97
8	Meat	5.23	2.96
9	Fruits	4.44	2.52
10	Oil and Fats	4.35	2.46
11	Baked / Processed Products	4.23	2.4
12	Poultry and Poultry Products	3.86	2.19
13	Other Miscellaneous foods	3.11	1.76
14	Maize	2.96	1.67
15	Non-Alcoholic Drinks	2.42	1.37
16	Milk and Milk Products	2.11	1.2
17	Coffee, Tea, Cocoa, and other beverages	1.3	0.74
18	Sugar, Sweets, and Confectionary	0.9	0.51
19	Alcoholic Drinks (Bottle and Can)	0.66	0.37
	Total	**100**	**56.65**

Source: National Bureau of Statistic

state (Apapa and Tin Can port), two in Rivers state (Onne and Port-Harcourt port), one in Delta state (Warri port), and one in Cross Rivers (Calabar port). Lagos state ports handle about 70% of all imports, while South-South ports handle about 80% of export (usually crude oil). There are observed inefficiencies in load distribution and poor management of the ports. Insecurity, sea piracy, and politics are some likely reasons attributed to these inefficiencies.

2) GOVERNMENT THREEFOLD INTERVENTION IN AGRICULTURE

The federal government of Nigeria has responded on several occasions to the challenges facing agriculture in Nigeria. We shall briefly highlight these interventions from three perspectives:

- Government initiatives to enhance local trade and exports.
- Government intervention on improving agricultural infrastructure.
- Government agencies that are responsible for standards development, regulation, monitoring, and control.

a: CURRENT GOVERNMENT INITIATIVES TO ENHANCE LOCAL TRADE AND EXPORTS

We can summarize Nigeria's federal government's initiatives to enhance local agricultural trade and export capacity in the following five points [41]–[43].

1) **Presidential Economic Diversification Initiative (PEDI):** PEDI was launched in July 2017 by President M. Buhari's administration. PEDI[8] aims to enhanced agricultural trade capacity through the facilitation of new investments, reducing regulatory bottlenecks, and enabling access to credit facilities.
2) **The Presidential Fertilizer Initiative (PFI):** PFI[9] was launched in December 2016 as a product of the partnership between Nigeria and Morroco. Its implementation is a public-private partnership in Nigeria, led by the Nigerian Sovereign Investment Authority (NSIA) and the Fertilizer Producer and Suppliers Association of Nigeria (FEPSAN). The Presidential Initiative aims to 'disrupt' this import of blended Fertilizer status-quo by negotiating subsidized contracts directly to procure NPK Fertilizer's four constituent raw materials-locally-sourced Urea, locally-sourced Limestone Granules (LSG), Diammonium Phosphate (DAP) imported from Morocco, and Muriate of Potash (MOP) sourced from Europe-and blending these locally to produce NPK Fertilizer at a reduced cost.
3) **Youth Farm Lab (YFL):** This is an initiative of the Federal government of Nigeria (FMARD[10]) and Synergos[11] to educate young Nigerians in the development of livestock and sustainable urban agriculture. YFL searches for Nigerians between the ages of 18 and 35 who are excited about agriculture and believe in its profitability potential.
4) **Anchor Borrowers Programme (ABP):** ABP [44] was launched on 17th November 2015. Its objective is to link anchor companies in processing and smallholder farmers with the required key agricultural products. According to the CBN govern Godwin Emefiele, over ₦55.526 billion has been disbursed to about 250,000 farmers who cultivated almost 300,000 hectares of farmland within the first two years of implementation, an estimated 890,000 direct and 2.6 million indirect jobs. The CBN facilitates interest-free credit facilities for farmers through this program.
5) **Food Security Council (FSC):** The FSC was inaugurated on 26th March 2018, with President M. Buhari as chairman. Its objectives include the development of permanent responses to the conflicts between farmers and herdsmen; climate change and desertification and their effect on farmland; grazing areas and dams, rivers, and other bodies of water; oil spillage and its impact on Niger Delta Fishing Communities; piracy and banditry; agricultural research institutions and extension services; and smuggling issues. The Council will also be interested in regional and global policies and developments with food security consequences in Nigeria.

[8] https://www.vanguardngr.com/2018/05/economic-diversification-yielding-results-buhari/

[9] https://theasovilla.medium.com/everything-you-need-to-know-about-the-presidential-fertilizer-initiative-pfi-e6879d424dd6

[10] https://fmard.gov.ng/

[11] https://www.synergos.org/

6) **Agricultural Promotion Policy:** Agricultural promotion policy aims to improve access to international trade. Its objectives include enhancing access to market information through the National Agricultural Information System and creating a specialized export market support team to enhance export capacity.
7) **Economic and Export Promotion Incentive:** Through this program, the federal government placed trade barriers on selected goods to protect local producers and stimulate their growth. The banned products include rice, poultry, beef, egg, refined vegetable oil, fats, spaghetti, sugar, and sugarcane. The government also restricted forex access to the above-banned products.
8) **Nigeria-Africa Trade and Investment Promotion Program (NATIPP):** NATIPP is a joint program of African Export-Import bank, Nigeria Export-Import Bank, and Nigeria Export-Import promotion council. NATIPP aims to facilitate the expansion of Nigeria's trade and agribusiness investment in Africa.

b: CURRENT GOVERNMENT INTERVENTION IN AGRICULTURAL INFRASTRUCTURAL DEVELOPMENT

The federal government of Nigeria earmarks ₦169.88 billion on road construction in 2020.[12] Similar efforts by the government in railway and ICT are also ongoing. We summarize the interventions as shown below;

- **Development of road infrastructure:-** This includes road rehabilitation across the country to facilitate internal and external trade. Earlier in December 2020, the Federal Executive Council approves ₦120.7 billion for roads and bridge rehabilitation.
- **Development of railway infrastructure:-** There are massive railway renovations and rehabilitation ongoing across Nigeria. Railway lines link major agribusiness cities like Lagos, Kano, Kaduna, Port Harcourt, Ibadan, Warri, etc. These infrastructural developments aim to aid the free flow of agricultural produce and industrial goods. Once completed, they will act as alternatives to road transportation.
- **Enhancing Port Infrastructure Capacity:-** The federal government of Nigeria is currently developing an additional seaport at Akwa Ibom and Lagos. The Nigeria Port Authority (NPA) has signed a Memorandum of Understanding MOU) with Antwerp's Royal Port to facilitate capacity enhancement.

c: GOVERNMENT AGENCIES RESPONSIBLE FOR STANDARD DEVELOPMENT, REGULATION, MONITORING, AND CONTROL

The federal government of Nigeria enforces compliance with standards, food quality regulation, monitoring, and control through the following agencies [43].

[12]https://punchng.com/federal-govt-allocates-n169-88bn-for-roads-in-2020/

1) **National Agency for Food and Drug Administration (NAFDAC).** NAFDAC is responsible for regulating and controlling the manufacture, importation, exportation, distribution, advertisement, sales, and use of regulated agricultural food and drug products.
2) **Standards Organization of Nigeria (SON).** SON is responsible for preparing standards relating to product measurement, material processes, and services. They are also involved in the promotion of standards at national, regional, and international levels.
3) **Nigeria Export Promotion Council (NEPC).** NEPC is responsible for promoting developing and diversifying exports in Nigeria. It coordinates all export promotion and administration activities and other capacity building.
4) **National Export Processing Zone Authority (NEPZA).** NEPZA is responsible for promoting economic development and diversification in Nigeria by establishing and regulating free trade zone areas.
5) **National Agricultural Quarantine Services (NAQS).** NAQS is responsible for harmonizing plants, veterinary, and aquatic resources to promote and regulate sanitary measures connected with the import and export of agricultural products.

B. THREATS TO FOOD SECURITY IN NIGERIA

From our reviewed literature, we identified six threats to food security in Nigeria. These threats are drastic demographic growth, land degradation, the effect of climate change on food production, insecurity and violence, and massive food wastage. This is the answer to our second research question. These factors are as shown in Fig.7.

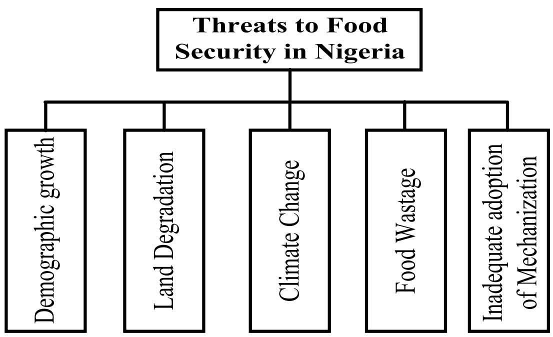

FIGURE 7. **Six identified threats to Nigeria's food security.**

1) INSECURITY AND VIOLENCE

The insecurity challenges posing threats to food security in Nigeria are Boko Haram insurgency, Indigenous People of Biafra (IPOB) insurgency, Fulani herdsmen attacks, Niger Delta conflicts, kidnapping, armed robbery attacks, etc. [45]. Insecurity is making the Nigerian agricultural sector unattractive to both foreign and local investors. There is an increase in poverty, hunger, unemployment, and humanitarian crisis (displaced persons) due to the Boko Haram insurgency in northern Nigeria [46], [47]. There are disruptions in farming activities due to herdsmen-farmers clashes and loss of revenue to both farmers and government due to Niger Delta and IPOB militancy. No sustainable growth and development can happen in any country without the security of life and property. Insecurity and violence are crucial factors the Nigerian government should address to ensure food security.

2) DRASTIC DEMOGRAPHIC GROWTH RESULTING IN HIGH FOOD DEMAND

Nigeria's population is growing at a very alarming rate. According to Worldometer[13] as at 26/10/2020, Nigeria's population increased by 14.68% from 2015 (from 181, 137, 448 in 2015 to 207, 726, 439 in 26/10/2020). Our population is estimated to increase by 26.61% by 2030 and 93.19% by 2050. Food demand (especially high-value proteinous meat) will increase with this drastic population growth.

The urban population grew from 47.8% in 2015 to 52.0% in 2020, representing a drift from rural settlements and farming. Urbanization leads to infrastructural development and increases income. However, it also increases the demand for processed food. Excessive demand for animal meat (processed food) can lead to devastating health challenges such as cardiovascular diseases, colorectal cancer, type 2 diabetics, and total mortality [48].

The impact of agriculture on our environment is alarming. Food is responsible for about 26% of global greenhouse gas emissions [49]. Agriculture uses nearly half of the world's habitable land. Food production uses almost 70% of the world's freshwater. Livestock is responsible for about 18% of human-caused greenhouse gas emissions. With the estimated drastic future population growth, the impact of food production activities will also drastically increase. The small increase noted in food production volume cannot withstand this drastic population growth and urbanization. There is an urgent need for a sustainable approach to food production in Nigeria.

3) LAND DEGRADATION

Our natural resources for food production are fixed while the population is drastically increasing. Our farmlands are increasingly becoming heavily degraded. Nigeria has a land area of about 909, 809km^2, of which nearly 351, 000km^2 are being lost to desertification at a rate of 0.6km per annum [50]. We have fifteen states (including the FCT) classified as desertification frontlines, accounting for 63.83% of our total land area. Nigeria is divided into eight agro-ecological zones, namely; semi-arid (4%), dry sub-humid (27%), humid (26%), very humid (14%), ultra humid – flood (2%), mountainous (4%), and plateau (2%) [51]. The main drivers of land degradation in Nigeria include unsustainable agricultural practices, mining & quarrying, population increase, transportation & energy, unemployment, infrastructure, etc. The effects of land degradation include poor agricultural yield, ethnic conflict over scarce resources (herdsmen crisis), food insecurity, flood & erosion, unemployment, and desertification [52].

Nigeria lost about 126 Kha (kilo hectares) of its primary forest trees (representing 14% of its total forest) from 2002 to 2019, according to Global Forest Watch.[14] Deforestation reduced our total humid primary forest by 93% during that period. Only 30% of northern Nigerians have access to safe and drinkable water (USAID.[15] Less than 1% of our farmlands are under irrigation (FAO.[16] The system of procurement, distribution, and application of fertilizers to our farmlands is inefficient. Over-application of fertilizers to farmlands can result in water pollution, which is unsafe for aquatic life. The factors responsible for land degradation in Nigeria (see Fig.8) are;

- **Deforestation:-** the encroachment of forests for human needs like logging, urbanization, increase in farming lands, woods for fuels, fire haunting, mining, etc. It opens the land to erosion and other exploitation when done in sloping land.
- **Inadequate fallow period for farmlands due to scarcity of land:-** Our traditional shifting cultivation period is gradually being reduced to short periods and, in some cases, none.
- **Poor crop rotation:-** Most rural farmers in Nigeria focused on two or three types of crop farming [53]. The numbers of farmers that practice crop rotation in Nigeria are really few.
- **Lack of Policy on farmland encroachment:-** No policy protects fertile farmland for building construction, industrialization, and other activities that infringe on cropland [54]. This is because those fertile farmlands are used for residential and construction purposes, leaving farmers with unsuitable land.
- **Petroleum industry activities:-** Petroleum exploration and production in Nigeria has seriously degraded the quality of farmlands in the Southern region. Oil spills, blow-outs, improper disposal of drilling mud or wastes from petroleum industry operations, and gas flaring returning to the earth in the form of polluted rainfall are some examples of degrading oil industry activities in Nigeria [55]–[57]. Onyena and Sam [58], investigated the effects of crude oil exploitation on the health, culture, and economy (agricultural productiveness) of the people in the Niger Delta mangrove.
- **Overuse of fertilizers:-** Imbalanced use of fertilizers can affect soil pH, soil nutrient imbalance, and the contamination of drinking water when excess fertilizers are washed away by erosion [59].
- **Overgrazing.** Excessive grazing reduces soil vegetation cover and encourages erosion. The quality and quantity of soil are directly affected by overgrazing [60]. Herdsmen and other humanitarian crises in Nigeria

[13] https://www.worldometers.info/world-population/nigeria-population/

[14] https://www.globalforestwatch.org/dashboards/country/NGA/
[15] https://www.usaid.gov/nigeria/water
[16] http://www.fao.org/nigeria/fao-in-nigeria/nigeria-at-a-glance/en/

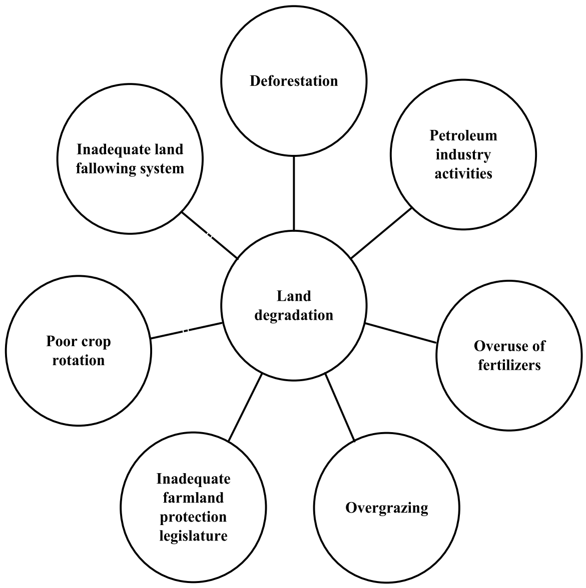

FIGURE 8. Factors affecting land degradation in Nigeria.

are evident from the effect of overgrazing on our farmlands [61].

4) THE EFFECTS OF CLIMATE CHANGE ON FOOD PRODUCTION

Climate change affects nature and human activities and may pose a severe problem to agriculture, especially in developing countries like Nigeria [60]. Food production depends on the climate, and any climate change could lead to the following hazards; flood, drought, heatwaves, global warming, etc. All these hazards affect food production in different ways. For instance, drought and flood destroy crops, while heatwaves are harmful to livestock. Climate change leads to global warming (increase in temperature), which has affected the cultivation of certain food crops. Unpredictable rainfall, changes in weather, and seasons directly affect planting timing, reproduction, and migration of fish and other aquatic animals. An increase in atmospheric CO_2 is making our rivers more acidic, which is also a direct threat to aquatic lives.

Climate change also affects other aspects of our lives, apart from food production. An extreme shift in temperature exposure patterns can lead to a breakdown of infrastructure, damage to properties, and reduced household and community resilience. Global warming with increasing temperature creates a conducive environment for diseases to thrive in both humans and livestock.

Ologeh *et al.* [62] emphasized the need for climate-smart agriculture through the adoption of space applications. They emphasized the need for strong collaboration between the Ministry of Agriculture (MOA), Nigeria Meteorological Agency (NIMET), and the National Space Research and Development Agency (NASRDA), as there are perceived gaps of information flow between them.

5) MASSIVE FOOD WASTE

Food waste is a significant challenge for our world. The statistics of wasted food are alarming, considering the number of people living with hunger worldwide. According to the Food and Agriculture Organization of the United Nations (FAO[17]); about 1.6 billion tonnes of global food is wasted annually, accounting for about 3.3 billion tonnes of CO_2 equivalent Green House Gas (GHG) emitted into the atmosphere. At the same time, $250km^3$ of water is used in producing this wasted food annually (almost three times the volume of Lake Geneva). Farmers use approximately 1.4 billion hectares of land (28% of the world's agricultural land) to produce wasted food. The total annual food waste amounts to about \$750 billion, while developing countries (like Nigeria) lose more food during processing and harvesting. In contrast, food waste at retail and consumer levels continues to be higher in middle and high-income regions. The statistics of wasted food in Nigeria are estimated to be 25% amidst hunger (Businessday News.[18] We identified five different stages of food wastage in Nigeria, as shown in Table 4.

6) INADEQUATE ADOPTION OF AGRICULTURAL MECHANIZATION

Mechanization involves the production, distribution, repair, maintenance, management, and the use of agricultural tools, implements, and machines [9]. Its benefits are threefold; economic, social, and environmental. Agricultural mechanization will increase food production volume (leading to export), improved efficiency of the farming process, higher farm revenue (with reduced production cost), and encourages youth participation in agriculture. It also strengthens marketing processes such as packaging and standardization by eliminating marketing, warehousing, and storage channel losses.

About 3% of the food production in Nigeria is mechanical powered. Subsistence and semi-subsistence household farmers cultivating less than 3 ha constitutes about 90% of Nigeria's agriculture [63]. According to the World Bank Group [64], Nigeria rated 49.7% in enabling the business of agriculture. Most subsistence farmers in Nigeria have small plots of land scattered in geographically difficult-to-access terrain. To answer our research question 3, we shall discuss the factors responsible for the poor adoption of mechanization in Nigerian under five subheadings; economic, myth and ideological, demographic and geographical, technical, and legal/statutory factors. Fig. 9 summarizes these factors.

a: ECONOMIC FACTORS AFFECTING THE LOW ADOPTION OF MECHANIZATION IN NIGERIA

The principal economic factors are the forces of demand and supply for mechanization in Nigeria. The need for mechanization in Nigeria is shallow, as more than 90% of farmers

[17]http://www.fao.org/news/story/en/item/196402/icode/
[18]https://businessday.ng/agriculture/article/the-africa-farmers-stories-the-irony-of-food-shortage-amidst-food-wastage/

TABLE 4. Five stages and their associated food wastes.

S/No	Stages	Type of food wastage
1	Food Production	These are food waste during production and harvesting. Examples include (1) Bruised or damaged produce during harvest. (Poor crop harvest) (2) Spillage waste during harvest (3) Animals' and fishes' death during production. (4) Overproduction of food. (5) Wastage by insects and pests.
2	Post-harvest, handling, and storage	(1) Transportation waste (from farm to storage) due to delay of bad roads (2) Poor storage – food wastage due to extreme temperature, humidity, and pressure, lack of electricity or proper storage facilities (3) wastes associated with non-conformity with acceptable standards or food quality. (4) Bruised or damaged food during storage.
3	Processing	These are food waste that results from processing activities like dressing and slaughtering of meat, poultry, fish, and other foodstuffs. Examples include; (1) waste resulting from spillage and trimming. (2) waste resulting from washing, peeling, packaging, etc. (3) Bruised or damaged goods during processing. (4) food wastes resulting from food not meeting acceptable processing standards. (5) waste due to inadequate post-processing storage facilities.
4	Distribution	This is another source of food waste in Nigeria recently. Examples include; (1) Wastes due to transportation from storage to distributors (wholesaler) (2) Wastes due to issues with the marketing system. (3) Wastes resulting from seizure by regulatory bodies by NAFDAC, Nigerian Customs for non-compliance with standards. (4) Wastes that are caused by unsold products for any reason.
5	Consumption	(1) Preparation and cooking mistakes and plate wastes. (2) Over-purchasing (3) food waste resulting from inadequate and improper storage. (4) Not consuming in first-in-first-out order. (5) food waste from the short shelf life of the perishable foodstuff

Source: Authors

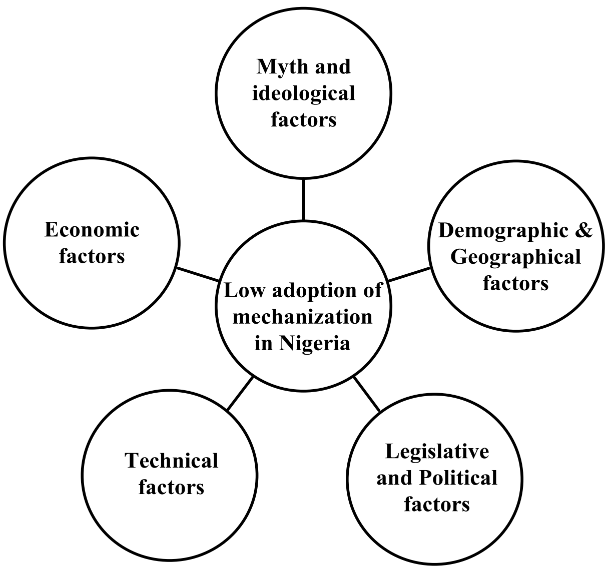

FIGURE 9. Factors contributing to low mechanization in Nigeria.

involved in farming do not use mechanization [65]. Most of these farmers are low-income earners who cannot afford the initial high starting cost of mechanization. The result is that their productivity and savings are equally very low. The suppliers of the mechanization market equally face a similar challenge. Their products' demand is low, resulting in a meager mechanization supply, high capital costs, and substantial operating costs. The high cost of operation and low patronage makes the mechanization business unattractive to investors and suppliers.

b: MYTHICAL/IDEOLOGICAL FACTOR AFFECTING THE LOW ADOPTION OF MECHANIZATION IN NIGERIA

Some farmers, researchers, and policymakers believe that mechanization will lead to unemployment in Nigeria [65]. Others think that smallholder farmers will not benefit much from the heavy initial financial investment of mechanized farming. Some stakeholders see mechanization as destructive to our environment, claiming that it increases deforestation, erosion, soil degradation, and GHG emissions. Other mythical opinions on agricultural mechanization include; mechanization is beneficial to only men; it is challenging to finance; It is a failed business; hence, the government should not get involved in its importation, it is not the responsibility of government, and it does not contribute to total productivity even though it may save labor. According to Daum *et al.* [65], mechanization may increase or decrease unemployment, subject to many other factors and application scenarios; if appropriate technology and planning are in place, smallholder farmers have numerous benefits from adopting mechanization. Their study also revealed that with proper policies and operation culture in place, we could avoid mechanization's adverse effect on our environment; women can benefit from mechanization if they develop interest and acquire technical know-how. The study also affirmed that mechanization is challenging to finance; both the government, public, and private sector's participation is needed for any practical mechanization realization. The government is responsible for creating an enabling environment for all stakeholders to participate. Mechanization can produce a positive effect on yield in addition to saving working hours labor.

c: DEMOGRAPHIC/GEOGRAPHICAL FACTORS AFFECTING THE ADOPTION OF MECHANIZATION IN NIGERIA

These factors include the geographical location of farmlands, accessibility of rural areas where farming occurs, lack of infrastructure like a road that makes the deployment of mechanization difficult in some cases, etc. [66]. Nigeria has eight agro-ecological zones with different mechanization requirements. Lack of adequate infrastructures like roads to farmland where pieces of machinery are needed is a serious deployment problem. There are practical instances where a farmer has about eight to ten pieces of small land scattered in different locations that tractors cannot access. The Nigerian government plans to cluster farmers to the same farming location to enable them to have access to mechanization. Most farmers consider their farmlands as a family inheritance that they need to pass along to their children. Abandoning these plots of land for new locations may be difficult.

d: LEGISLATIVE AND POLITICAL FACTORS

These are factors relating to regulation, tax, and laws affecting the adoption of mechanization in Nigeria. There are instances where machinery that is over 35 years old is imported to Nigeria by suppliers. In some cases, there are no available spare parts for these technologies. Other constraints that a viable mechanization regulatory framework can resolve include delays at clearing ports, high clearing costs, hefty tax, etc. [67]. Political affiliation leading to MoU with substandard mechanization companies denies farmers and suppliers their investment return in the mechanization market. The Nigerian government has laid out many plans to improve mechanization in Nigeria.[19] [20]

e: TECHNICAL FACTORS AFFECTING THE ADOPTION OF MECHANIZATION IN NIGERIA

The technical factors include inadequately trained personnel (repairs and maintenance technicians/engineers and extension officers) and poor production capacity for agricultural mechanization. Almost all pieces of machinery used in Nigeria are imported. There are indigenous companies like Innoson, IMC (Steyr Motors), Monaplex, Nissan, Peugeot, etc., that are not actively involved in Nigerian agricultural mechanization for the aforementioned economic reasons.

C. AGRICULTURE 4.0: MEANING, COMPONENTS, AND ENABLING TECHNOLOGIES

Agriculture 4.0 is the 4th agriculture revolution that involves digitalizing the entire agricultural production process (through smart / precision farming) and its supply chain. Digital agriculture involves remotely gathering and saving, reviewing, and exchanging data for optimum activities across the entire food supply chain using software and resources. In agriculture 4.0, decisions are made at three distinct stages (pre-farming, on-farm, and supply value chain – after-farming) based on available data to improve food production, processing, storage, distribution, and consumption. The application of agriculture 4.0 to modern agriculture is summarized in fig. 10. This answers our third research question.

1) PRECISION AGRICULTURE

Precision agriculture (PA) uses digital technology to manage and control all aspects of food production, processing, and storage to improve production sustainability [68]. It uses digital technologies of IoT, GPS guidance, GPS-based soil sampling, control systems, drones, robotics, autonomous vehicles, variable rate technology, automated hardware, telematics, and software. Farmers can apply PA before and during farming through a decision support system. The pre-farming stage helps farmers to plan, select seedlings or agricultural inputs, choose a farming approach, and apply the appropriate technology based on the available data. During farming, PA enables farmers to use the proper amount of farm inputs, fertilizer, and other resources to improve farming output sustainability by adopting appropriate digital technologies. Farmers can do farming in a whole new way with PA through approaches like desert farming using drip irrigation, hydroponics, urban farming, etc., which are now possible. PA assumes that growth, stability, and performance are affected by a farm's topology, environmental factors, and morphology. This phytogeomorphological approach is based on the fact that the geomorphology component dictates a farm's hydrology [69]. It also assumes that agricultural fields (soils) are not homogenous but exhibit spatial variability in soil properties, landscape features, crop stresses, and crop yield. Farmers identify and use these economic importance patterns as input data to determine the variable amount of agricultural inputs like fertilizer, herbicides, irrigation, etc. Farmers can manually obtain the sample collection used in precision agriculture by measuring topographic elevation, soil crop characteristics measurements, or remote sensing measurements.

a: GUIDANCE, NAVIGATION, AND CONTROL SYSTEM

Guidance, Navigation, and Control systems are one of PA's core components: either a virtual or physical device or group of devices implementing the control of the movement of smart machinery used in agricultural production, processing, and storage. This system processes the changes in position, velocity, altitude, and or rotation rate of the moving machinery required to follow a given trajectory [70]. This system consists of three main subsystems;

- Input – sensors, course data, radio, satellite links, and other information sources.
- Processing – one or more CPUs integrates the data and determines the course of action.
- Output – This subsystem uses the processed information to affect the system course directly.

The Guidance, Navigation, and Control System have three essential parts; navigation, guidance, and control.

[19] https://nairametrics.com/2020/01/26/fg-offers-1-1billion-agric-mechanisation-scheme/

[20] https://www.premiumtimesng.com/agriculture/agric-news/401185-fg-to-establish-over-600-farm-mechanisation-centres.html

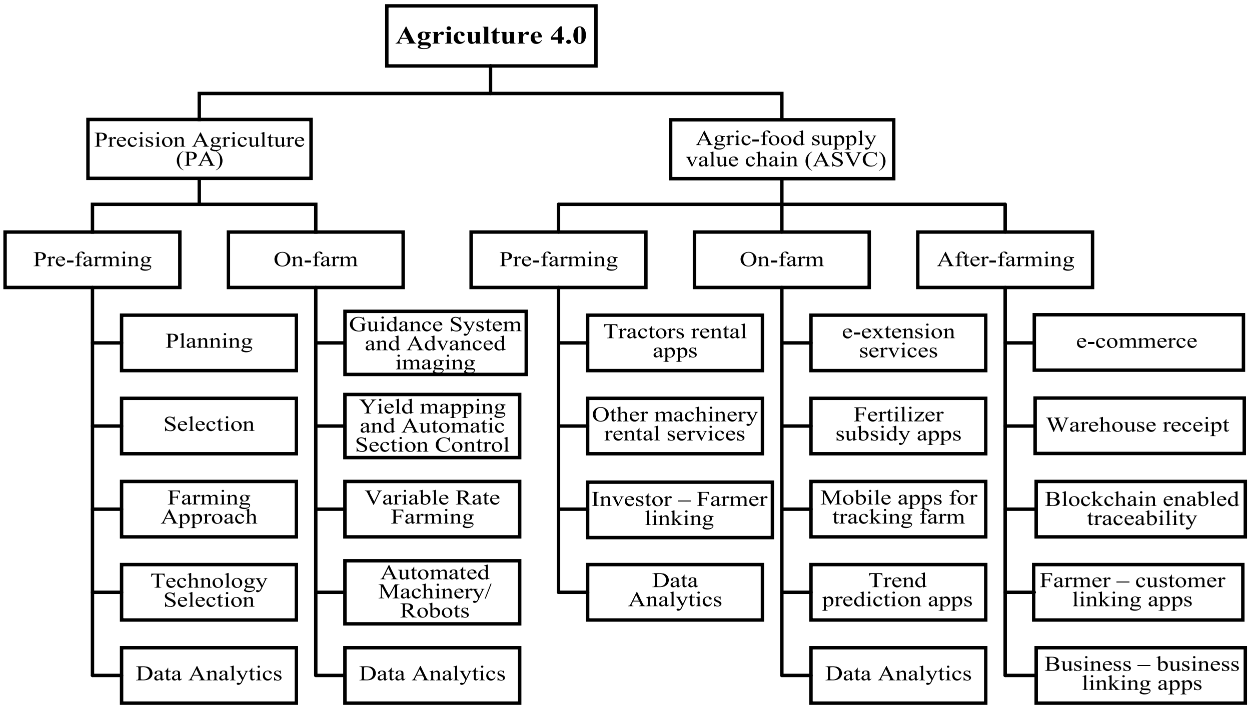

FIGURE 10. Structure of Agriculture 4.0.

The navigation component is responsible for tracking location. The typical navigation system used in PA includes Geographical Position System (GPS), Geographical Information System (GIS), Global Navigation Satellite System (GNSS), and Long-Range Navigation (LORAN). GPS uses satellite signals (radio waves) for its location-tracking functions. GIS is a computer-based application used for geographic data set entry, storage, retrieval, and evaluation. The GIS is typically composed of maps of layers that provide information on many attributes such as elevation, land possession and use, crop yield, and the level of soil nutrients. GNSS is a satellite navigation system that delivers worldwide coverage of geo-spatial positioning using satellite time signals. LORAN is a long-distance navigation system that calculates the position between pulses obtained from broadly spaced radio transmitters.

b: ADVANCED IMAGING SYSTEM (AIS)

AIS is one component of PA that has led to increased food production and efficiency in farming. Remote sensing is the acquisition of data from a farm without physical contact through satellite and aircraft-based sensor technologies [71]. The two types of sensors used in this field include passive and active sensors. Passive sensors measure radiation reflected or emitted by farm crops and animals. In contrast, active sensors use their radiated or emitted energy to measure farm crops and animals by measuring their surface's reflected radiation. Please note that geology and archeology also use remote sensing, but we shall restrict our discussion to agricultural applications. Drone technology and mobile phones can enable advanced imaging compared to older imaging systems that use satellite imaging. Farmers can get multispectral imaging solutions (e.g., Landsat, Sentinel, and SPOT images) to monitor the health of crops and livestock using a drone that flies over the farmland. Farmers can use multispectral images to retrieve various crop and soil attributes, such as crop chlorophyll content, biomass, yield, and soil degradation [72]. AIS has led to early detection of disease and pests and consequently increased agricultural output. AIS is possible because plants reflect different amounts of visible light and new infrared light, depending on their health. We can use the varying intensity of the reflected rays to create a normalized difference vegetation index (NDVI), demarcate unhealthy crops with a different color. AIS enables farmers to detect problems early enough and offer immediate solutions, thereby improving yield and product quality. The main limitation of multispectral imaging is inadequate spectral resolution.

Hyperspectral imaging measures spectral signals with the narrow spectrally bandwidth (e.g., usually under 10nm) in a spectrum of continuous channels and may capture fine-scale spectral characteristics of targets that would be otherwise affected. Farmers can use it to study soil characteristics, crop nutrient evaluation, crop types, weeds, and disease classification. We can incorporate hyperspectral imaging in multiple platforms such as satellites, UAVs, airplanes, and close-range platforms [73].

c: YIELD MAPPING (Monitoring) AND AUTOMATIC SECTION CONTROL

In yield mapping, information obtained from the guidance system and advanced imaging produce a farm yield map.

Yield maps give a representation of the crop production capability of a farm [74]. Farmers can also use it to investigate the existence of variability in soil structure and composition. Farmers can also use this information to determine the type of field management (uniform or site-specific field management) a farmer should apply to his farm. They can also then divide the farmland into different sections based on the input requirements of the farm. Farmers can apply different agricultural inputs to various sections based on information from the yield maps and guidance system in variable-rate farming. They can also make this application of a varying amount of input manually or automatically. In automatic section control, farmers generate the variable-rate application information automatically and use robots, drip irrigation, or smart agricultural mechanization for applying the inputs. Robotics, drone technology, and data analytics play a vital role in the above processes.

2) DIGITALIZATION OF AGRIFOOD SUPPLY VALUE CHAIN

Agrifood supply chains are a series of related events (linked services) from food production to processing, storage, trading, distribution (including transportation), and final consumption (FAO).[21] In the agri-food supply value chain, the emphasis is on decision support systems (DSS) through mobile phones, software, and apps, including activities, technologies, and processes that add value, improve, enhance, or optimize any or all the blocks in the agri-food supply chain. As shown in Figure 7, the agri-food supply value chain covers operations before the actual farming like services or mobile apps that link farmers with tractors, other machinery (drones), investors, and agritech that handles data analytics. During the main farming operation, stakeholders can also provide value addition through e-extension service apps, fertilizer subsidy apps, mobile apps for farm tracking/monitoring, trends prediction apps, and agritech service providers for various aspects of data analytics [75]. We can do similar value addition during processing and storage. Insufficient agricultural product processing is one major problem for high waste and rejection of agricultural produce in Nigeria. Our consumers are willing to pay more for adequately processed rice than the local ones with substandard processing. Applying novel technologies in processing and storage will make a great difference in Nigeria's food security. After farming, e-commerce, warehouse receipt, blockchain-enabled traceability, farmer–customer linking apps, business–business connecting apps can significantly add more value to the agricultural food supply chain.

a: TRACTOR (Other MACHINERY) RENTAL SERVICES

Agricultural mechanization is characterized by high initial investment costs, which most smallholder farmers cannot afford. There is a need for maintenance and operation costs and technical know-how, which most farmers do not have. Technology is growing rapidly, making some heavy investments in machinery obsolete after a short application and operations. In terms of efficiency, these machines are used by farmers for only a brief period and remain idle for a very long period. Tractor rental services enable all farmers (both small-scale and large-scale) to benefits from mechanized farming without necessarily incurring the high initial investment, maintenance, and obsolete risk costs associated with it. It affords farmers to effectively put their machinery into effective use even in an idle period and increase their farming scale [76]. With agriculture 4.0, the concept of seasonality in farming will be a thing of the past. It is most effective in areas where farmers are clustered. The availability of infrastructures, such as good roads, electricity, etc., also enhances its adoption. Practical examples of tractor rental services include farmease,[22] hello tractor,[23] landwirt.com,[24] trringo,[25] etc.

Other agricultural machinery such as harvesters, processing machines, packaging machines, storage services, and drone monitoring services are also available as rental services. The same benefits, as stated above, can be derived from these services. A small-scale farmer could rent drone services only when needed instead of purchasing and operating one. Such a farmer could also send their agricultural produce to a central processing/storage facility to minimize wastage and rejection due to substandard processing.

b: Farmer2X LINKING PLATFORMS

Farmer2X linking platforms are digital platforms that link farmers to any other stakeholder in the agri-food supply chain. Examples include farmer-to-investor, farmer-to-farmer (farming community support), farmer-to-customer, farmer-to-inputs (fertilizer, pesticides, improved seedings), farmer-to-extension service support, farmer-to-government incentives, and business-to-business linking, etc. Agriculture 4.0 will ensure timely communication/connection between farmers and other stakeholders that can improve the efficiency, effectiveness, and productivity of farmers. Some advantages of these linking platforms include a reduction in food waste, increase in farmers' income as a result of a reduction in exploitation by supply chain intermediaries, increase in quality of final agricultural products resulting from collaboration among stakeholders, and access to credit facilities from historical partnership data and past performance [77].

c: E-ExtEnsion SERVICES

Agricultural extension is the process of communicating new knowledge to small-scale farmers in a rural area while receiving feedback from the same to improve productivity, efficiency, and farmers' outlook towards farming difficulties [78]. It is a political and organizational instrument for facilitating social and economic development. Agricultural

[21] http://www.fao.org/energy/agrifood-chains/en/

[22] https://www.farmease.app/

[23] https://hellotractor.com/

[24] https://www.landwirt.com/

[25] https://www.trringo.com/

extension is a means of technology transfer to rural farmers while communicating appropriate application feedback to research centers. The new knowledge shared could be farm inputs, credit, market, processing, or farm management skills. Agricultural e-extension services are using a digital platform to provide the above services to all farmers.

In 2019, the ratio of extension agents to farmers in Nigeria was between $1 : 50,000$ to $1 : 10,000$ and was inadequate for an effective extension service [79]. Other problems facing agricultural extension service in Nigeria include technical, logistics problems, difficulty accessing remotely located rural farms, etc. Agriculture 4.0 could remedy all these problems through e-extension services to provide quality, timely, effective, and automated electronic extension support to all categories of farmers. Agricultural e-extension (according to FAO[26] and Ikore.org[27]) uses ICT technology in the provision of timely, independent, and complimentary services such as Good Agricultural practices (GAP), weather advisory services, connection to buyers/off-takers, and access to reliable Agricultural inputs (seeds, pesticides, and fertilizer), through USSD codes, SMS, calls, smart mobile phone apps, radio/TVs, videos, and the Internet.

d: FARM MONITORING/FORECASTING PLATFORMS

Farm monitoring/forecasting platforms are integrated with the most precision farming and smart mechanization services to manage and optimize the food production process [80]. Farm monitoring is achieved through the data obtained from IoT, drone technology, satellite aerial imaging, etc., and customized to meet specific farm requirements. We can perform trend analysis and prediction from big data analytics of historical and current data from the farm. Farmers can use the results from farming monitoring for a variable-rate farming application of inputs to different farm sectors. Forecasting/prediction of farm yield is possible with additional data from weather/metrological centers. Yield prediction and what-if analysis are also performed from these data to improve output at minimum inputs in a sustainable farming approach. Farm monitoring platforms also provide early warning systems to farmers to mitigate the risk of low yields due to unfavorable environmental conditions like bad weather, pest, and disease invasion. Examples of farm management software include FarmLogs,[28] AgWorld,[29] Agrivi,[30] Trimble,[31] FarmERP,[32] etc. In summary, Farmers can use farm monitoring platforms to predict/measure farm profit; create crop plans; track and measure field activities; manage farm risk portfolios, and track and monitor field workers' progress. In addition, farmers can also use these platforms for farm accounting and management (crop, livestock, inventory, etc.).

[26]http://www.fao.org/e-agriculture/blog/icts-and-agricultural-extension-services
[27]https://ikore.org/e-extension-program/
[28]https://farmlogs.com/
[29]https://www.agworld.com/za/
[30] https://www.agrivi.com/en
[31]https://www.trimble.com/
[32]https://www.farmerp.com/

e: AGRI-FOOD E-commErcE SERVICES

Agricultural e-commerce service is the application of ICT in the distribution of farm produce to reduce its inefficiency, add transparency to the value chain, and increase farmers' income. It enables farmers to sell farm produce directly to buyers (retailers, consumers, and companies using agricultural produce as raw materials in the manufacturing processes [81]. Other benefits of agricultural e-commerce include reduced wastage, financial inclusion of mobile money, increased productivity, and its positive impact on adjacent services. The reasons for the low adoption of e-commerce in Nigeria include the logistic complexity of handling perishable agricultural produce, lack of standard measurement for some agricultural produce, the existence of a well-organized middlemen structure in the agri-food supply chain, final consumers' preference of accessing some agricultural produce in person instead of online, and the need for farmers to sell their produce in bulk instead of retailing to final consumers. Zeng *et al.* [82] gave a comprehensive review of all general factors affecting agri-food e-commerce adoption and development.

Agri-food e-commerce enablers include the following;

- **Urbanization.** The more young people migrate/drift to urban areas, the better the chances of adopting agri-food e-commerce platforms.
- **Smart Mobile Phone penetration.** The penetration of smartphones and internet connectivity is increasing rapidly in Nigeria. This has led to more network coverage and increased accessibility to the Internet. Agri-food e-commerce adoption will increase with an increase in the number of smartphone users in Nigeria.
- **Mobile digital payment solutions.** The use of mobile money facilitates agri-food e-commerce in rural areas where banking services are not present. Mobile money could be an alternative secure payment method for agric-food to produce transactions in e-commerce platforms. Most telecommunication operators in Nigeria now operate their own mobile money. An efficient digital payment solution is necessary for the effective adoption of agri-food e-commerce.
- **Logistics and Infrastructural Networks.** Good road networks, train transportation, the availability of haulage services for agri-food is a strong enabler for agri-food e-commerce adoption in Nigeria. Logistics also include setting a standard measurement for agri-food produce, standard processing, and storage. An effectively distributed supply chain is necessary for the wide adoption of agri-food e-commerce.
- **Farmers' readiness.** All farmers (small, medium, large, and co-operatives) must be willing to incorporate e-channels into their farming operations to adopt agri-food e-commerce effectively. This will involve training on how to use e-channels for

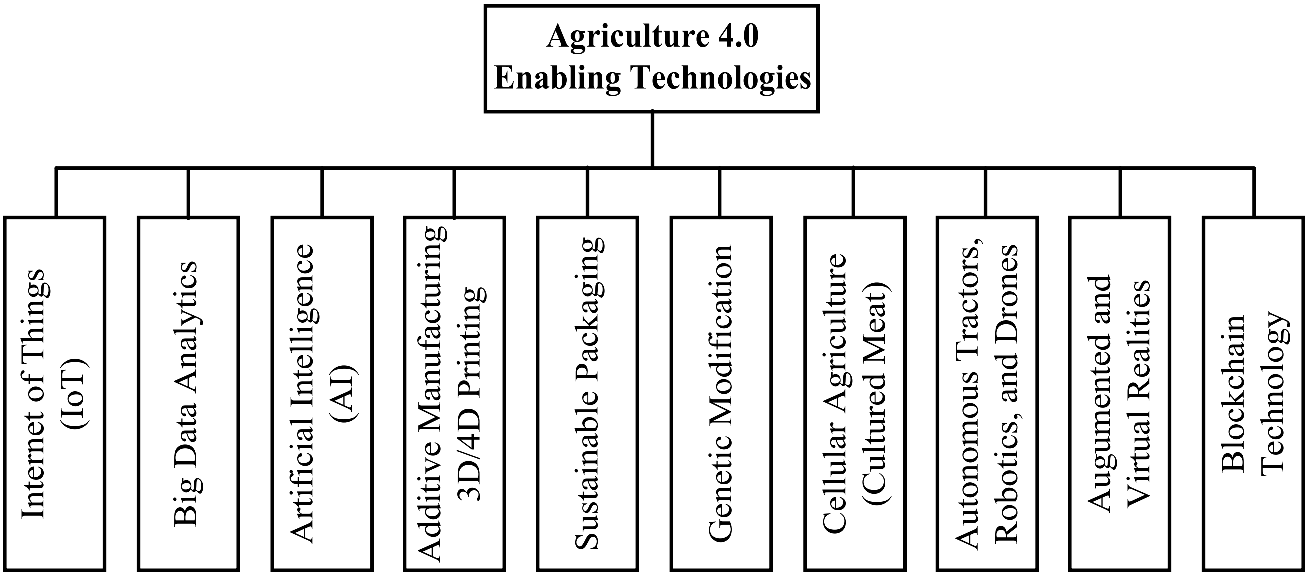

FIGURE 11. Enabling Technologies for Agriculture 4.0.

e-commerce operations. Third-party Agritect startups can also be interested in hosting websites and providing support for digital platforms for farmers.

Augmented and virtual realities will play a vital role in the future of e-commerce. Consumers will have a real look and feel of the agricultural produce of interest and make the shopping experience online eventful.

f: WAREHOUSE RECEIPT SYSTEM (WRS)

A warehouse receipt system enables a named depositor (farmer, farming corporative, or trader) to store their agricultural produce (of stated quantity and quality) at specified central storage (locations). In contrast, a warehouse receipt (WR) is issued to the depositor as evidence. Usually, the price of agricultural produce drops immediately after harvesting. WRS can increase farmers' income when adopted at these periods of an abundance of agricultural produce. In some cases, the depositor may pledge the WR to a lender (as collateral) or transfer it to a buyer after sales [83]. A WRS may be regulated in which a third-party (government-based or private sector-based) independent regulator is responsible for the licensing and registration of warehouse operators. It may also be non-regulated in which the whole operation is based on existing contract laws.

In light of agriculture 4.0, WRS can also centralize agricultural produce to reduce substandard products. One major problem facing rice production in Nigeria, apart from manual labor, is substandard processing leading to rejection of locally produced rice and high preference for imported rice even at a very high cost.

3) ENABLING TECHNOLOGIES FOR AGRICULTURE 4.0

To answer our research question 4, we shall consider the enabling technologies that apply to agriculture 4.0 from our reviewed studies. We summarized the enabling technologies for agriculture 4.0 full implementation in fig. 11

a: INTERNET OF THINGS (IoT)

IoT means the internetwork of things (sensors and actuators) and not humans (machine-to-machine communication, M2M). IoT connects physical and digital components in a network while transmitting measured (necessary) data without human intervention. These devices have the characteristics of low cost, low computational capabilities, small storage, and long battery life (about $10 - 15$ years for 5G mMTC use case). Each IoT has a unique identifier (UID), which operators can access at any time through a telecommunication network (wired or wireless), the Internet, or any other radio technologies (RFID, NFC, Wi-Fi, Bluetooth, Zigbee, LoRaWAN, etc.). IoT devices' numbers and applications are growing exponentially, from 8 billion devices in 2018 to an estimated 31 billion devices by the end of 2020, with a global market spending of about \$1.29 trillion. There are five categories of IoT; consumer, commercial, infrastructure, and military IoT (according to security today[33]). They have applications in personal consumer goods, health, agriculture, production, automation, automobile, building, etc. IoTs are used for smart sensing, monitoring, and controlling in precision agriculture. Farmers can use it in animal health monitoring, plant monitoring, and aquatic life monitoring. The information sensed and monitored by IoT can include temperature, pressure, humidity, blood pressure, etc. All IoT has three layers; the sensing (layer 1), the network (data transfer – layer 2), and the application (data storage or processing – layer 3) [84]. Controlled environment agriculture is possible with IoT.

[33]https://securitytoday.com/articles/2020/01/13/the-iot-rundown-for-2020.aspx

There are several literature reviews on IoT applications in agriculture [21]–[23]. Four open research issues on IoT application in agriculture include the need for professionally customized agricultural sensors, wireless power transfer (ambient energy harvesting) to IoT sensors, cross-media/technology communication, and robust wireless networks for IoT applications [24]. We need professional customized biosensors for livestock and plant phenotyping with high quality, resolution, and reliability. The recent research effort is being directed to sensorless agricultural sensing using radio signals. Ding and Chandra [85] use Wi-Fi for the measurement of soil moisture and electrical conductivity. Generally, we may install IoT devices on different media, such as underground, underwater, trees, livestock, etc. It is sometimes challenging to replace sensors and batteries in such media, hence the need for wireless power transfer/charging to ensure these installed devices' continuous operation. Due to the rapid advances in sensor technologies, there may also be a need to replace some already installed sensors with newly improved versions, which may be difficult in bio-nano things. Yang *et al.* [86] investigated the application of photovoltaic agricultural IoT using distributed wireless chargers. Another research trend to solve this problem is harvesting energy from the environment (Ambient energy harvesting). Ambient energy can be harvested from rivers, fluid flow [87], from the movement of the train [88], and ground surface [89]. Farmers can install agricultural IoT in indoor greenhouses, outdoor farmlands, underground areas, and even underwater. No single networking standard is self-sufficient for all these communication boundaries; hence, cross-technology communication is needed. Tonolini and Adib [90] investigated inter-boundary communication between air and water. A robust wireless network that can withstand the effect of changes in environmental factors (temperature, relative humidity, multipath, etc.) is another IoT research challenge. Generally, the performance of a network is affected by variations in these environmental factors. The effect of changes in temperature on mesh networks was investigated by Boano *et al.* [91], while authors of [92] studied the same effect on long-range (LoRa) networks.

b: BIG DATA AND CLOUD COMPUTING

Big data is a computer science field concerned with the analytics of big (large and complex) data to draw useful information. On their own, the individual data may not make much sense, but when analyzed on a large scale using artificial intelligence, helpful information, trends, and patterns can be drawn from big data analytics. Big data uses statistical analysis, optimization, inductive statistics, and principles from nonlinear statistics to derive laws (regression, nonlinear interactions, and causal effects) from large data sets with low information density to discover relationships and dependencies or perform forecast outcomes behaviors [25]. Five Vs characterize big data; volume, velocity, variety, veracity, and value [93]. Big data requires high computation, storage, and processing resources, which the IoT network cannot handle in isolation. Edge and Fog computing technologies (Cloud computing technologies) enable processing information at the edge and IoT networks, respectively. With big data analytics, the prediction, inferences, and smart decisions of farm management are possible through third-party data analytics agritech companies. We can also analyze guidance systems and satellite imaging data through big data analytics. Cloud computing provides three distinct services; Software-as-a-Service, Infrastructure-as-a-Service, and Platform-as-a-Service (SaaS, IaaS, and PaaS, respectively). Cloud computing enables smart farms to uninterruptedly access the above resources by paying for only the services used. Modeling, data storage, analysis, and forecasting can be done without the heavy high initial installation and maintenance cost of such services by farmers. Li *et al.* [94] investigated how to use big data for fault analysis of agricultural machinery.

Big data adoption in agriculture is hindered by agricultural data security and ownership, data interoperability, lack of decentralized machine learning, and shortage of technical experts.

c: BLOCKCHAIN TECHNOLOGY

Blockchain technology enables recording information digitally that is very difficult to change, hack, or alter. It consists of an increasing list of records (blocks), with each block containing a cryptographic hash of the previous record. It is a digitally distributed ledger system with seven distinct properties: programmable, secure, immutable, unanimous, distributed, anonymous, and time-stamped. Blockchain technology is secured because all its records are individually encrypted; it is immutable because any validated record in Blockchain cannot be reversed or changed. The approach is unanimous because all participants must agree to the validity of each entry. All network participant has a copy of the transaction records for transparency. It is anonymous because the identity of all participants is either anonymous or pseudonymous. Finally, all its records are time-stamped blocks. Blockchain technology enables traceability, information security, and efficient use of resources within the agriculture 4.0 context. Some benefits of blockchain technology adoption in agriculture 4.0 [18] include reduction in food wastage by detecting bottlenecks in the agri-food supply chain; combating food fraud such as fraudulent labeling of food, thereby increasing food safety. Other benefits include preventing price extortion and delay payments while simultaneously eliminating intermediaries in the agri-food supply chain, thereby increasing farmers' earnings; easy identification of contaminated and substandard foods leads to increased safety, quality, and reduced contamination risk; and data security by ensuring data integrity, preventing tempering and single point of failure.

Caro *et al.* [26] introduced AgriBlockIoT, a platform that integrates IoT and blockchain technologies using hyperledger sawtooth.[34] AgriBlockIoT ensured easy traceability

[34] https://www.hyperledger.org/use/sawtooth

within the agri-food supply chain stakeholders (ten blocks involved are raw material purchasing, planting, growing, farming, harvesting, delivery to the processor, processing, delivery to retailers, retailing, and consuming). Similarly, Salah *et al.* [95] proposed an Ethereum-based[35] Blockchain traceability platform for Soybean. Zhang *et al.* [96] proposed a hyperledger fabric-based[36] blockchain safety management platform for grains that guarantees food security and enhances safety process traceability within the grain supply chain.

The challenges to blockchain technology adoption include;

- It is dependent on internet availability and infrastructure capacity.
- It has interoperability issues with other platforms, as most blockchain platforms operate in isolation [97], [98].
- It has scalability issues as Bitcoin and Etherum can handle less than 20 transactions per second instead of millions of transactions per second required for a typical agri-food supply chain.
- It has high energy consumption issues for operations like Bitcoin mining and complex convergence (consensus).
- It has security and privacy issues as Blockchain is now a primary target of interest to cybercriminals [99].

d: ARTIFICIAL INTELLIGENCE (AI)

Artificial intelligence involves the intelligence demonstrated by machines or computers. It is the study of intelligent agents. It affects devices that perceive their environment and maximize their chances of successfully achieving their goals. AI describes machines that mimic human cognitive functions like learning and problem-solving. AI makes machines more capable of understanding human speech, competing with professionals at the highest levels of strategic games, autonomously operating vehicles, intelligent routing and content delivery networks, and military simulations.

Modern AI approaches include deep neural networks (computational intelligence), statistical methods, and traditional symbolic AI. The tools commonly used for AI applications include search and mathematical optimization, neural networks, and strategies based on probability and economics. The following fields are strongly related to AI; computer science, information engineering, mathematics, psychology, philosophy, linguistics, etc.

All enabling technologies of agriculture 4.0 require the application of AI at one point or the other. AI applications include machine learning, natural language processing, expert systems, computer vision [100], robotics, etc.

e: ROBOTICS

Robots are used in agriculture to automate simple, dirty, dehumanizing, repetitive, or dangerous tasks (like weed control, planting, harvesting, sorting, packing, or pest control), thereby enabling farmers to focus on more critical tasks [101]. The application of robotics to the agri-food supply chain is demanding due to agricultural food production's peculiarities. The produce is unstructured, delicates, slippery as they can easily be bruised. Four essentials service units of agricultural robots include guidance, detection, action, and mapping [102]. These four service units are interrelated in operation. The guidance unit is responsible for the navigation of the robot within the farm environment. A robot's navigation within a farm could follow a gridded path (with no time constraint) or trajectory (with time constraints). The robot uses information (from sensors) about its location on the farm to aid its navigation. The detection service unit is responsible for the extraction of biological features from the farm. This could be in the form of detecting between a crop plant and a weed or differentiating a ripe fruit from others. Robots use range lasers, ultrasonic devices, and artificial vision cameras for their detection function. The action service unit is responsible for executing the specific task the robot is programmed to do. Some everyday actions performed by robots include grasping, placing objects, and carrying [103]. Grippers (hands of robots) are versatile components of robots interacting with the farm and objects to supplement or replace humans to perform repetitive, tedious picking and placing manipulations. A robot manipulator handles heavy materials on the farm. Mapping is the creation of the farm with its most significant features. Mapping is concerned with how the robot interprets its surrounding environment and stores information regarding such an interpretation.

f: SMART MECHANIZATION AND DRONE TECHNOLOGY

Smart machinery and drone technology are other enabling technology for agriculture 4.0. Smart mechanization involves using autonomous tractors/drones for planning, automation, monitoring, optimization, and management of farm operations in providing more food sustainably from our limited land resources and changing climatic conditions for our teeming population. Smart mechanization uses IoT sensors, software, autonomous solutions, and artificial intelligence for soil preparation, planting, crop treatment, farm monitoring, harvesting, and processing using data from the farm. Autonomous tractors can eliminate operator fatigue by ensuring more daily working hours (making most of the short favorable weather conditions). Smart machinery is equipped with advanced obstacle detection using appropriate technologies and sending automated alerts to an operator for further instructions (to avoid an obstacle or run over depending on the barrier's nature). In some cases, when an obstacle crosses the programmed path of the smart machinery, it stops and resumes operation when its path is cleared. There are five levels of autonomy defined by Case IH [104] of CNH international[37];

[35] https://ethereum.org/en/
[36] https://www.hyperledger.org/use/fabric
[37] https://preview.thenewsmarket.com/Previews/CNHA/DocumentAssets/500708.pdf

- **Level 1: Guidance:** These smart machines are equipped with GPS information to automatically follow a pre-programmed route with a driver in the cab.
- **Level 2: Coordination and Optimization:** These smart machines are equipped to communicate, transmit data, and synchronize their operation with other machines. For instance, a smart tractor (with an operator in a cab) is coupled with a harvester and a storage machine whose operation is synchronized.
- **Level 3: Operator Assisted Autonomy:** This is when two or more machines operate simultaneously on a farm, with a driver in one cab operating all the machines. This is the proposed solution for scenarios when there is a shortage of trained operators at a farm.
- **Level 4: Supervised Autonomy:** This level is when two or more smart machines (tractors) operate autonomously (without an operator in a cab) on a farm with an operator on the ground for supervision.
- **Level 5: Full Autonomy:** This level is when all autonomous tractors (smart machines) are completely cabless, and no operator is physically on the farm but in the office or central control room monitoring smart machine operations and responding to all necessary alerts.

Drone technology (Unmanned Aerial Vehicle) adoption in agriculture is gaining popularity. Farmers can use them in terrain where other agricultural smart machinery adoptions are not possible [105]. Drone technology is applicable in the following five areas of agriculture.

- Farm planning data acquisition and analysis. Creation of 3-D maps of the farm and soil property analysis of farm at the planning stage.
- Seed Planting of a farm, resulting in drastic production costs. The seedlings are mixed with appropriate nutrients and shot on the prepared farmlands.
- Farm spraying with pesticides and herbicides.
- Farm irrigation at an economical and effective rate.
- Farm monitoring for diseases, pests, and weeds.

g: ADDITIVE MANUFACTURING

Additive manufacture (3D and 4D printing) is computer-controlled three-dimensional manufacturing by depositing materials in layers. It uses binder jetting, directed energy deposition, powder bed fusion, sheet lamination, vat polymerization, and material extrusion in creating new three-dimensional objects. Three additive manufacturing technologies are sintering (melting materials without liquefaction to create complex, high-resolution products), melting (electron beam), and stereolithography (photopolymerization whereby an ultraviolet laser is fired into a vat of photopolymer resin to create torque-resistant ceramics parts able to endure extreme temperature. With the inclusion of biodiversity in greenhouses, vertical farming, hydroponics farming, urban farming, etc., there will be a need for customized tools and grippers that can be printed using additive manufacturing [106]. Farmers can also print food from its constituent ingredients, and engineers can provide robots with self-repair capabilities utilizing this technology [107]. 4D printing uses 3D techniques to transform (decomposed) a printed object to another structure due to external energy inputs (temperature, light, hot water, etc.). The fourth dimension added to 3D is time. This technology can be used for self-repairing systems in the future by varying appropriate stimuli to obtain the desired shape [108].

h: AUGMENTED AND VIRTUAL REALITY (AR AND VR)

Augmented reality (AR) uses digital technology to superimpose generated text, graphics, images, etc., on the real physical view of objects, thereby providing an enhanced user experience [109]. AR user interface includes a screen, monitor, helmets, facemask, glasses, goggles, head-mounted display (HMD), window, windshield, etc. This technology blurs the boundary between the physical and digital worlds. For an AR user, the real and virtual worlds coexist. The user can obtain helpful information about an object or location while interacting with virtual content in the real world. The enhancement (simulated perceptual information) of AR may sometimes affect multiple sensory modalities like visual, auditory, haptic, olfactory, or somatosensory. Virtual reality uses technology to immerse a user into a simulated environment through an avatar (a material/physical medium of interacting and experiencing the artificial world). AR and VR applications in digital agriculture will revolutionalize the agri-food supply chain sector. Educating farmers on using new emerging digital agricultural technologies, planning, agricultural e-commerce, etc., is one area of using these technologies.

i: OTHERS (SUSTAINABLE PACKING, GENOMICS, AND CELLULAR AGRICULTURE)

Other disruptive technologies include bioplastics for sustainable packaging (e.g., starch-based bioplastics [110]) that will result in entirely biodegradable waste on its stated lifespan. This is intended to solve the plastics problem that takes several years to decompose and constitutes a severe threat to aquatic life. Genetic modification (genomics) enables new breeds with improved yields and resistance to harsh environmental conditions. It can also develop crops with particular vitamins and minerals for healthy living [111]. Cellular agriculture produces food (agricultural produce) from cell cultures using different applicable technologies such as biotechnology, molecular biology, synthetic biology, and tissue engineering. Culturing food is another technology that can produce meat and grow plants in the lab (of commercial quantity) to ensure food security in the future [112]. Cellular agriculture has a lot of potential and positive environmental effects for the future of farming. It will enable space astronauts to culture meats on spaceships in the future while eliminating animal cruelty in slaughterhouses. Cellular agriculture has applications in meat, dairy, eggs, gelatin, coffee, horseshoe crab blood, fish, fragrances, silk,

TABLE 5. Threats to food security and proposed solutions through the adoption Agriculture 4.0.

S/No	Food security threat	Remedies through the adoption of agriculture 4.0
1	Insufficient food supply due to a drastic increase in population	The use of autonomous machines, robots, and drone technology to ensure large-scale farming resulted in a sufficient food supply.
2	Poor food quality that does not meet the dietary needs of consumers	The use of digital technologies in cellular agriculture to enhance inputs (seeds) with desired nutritional constituents.
3	The high cost of quality food that meets dietary requirements	The use of agriculture 4.0 technologies will improve yields, optimize food production, and reduce the production cost, thereby reducing agri-food produce
4	Impact of agricultural activities on the earth, thereby making it unsustainable.	Sustainable farming through variable-rate application and farming differently by making the best use of available resources. Sustainable packing technology together with sustainable farms.
5	Inadequate farming land and degraded farmlands	The use of greenhouses, urban farming, vertical farming, and hydroponics (farming on water)
6	Poor crop rotation	With variable-rate farming, crop rotation won't be necessary.
7	Overgrazing	Farm monitoring technologies will eliminate overgrazing
8	Climate change	The use of greenhouses, desert farming, and variable rate farming.
9	Food waste	Optimization of planting, harvesting, processing, and storage.
10	Fraudulent labeling	Blockchain and big data analytics will eliminate fraud.

Source: Authors

leather, pet food, etc. There is a religious and ethical opinion by different stakeholders on these technologies.

4) HINDRANCES TO THE ADOPTION OF AGRICULTURE 4.0 IN NIGERIA

The major hindrances to adopting agriculture 4.0 in Nigeria are the high initial cost of implementation, high technical know-how requirements, inadequate maintenance personnel for the smart systems, lack of historical data to facilitate informed decisions, and lack of interested investors (perceived increased investment risk in the agricultural sector). Other infrastructural-related hindrances include lack of good roads to farmlands, inadequate electricity supply resulting in high production cost, and inadequate telecommunication facilities. Ideological factors include farmers perceiving digital agriculture as a pathway to unemployment and lack of biodiversity as only the selected food types are produced in large quantities. Generally, the choice of food type produced is not made by the final consumers but by the producers. In addition, violence, insecurity, political and economic instability, corruption and nepotism, abject poverty prevalence in Nigeria, and poor policy implementation.

IV. IMPLEMENTATION FRAMEWORK FOR AGRICULTURE 4.0 IN NIGERIA

Interested Nigerian stakeholders should implement agriculture 4.0 with strategic (long-term) objectives. It will be financially and technologically intensive; hence, Nigerians will require viable investments and technology transfer from precision agriculture companies in developed countries (US, Netherlands, etc.). Stakeholders can do this by signing contracts lasting for up to three years after project commencement to enable farmers and their workers to learn under expert supervision. Agriculture 4.0 is data and information-driven; hence, stakeholders' consultation and collaboration for effective and successful implementation will be a frequent need. Digitization of the food production, processing and storage system in the developed countries may not wholly align with our local (staple food) requirements. Hence, recalibration, modification, and reengineering of the technologies to meet our local food requirements may be necessary in some cases. Agriculture 4.0 will require collaborative research and development efforts from all stakeholders. A pioneering project of this nature will require a well-defined business plan, business model, operation support, and business support system for its realization in Nigeria. We will need a paradigm shift from our traditional feeding preferences of consuming carbohydrates to the food of healthy dietary contents. The choice of the type of food to produce, where such food should be produced (location), who should be the producers (farmers and scale of production), and for whom (targeted market segments) are very crucial at the planning stage. Stakeholders should critically examine the feasibility, profitability, acceptability, and sustainability of any chosen path before its actual implementation.

First, we need to identify the problems facing food security in Nigeria and how agriculture 4.0 can help us combat these challenges. We summarized our observations from the reviewed literature in Table 5.

A. IMPLEMENTATION OF AGRICULTURE 4.0 IN AGRI-FOOD SUPPLY CHAIN

Agrifood Supply Chain (ASC) is a sequence of physical and decision-making processes involving an agricultural product, information, or money flow that meets the final consumers' needs. ASC cuts across distinct but interrelated agricultural business units that collaborate to minimize cost, wastage, risk, and maximize revenue or profit through the satisfaction of stakeholder's needs [30]. Agrifood Supply Chain Management (ASCM) integrates planning, implementation, coordination, and control of all Agrifood business units and activities necessary for the efficient production and delivery of agri-food that satisfies market requirements [26], [113]. ASCM involves the following six fundamental processes or tasks; plan, analyze, develop, integrate, deliver, and return. ASCM associated processes are shown in Fig.12.

The implementation of agriculture 4.0 will be at each of the eight interrelated and distinct food production stages, farm to fork (see fig.)13. The respective tasks carried out at each production stage depend on four factors. First is the type of

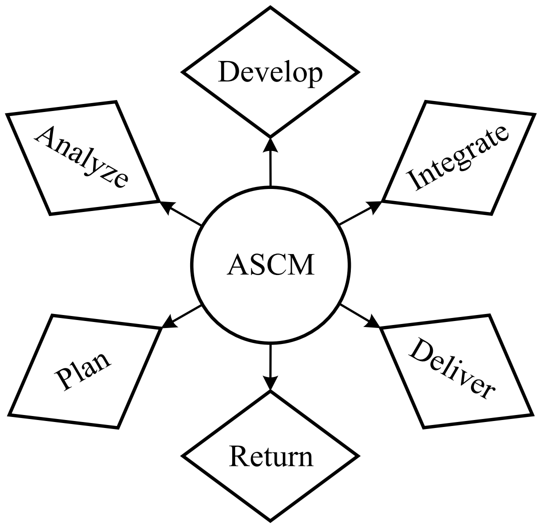

FIGURE 12. Agrifood Supply Chain Management processes/tasks.

food expected (what is being produced?), second is the farm's location and prevailing environmental conditions (where is the farm located?). The third factor is the type and scale of farming (How is production done?), and finally, the targeted market segment (For whom is the food produced?).

1) FARMING INPUTS

Farm inputs are the initial resources required to commence the food production process. These factors include land, finance, improved seeds (other inputs), fertilizers, pesticides, water for irrigation, historical data of farming/farmland, farming technologies, and agricultural machinery. Fig. 14 shows a summary of all inputs required for food production.

a: LAND

The term land refers to the physical arable land used for farming. Nigeria is endowed with diverse soil types suitable for farming different crop types. A majority of Nigeria's farming land is used for small-scale (subsistence) farming. In Nigeria, the land ownership system makes the availability of large land hectares for medium to large-scale commercial farming difficult.

b: FARM FINANCE

Finance is a key farm input as its availability influence the success and smooth running of the food production system. Finance is necessary for the acquisition of all other farming inputs. Agricultural 4.0 is finance-intensive; hence, it needs an adequate finance source for its smooth adoption. Finance expenditure required as farm input can be grouped into capital (Capex) and operational expenditure (Opex). Farm finance sources include private equity, venture capital, angel capital, family loans, financial leases, value chain finance, credit unit, crowdfunding, investment funds, etc.

c: IMPROVED SEEDS AND OTHER INPUTS

Improved seeds, seedlings, stems, tuber, etc., are required as inputs in crop cultivation, while improved hatchlings (livestock and fishery) are key inputs in livestock production. The planted input (seeds, seedlings, stem, etc.) directly determines the farm's final yield. Cross-breeding and cellular agriculture play a vital role in improving breeds planted in agriculture 4.0.

d: WATER (FOR IRRIGATION AND OTHER FARM OPERATIONS)

Water is another essential farm input that must be accounted for at the planning stage. Water is required for irrigation in crop cultivation and livestock farming (fisheries, poultries, animal ranch, etc.). We must take the availability of rivers or sources of water for irrigation and other farm requirements into serious consideration.

e: FERTILIZERS

Fertilizers are material substances (natural or synthetic) applied to soil or plant tissues to improve the supply of required nutrients by the plant, thereby increasing yields or promoting certain desired qualities in the final plant produce. The fertilizers as are necessary for improved inputs may differ from conventional fertilizers. There is a need at the planning stage to identify the essential nutrients vital to farm yield improvement and make provisions for such inputs.

f: PESTICIDES

Pesticides are pest-controlling chemicals (substances). In agriculture, pest refers to any harmful plant or animal or causes a nuisance to crops and livestock. It includes insecticides, herbicides, nematicides, fungicides, bactericides, animal repellents, insect repellents, etc. Pesticide requirements differ based on environmental factors; however, provision should be made at the planning stage for pesticides.

g: DATA (Historic AND FARMING CONDITION DATA)

Agriculture 4.0 is heavily data-driven. Historical data of farm parameters such as temperature, humidity, soil pH, rainfall, sunshine, etc., must be analyzed at the planning stage. The prevailing environmental parameters of the farm must also be measured and analyzed. Appropriate digital technologies can be applied when the dominant ecological parameters are not favorable for the proposed farm.

h: AGRICULTURAL MACHINERY

Smart and autonomous machinery such as autonomous tractors, smart planters, harvester, agricultural drones, and agricultural robots are also inputs for the planning stage. Other factors and inputs already discussed will influence the choice of agricultural machinery required.

2) FARMING SCALE

Farming scale can be grouped into three; small-scale, medium-scale, and large-scale farming based on several factors such as land cultivated, number of labor used, the economic impact of the farm, and contribution of the national farm GDP. The amount of investment in farm inputs is a function of the farming scale adopted in a particular farm.

FIGURE 13. Stages of agrifood supply chain.

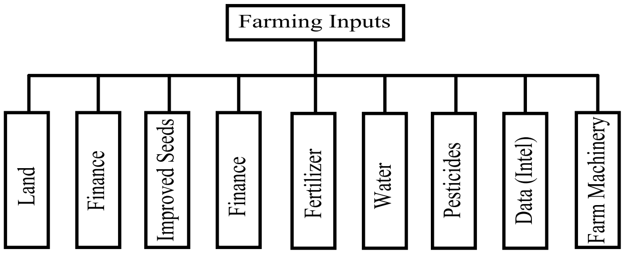

FIGURE 14. Agricultural farming inputs required for food production.

a: SMALL-SCALE AGRICULTURE

Small-scale agriculture (smallholding farming or family farming) is characterized by farmlands of less than 5 hectares, mixed cropping, family labor, and usually located in rural areas. About 90% of the 570 million farmers globally are small-scale farmers living in poverty, facing severe food insecurity, and have limited access to market agricultural extension services (FAO[38]). In Nigeria, small-scale farming constitutes about 88% of our agriculture, cultivating an average of 0.53 hectares of land, and usually headed by men, while females head about 13%. Small-scale farming in Nigeria relies heavily on rainfall for irrigation as less than 2% does irrigation. About 16% of smallholding farming in Nigeria has access to motorized agriculture, 44.5% uses fertilizers, 6% receives extension services, 7% has access to credit facilities, and only about 26% of their agricultural products are sold as the majority of produce is met for domestic consumption (FAO[39]).

Today (2020), most Nigerians' food is from small-scale farmers [41]. Our proposed framework shall incorporate small-scale farming at level 3 of its implementation. Small-scale farming is not economically viable for digital agriculture due to the high initial financial cost of agriculture 4.0.

b: MEDIUM-SCALE AGRICULTURE

Medium-scale agriculture is characterized by farmlands of size ranging from 5 – 100 hectares, monocropping or mixed cropping, owned by relatively wealthy and influential (urban-based or rural elites) farmers, and mechanization, sometimes with manual labor. Farmers in these categories have education and access to agricultural extension services. Smallholder farmers can obtain entrants to medium-scale farming through stepping-up or stepping-in [114]. Stepping-up occurs when small-scale farmers grow and expand their farming operations to medium-scale farming. Stepping-in occurs when a farm owner hires a farm manager and a professional to manage a new medium-scale farm. Due to the high initial cost of land in urban areas, this scale of farming is encouraged in the outskirts of urban centers or areas with easily accessible land from communities.

Our proposed framework for agriculture 4.0 shall adopt medium-scale agriculture at the first level of its implementation. This agriculture scale is economically viable and feasible for digital agriculture in our Nigerian context.

c: LARGE-SCALE AGRICULTURE

Large-scale agriculture (commercial farming) is characterized by farmlands greater than 100 hectares, monoculture farming, intensive use of mechanization, and high economies of scale. Ownership of large-scale farms is giant company-based. They invest heavily in storage, processing, automation, mechanization [115]. Large-scale agriculture is driven by abundant agricultural land, favorable environmental and climatic conditions, access to external financial resources, and the automation of repetitive tasks. This type of farming is ineffective in developing countries with abundant and cheap human labor. A decline in farming biodiversity and wealth inequality are other demerits of this type of farming. Large-scale farmers also have substantial economic (monopoly), social, and environmental impacts, especially if automation and sustainable farming approaches are not adopted.

We shall adopt large-scale agriculture at level 2 of our proposed implementation framework. Critical success factors in large-scale farming include successful farmland consolidation, heavy investment in machinery, effective fundraising/financing from internal and external sources, and the implementation of modern digital technologies. A good study of the land-use system is the key to ensuring successful legal acquisition and consolidation of farmland.

3) FARMING APPROACH

Food production (from plants and animals) can be done on land or water, domesticated or undomesticated, in a controlled environment, semi-controlled environment, or in an uncontrolled environment. Farming on land is the most common form of agriculture, cultivating crops (plants) and animals' rearing. While farming on water could be in the form of aquaculture, mariculture, hydroponics, and hydroculture. While the most common form of agriculture involves domesticating plants and animals for direct or indirect human needs, some agricultural forms such as fishing, hunting, forestry (lumbering), etc., include gathering undomesticated food from the wild (an unsustainable approach of farming). The domestication of plants and animals can also be done in an uncontrolled environment, semi-controlled environment,

[38] http://www.fao.org/family-farming/themes/small-family-farmers
[39] http://www.fao.org/family-farming/themes/small-family-farmers.

or completely controlled environment. An uncontrolled environment is when farming is subjected to natural environmental factors. In a semi-controlled environment farming, some essential biotic and abiotic factors necessary for improved food production, such as water, fertilizers, etc., are augmented manually. While in a completely controlled environment (like greenhouses), farming of certain agricultural products is possible in environmentally unfriendly locations.

There are six types of crops (plants) cultivated in agriculture; food crops (for human consumption, e.g., fruits, vegetables, grains, etc.), feed crops (for feeding livestock, e.g., oats, alfalfa, forage, hay, etc.), fiber crops (for textile and paper production, e.g., cotton, hemp, etc.), oil crops (for making edible oil and biofuel, e.g., palm oil, soybeans, canola, corn, etc.), ornamental crops (for landscaping and gardening, e.g., flowers, dogwood, etc.), and industrial crops (for industrial use, e.g., rubber, wheat, etc.). Animal husbandry could be in the form of a dairy farm, poultry, fish farming (pisciculture), insect farming (such as bee – apiculture), dog farming, horses, pigs, cattle, sheep, etc. Seaweed (kelp) farming is the cultivation and harvesting of seaweed for food, biofuel, chemicals, and fish farms. Other marine life like crustaceans, mollusks, amphibians, invertebrates, etc., are also farmed for food production.

We shall consider farming approaches to include open farms, greenhouses, urban farming, vertical farming, desert farming, and hydroponics, (see fig.15 in our proposed implementation context.

a: OPEN FARMS

In our farming approach, open farms refer to farms open to environmental biotic and abiotic factors. There may be a physical fence or demarcation between farms, but there is no closed boundary between the farm and its surrounding environment. These farms rely on natural rainfall, sunshine, etc., for their operation. There may be compensation for the shortage of some of these variables in certain situations. Most agricultural farms are open. A majority of our proposed farms under agriculture 4.0 in Nigeria will be open farms with variable rate inputs.

b: GREENHOUSES FARMS

Greenhouses are enclosed farms made of transparent glass (or plastic) material with metal (or wooden) frames used only for growing crops. It enables complete control of all biotic and abiotic factors of a farm. The temperature, humidity, pH, sunlight, etc., of a farm can be controlled using a greenhouse [116]. Greenhouse farms can exist in different forms, such as glasshouses (structures enclosed with glass), shade houses (designs surrounded with shade from woven or other materials), or screen houses (buildings covered with nets or screening materials). Greenhouse design plans start with the foundation, which acts as an anchor of the greenhouse structure to the ground. Both inner and perimeter foundations are usually constructed at an angle with a slope applied lengthwise to ensure optimal water (ice) discharge.

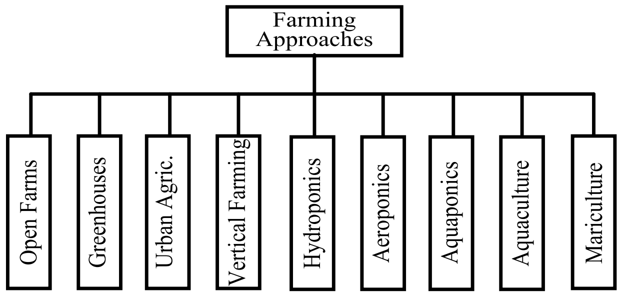

FIGURE 15. Agrifood farming approaches.

Five essential factors for a greenhouse's successful operation are; ventilation, heating, cooling, lighting, and carbon dioxide enrichment. Ventilation is achieved using vents and is often controlled automatically through computers and recirculation fans. Adequate ventilation helps in regulating the temperature and humidity of the greenhouse to an optimal level. It prevents the build-up of plant pathogens that prefer still air condition by ensuring the movement of air. The heating of greenhouses is more applicable to colder climates. Combined Heat and Power (CHP), also known as cogeneration, generates electricity, heat, and CO_2 simultaneously. Cooling is what is really needed for greenhouses in Nigeria. Cooling can be achieved through air circulation using the installed cooling vents, a pad and fan cooling system, or high-pressure fogging. The principle of cooling by evaporation is used to apply to greenhouses, with a resultant increase in humidity. Electronic controllers are used for the monitoring and control of temperature in greenhouses. Natural sunlight and artificial light (LEDs) are used in greenhouses to increase plant yields. Grow lights mainly can supply light even at night when natural sunlight is out. Concentrating plants together in the greenhouse results in the drop of CO_2 within the greenhouse. Carbon dioxide (CO_2) is necessary for plant photosynthesis, which directly influences better crop yield. CO_2 enrichment in greenhouses is achieved by fuel combustion to generate heating or electricity with CO_2 generation as a by-product.

c: URBAN AGRICULTURE

Urban agriculture involves the cultivation, processing, and distribution of food in or around heavily populated towns, cities, or metropolitans on a commercial scale. It includes animal husbandry, aquaculture, apiculture (beekeeping), horticulture, etc. Due to the high land cost in urban areas, it is usually practiced at the perimeters of cities. Urban farming includes creating fresher foods, using unutilized spaces, increasing food security, and reducing food waste due to proximity to food load centers. Urban farming can be in the form of vertical farming, hydroponics, aeroponics, aquaponics, microgreens farms, shipping container farms, and rooftops farming, mushrooms farming, etc. [117]. In our proposed framework for adopting agriculture 4.0, we shall focus on peri-urban farm locations for an efficient realization of commercial-scale urban farms.

d: VERTICAL FARMING (Plant Factory)

Vertical farms are indoor farms that use soilless technologies such as hydroponics or aeroponics to grow crops. Vertical farming technologies ensure the optimal use of land by stacking the level of yields on each other. It uses artificial lighting in a highly controlled crop growing condition to ensure all-year-round growing and harvesting ps irrespective of the farm location's environmental conditions. The crops cultivated in a vertical farm are characterized by high edible mass percentage, low plant height, fast-growing plant species, and short shelf life. The idea of vertical farming is to reclaim land from agriculture to forestry, save clean freshwater, reduce CO_2 emissions resulting from long transportation of food, increased variety (biodiversity) of food, and freshness of food. Despommier first used the term vertical farm, Dickson in his book on the subject [118]

There are three phases of implementation in vertical farming. The first phase involves the cultivation of leafy greens and vegetables. The second stage involves the cultivation of ground fruits like tomatoes, strawberries, etc. The final and third phase is the cultivation of staple foods and grains. The energy requirements increase as we move from one phase to another. Phase 2 requires 2.5 times more energy than phase 1, while step three requires 30 times more energy than phase 1. Energy consumption is mostly in the form of electricity used for lighting, heating, cooling, etc. [119]. Availability of cheap energy sources is a significant consideration for the successful implementation of vertical farming technologies; otherwise, farm produce from the plant factory will be too expensive to be economically viable. Researchers are intensifying efforts to explore alternative renewable cost-effective energy sources like geothermal energy, thorium energy, modular nuclear electricity generation, and biofuel to heat plant factories using vertical farming technologies.

e: HYDROPONICS, AEROPONICS, AQUAPONICS, AQUACULTURE, AND MARICULTURE [120]

Hydroponics [121] technology is the soilless cultivation of plants, in which nutrients are supplied to the crops through the water. The nutrients can be from organic sources or inorganic/artificial sources. The nutrients solution can be static or continuous flow in design. The nutrient solution will cause eventual loss of its nutrient after prolonged usage, and the answer is usually drained out and replaced with a new solution. The drained solution can mix with ocean water leading to water pollution. One major limitation of hydroponics is the limited air holding capacity of water, as one kilogram of water can only hold 8 milligrams of air, even if aerators are used. This means that inadequate aeration may result; hence, the continuous water flow is crucial for successful operation. Also, certain species of plants can quickly become waterlogged.

Aeroponics [122] is the cultivation of crops with no substrate. It involves growing crops in an environment that is saturated with nutrient-rich water droplets. This farming approach provides excellent aeration and water saving. Aeroponics requires 65% less water than hydroponics and one-quarter of nutrients under the same farming conditions. Mist is generally easier to handle than water in a zero-gravity environment; hence, aeroponics is of particular interest to NASA's space research.

Aquaponics combines aquaculture (usually fish farming) and hydroponics. The aquatic effluents resulting from fish waste and uneaten feeds accumulate in the water and increase its toxicity. This nutrient-rich water is filtered and pumped to the hydroponics section for crop cultivation. Aquaponics has five basic units; rearing tank, settling basin, biofilter, hydroponics subsystem, and sump. It has the water-saving capacity of hydroponics coupled with an added advantage of eliminating environmental pollution from wastewater.

Aquaculture [123]is the farming of aquatic plants and animals such as fish, algae, crustaceans, aquatic plants, etc. It involves both the cultivation of fresh water and saltwater plants and animals under controlled conditions. Marine culture is the cultivation of aquatic organisms for food in a marine environment. The four commonly used mariculture structures are floating cage, net enclosures, earth ponds, and a constant water circulation system.

4) FARMING OPERATION

Farming operations are activities carried out in food production that contribute materially to the final output. In crop production, there are four basic farming operations: land preparation, planting, farm monitoring and control, and harvesting. The farming operations required in animal husbandry will differ depending on the type of livestock or farm. The farming operation process flow is shown in fig.16.

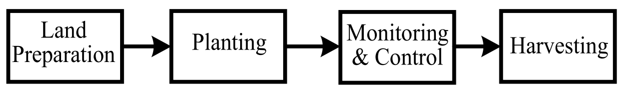

FIGURE 16. Farming operation process flow.

a: LAND PREPARATION OPERATION

Land preparation involves field selection, physical land preparation, and various smart IoT sensors for monitoring and control purposes. Field selection entails choosing the right type of soil and location for the farm. Physical land preparation includes mechanical preparations, irrigation system installation, soil improvement, etc. Mechanical preparation includes leveling the farmland, creating appropriate slopes for irrigation water flow, creating roads for farm workers and machinery, and physical removal of trees, rocks, etc. Irrigation system, sensor, and actuator installation are done before the actual planting and are dependent on the type of farm. Variable-rate input application may be made at this stage for heterogeneous soil before planting operation.

b: PLANTING OPERATION

Planting operation is done with the aid of tractor-planter assembly. The planter employed for a particular farming operation depends on the type of crop to be cultivated.

Planters exist in different sizes and rows. Critical factors considered during mechanized planting operations include plant spacing, planting depth, planting, transplanting stage, accuracy/precision of the planter, and speed of the planter. Optimal planter size is very crucial in agricultural mechanization design. If the planter is too heavy, it compresses the soil, thereby reducing the aeration of plants. Planting can also be done with agricultural drones or robots, depending on the crop/seeds being cultivated. The success of any farming operation is highly dependent on the efficiency of its planting operation.

With the adoption of agriculture 4.0 in Nigeria, we need more research in the design and customization of planters for our local staple food like yam, cassava, rice, etc., which may be missing in existing planters. We can achieve this through collaboration with top PA agritech and consultation with all stakeholders.

c: FARM MONITORING, MANAGEMENT, AND CONTROL

Farm monitoring uses IoT and sensor technologies to collect useful and real-time information about biotic and abiotic factors affecting farm operation. Abiotic factors such as temperature, humidity, sunlight intensity, soil pH, weather alerts, etc., are frequently monitored to determine the number of variable-rate inputs (irrigation, manure, fertilizers, pesticides, etc.). Biotic factors such as growth rate, yield, pests, etc., are also monitored accordingly. Management and control actions include corrective and sustaining actions put into the farming operation due to received monitoring information. Drone technologies, robotics, actuators, etc., are used for both management and control operations. Automation with artificial intelligence is the key at this stage of farming operations since most management and control operations are repetitive. Effective farm monitoring, management, and control are necessary to realize farming objectives and increase farm production yield. Farm monitoring, management, and control apps are integral components of precision agriculture technologies.

d: FARM HARVESTING OPERATION

Farm harvesting operation involves gathering ripened or matured crops produce. It is one of the essential stages of the cultivation process; if not adequately planned and handled, it could lead to substantial food waste. The harvesting of commercial agricultural produce is usually mechanized to save time, reduce waste, and make the farming operation attractive to youth, as manual harvesting is tedious, dirty, and demeaning. Harvesting machines are classified by the type of produce they harvest; hence there is a harvesting machine for crops, grains, root crops, vegetables, etc. A typical harvesting machine comprises traveling, reaping, and baler parts, while the combined harvester can efficiently implement four separate grain harvesting operations: reaping, threading, gathering, and winnowing. A combined harvester is highly economical and labor-saving.

5) FOOD PROCESSING

Food processing is any manipulation or process (physical, mechanical, biological, or biochemical) that transforms fresh agricultural produce into finished products for further use. They involve activities that make food looks and tastes its best by adding flavors, colors, and preservatives. Food processing increases the year-round availability of food, enhances toxin removal from food, and ensures food consistency and preservation. In addition, food processing reduces the incidence of food-borne disease and makes for easy marketing, distribution, and preparation by consumers. The processing of food can result in a decrease in the nutritional density of the processed food. It may also introduce several contaminants risks, resulting in health-related challenges such as cancer, type 2 diabetics, etc., or safety concerns from additives such as sweeteners, preservatives, stabilizers, etc. Food processing measurement parameters are hygiene, energy efficiency, minimization of waste, amount of labor employed, and minimization of cleaning stops. The quality, durability, and acceptability of agricultural products are highly dependent on the level of processing adopted.

Agricultural food processing could be primary, secondary, or tertiary. Primary food processing includes drying, threshing, winnowing, milling of grains, shelling nuts, butchering animals for meat, deboning, cutting meat, freezing and smoking (meat and fish), and canning food, etc. It is prone to the risk of contamination and spoilage. Control systems such as Hazard Analysis and Contact Control Point (HACCP) and Failure Mode and Effects Analysis (FMEA) are employed to reduce the harm during the primary processing of food. Secondary food processing is the conversion of food ingredients to edible food products. Different cooking methods, baking, sausage preparation, etc., are examples of secondary food processing. It may include physical processes such as milling, pressing, dehydrating, or chemical processes such as hydrolysis, hydrogenation, the addition of enzymes, or thermal processes such as heat treatment, fermentation, etc. Tertiary food processing is the commercial production of processed food (ready-to-eat foods) [124].

The following six novel food processing technologies are worth integrating for a digitized food production system; advances in membrane technology, supercritical extraction, and high-pressure processes. Microwave and radiofrequency technologies, ohmic, infrared heating, and cold plasma processing. Ultrasonication and hurdle technology, and sustainable food packaging technologies.

6) FOOD PRESERVATION AND STORAGE

Food preservation is any process that reduces or eliminates food spoilage, prevents food-borne illnesses, prolongs the durability of food for final consumption while maintaining its nutritional value, texture, and flavor. Food spoilage reduces food edibility due to physical, chemical, or microbial factors. Physical factors causing food spoilage include physical damage to food, moisture content migration (gain or loss), temperature, glass transition temperature, crystal growth, and crystallization. Chemical factors responsible for food spoilage are oxidation, proteolysis, putrefaction, Maillard reaction, pectin hydrolysis, and hydrolytic rancidity. Microorganisms like mold, yeast, and bacteria are the agents responsible for microbial food spoilage [125]. Food storage entails keeping the preserved food safe and in condition for future use. Food storage can be classified based on duration (short-term, medium-term, or long-term), scale (small-scale, medium-scale, or large-scale), or principle (physical, chemical, or biological). There should be sufficient food storage facilities at the various critical points of food spoilage. These vital points are immediately after food harvesting at the farm level, industrial storage level before the demand for food by distribution chain, transportation to distribution chain agents like wholesalers and retailers, distribution outlets, and the household level before final consumption.

Farmers should ensure adequate and conducive storage facilities for agricultural produce immediately after harvest. Centrally operated commercial agro-industrial storage facilities (warehouses, silos, etc.) privately owned should also be encouraged and established. This will reduce the initial startup and operation cost of long-term storage for farmers; a good example is the Global Cold Chain Alliance and ColdHubs in Nigeria. ColdHubs uses portable solar-powered cold storage for perishable food in markets to reduce spoilage and food wastage. Warehousing using modern technology is one major key to food security in Nigeria.

7) DISTRIBUTION AND LOGISTICS

Distribution and logistics is an integral part of the supply chain mechanism that prepares, implements, and monitors the adequate, efficient flow and storage from the origin (production) to the destination (consumption) of products, services, and related information to satisfy consumer and other stakeholder's (government and retail community). It comprises the packaging, transportation, marketing, and collaboration of all stakeholders in the agri-food supply chain [126].

Adequate packaging of food before transportation could significantly reduce spoilage. Transportation of agricultural produce in Nigeria involves using open trucks without proper packaging. There is improper vertical stalking of produce and truck loaders sitting on the farm produce in some cases. This results in spoilage, food quality degradation, and shell life reduction. There should be provision for the use of crates, bags, cartons, etc., for packaging before loading goods in closed trucks and adequate spacing of loaded goods to allow air circulation.

Long-distance road transportation of agricultural produce in an unconditioned environment is another major cause of food spoilage in Nigeria. Traders that transport food from northern to southern Nigeria suffers heavy losses in spoilage and livestock death due to poor transportation and food storage. This indirectly results in the high cost of food, thereby making food unaffordable. We intend to locate the production centers close to the food load centers. This will eliminate the need for long-distance transportation. Our framework shall incorporate mobile cold storage facilities for the food movement to ensure freshness and quality are preserved during transport.

Sales outlets shall be portable grocery stores and supermarkets known for fresh agricultural products. The traditional sales outlet for most agricultural produce in Nigeria is an open market, with inadequate packaging and food exposure to spoilage and other safety concerns. A lot of spoilage results from poor handling during post-harvest activities before the final consumption. The marketing functions to be addressed shall include;

- **Exchange functions:** This comprises buying and selling (demand and supply forces).
- **Physical functions:** This includes storage, transportation, and processing before final sale.
- **Facilitating functions:** This shall cover standardization, financing, risk-bearing, and market intelligence.

Standardization and risk-bearing are an integral part of sales and distribution, especially to ensure global distribution reach. Standardization identifies the fundamental grade limits or creates model processes and methods for producing, processing, and distributing products and services. Thus, standardization aims to make grade quality requirements consistent over space and time between buyers and sellers. In developed countries, some high-grade agricultural products are sold at a premium. Standardization and grading are based on product features of great value to consumers, facilitating agricultural products' marketing. Risk in agriculture includes uncertainties in weather, yields, costs, government policies, global markets, and other factors influencing agriculture that may trigger large farm income swings. Risk assessment means selecting options that reduce the financial consequences of those risks. Risks can be avoided, transferred, accepted, or mitigated based on the chosen assessment option. Five common risks associated with the agricultural supply food chain, according to the USDA (United States Department of Agriculture) [127], are

1) **production risks:** Risks relating to production processes of crops and livestock. The quantity and quality of goods produced are affected by weather, disease, pests, and other variables.
2) **Market (price) risks:** risk relating to farmers will receive the price for goods or the costs for inputs they have to pay. The essence of price risk varies considerably from product to product.
3) **Financial risks:** Risk that results when farmers borrow money that imposes a loan repayment commitment. Financial risk factors include rising interest rates, the possibility of debt being called upon by lenders, and a reduced credit supply.
4) **Institutional (regulation) risks.:** risk associated with the consequence of changes in government actions. Examples of political decisions that may significantly affect the agricultural sector are tax laws, pesticide use restrictions, livestock waste management guidelines, and market or income support payments.

5) **Human (personal) risks.:** Risks associated with factors such as farmer's health issues or personal relationships that may influence the farm business. Examples of personal crises that may threaten a farm business continuity include injuries, sickness, death, and divorce.

Agricultural market intelligence relates to a particular agricultural product market – its trends, competitors, and customers (existing, lost, and targeted). This information is collected and evaluated primarily for reliable and confident decision-making in assessing market opportunity strategies, market penetration, and market development. It is the first set of data that the farm investors analyze before making any investment decision. The information collected could be quantitative (giving a value in size or market share) or qualitative (giving preferences, opinions, and value systems). Six major components of market intelligence [128], as shown in Fig.,17 include

1) **Price:** The product's prevailing price and factors affecting the price.
2) **Products:** The distinguishing features that make a product attractive to consumers. Quality requirements, safety requirements, product use, existing marketing arrangements, substitute products, and market leader's products.
3) **Place:** The locations with the highest demand for the product. The size, volume, and value of required products. The demand, market trends, geographic and climatic conditions, which may affect food spoilage.
4) **Political and economic factors:** This includes political indicators, national economic performance data, agricultural policies, legislature affecting the intended product, infrastructural, industrial development in the food sector, and security.
5) **Period:** The right period for the product's highest sales/demand.
6) **People:** The stakeholders – farmers, processors, distributors, and consumers. Their level of education, infrastructure, and adoption of modern technologies. Their religion, norms, and values system. Land ownership system.

The final component of the distribution supply chain is stakeholders' collaboration in supply chain management. This will result in collective decision-making, cost-sharing, optimization, and information flow to ensure improved production and customer satisfaction.

8) FINAL CONSUMERS (The TARGETED Market)

The aim of food security through the adoption of agriculture 4.0 is to provide adequate food of the right nutritional content for all Nigerians at an affordable price. However, the digitization of agriculture in Nigeria will have to be a viable, sustainable, and profitable business to attract the high investment required for its smooth adoption and operation. This is particularly essential, especially for the first two phases of adoption. The Nigerian government may not provide all the finance and resources required to complete the digitization of agriculture in the country due to other pressing responsibilities (including combating the economic impact of Covid-19 on the country). Private investors will like an investment with good returns within the shortest possible duration. Therefore, there is a need for strategic and tactical plans to ensure the viability and profitability of digital agriculture in Nigeria.

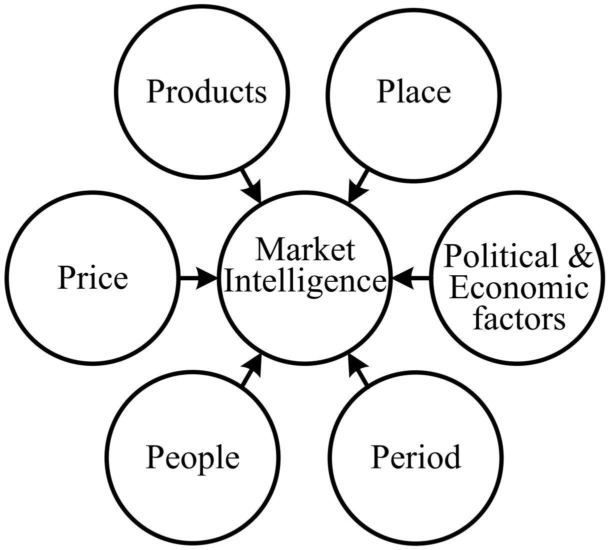

FIGURE 17. **Components of Agrifood Market Intelligence.**

The final consumers are the target market for each phase of implementation. At the early stage of adoption, agriculture 4.0 will target consumers that are using modern technologies. The Agrifood market needs to be segmented based on its needs, characteristics, and preferences. The distribution chain should specifically target medium to large consumers of agricultural produce consumers. Companies and industries that import one form or the other of agricultural input in their manufacturing processes. Distributors should have a deeper understanding of these consumers' quality requirements, the reason for importing these raw materials, and segment the market based on consumers' demographics, behavior, geographical location, and psychographic factors. Agri-food market classification's main factors are physical attributes, behavioral traits, and qualitative factors [129].

a: PHYSICAL ATTRIBUTES

Physical attributes comprise market size, geographic factors, and demographic factors.

1) **Size:** The market size is a measure of the number of units sold, the sales volume, and the market shares of all competing products.
2) **Geographic factors:** Geographic factors include physical boundaries, sales by region, city, location, specific location attributes that may influence spoilage, and types of competing brand outlets in each area.
3) **Demographic factors:** Demographic factors include sex, education, race, income, age, occupation, marital

status, ethnicity, etc. This is an essential factor in market segmentation.

b: BEHAVIORAL TRAITS

These are behavioral characteristics that influence the purchasing of agricultural products. Five behavioral features affecting Agrifood purchases include

1) **Purchasing time:** This is a measure of when purchases are made. Some products are purchased monthly, at the beginning or end of the month, weekly, on weekends, daily, in the evening, in the afternoon of the day, etc.
2) **Purchasing pattern:** This is a measure of how purchases are made. We consider the brand purchased, mode of purchase – direct request or online, frequency of purchase, the number of units purchased, purchasing habits, spending habits, etc.
3) **Purchase influencers:** This is a measure of the factors that influence the purchase. Who uses the product? Who makes purchasing decisions? Who influences the purchases, etc.
4) **Purchase profile:** This is a measure of the socio-economic-psychological profile of those making purchases. It includes social class, value structure, blue-chip or white chip, personality traits (introvert or extrovert), lifestyle, subconscious and conscious beliefs, priorities, etc.
5) **Purchasing justification:** This is a measure of why purchases are made. Factors such as utility value, psychological pressure, major issues, minor issues, etc., fall under this group.

c: QUALITATIVE FACTORS

Qualitative factors are defining factors of two contrasting levels of purchase. It includes heavy vs. light users of a product, frequent vs. infrequent purchases, firm vs. indefinite attitude to purchase a product soon, risk-takers vs. risk averters, etc.

B. IMPLEMENTATION OF AGRICULTURE 4.0 IN AGRI-FOOD PRODUCTION LIFE CYCLE MANAGEMENT

Agri-food production life cycle is the sequence of stages in which digitized food production progresses from its start to completion. A production stage is a series of technically linked tasks, resulting in one or more deliverables being achieved. The phases can be sequential, iterative, or overlapping. Digitized agri-food production management integrates procedures, techniques, expertise, and experience to meet a unique agricultural product's production goals. Digitized food production is a project temporarily undertaken to achieve a particular level of yield. It is It has a specific start, end date, and unique batch (cycle). Its successful completion involves using a cross-functional team of people, stretching across different departments and expertise, and requiring specific tools and technologies.

There are seven constraints to agri-food production management (see fig.18). These constraints are cost, quality, time, scope, risk, resources, and customer satisfaction. An effective

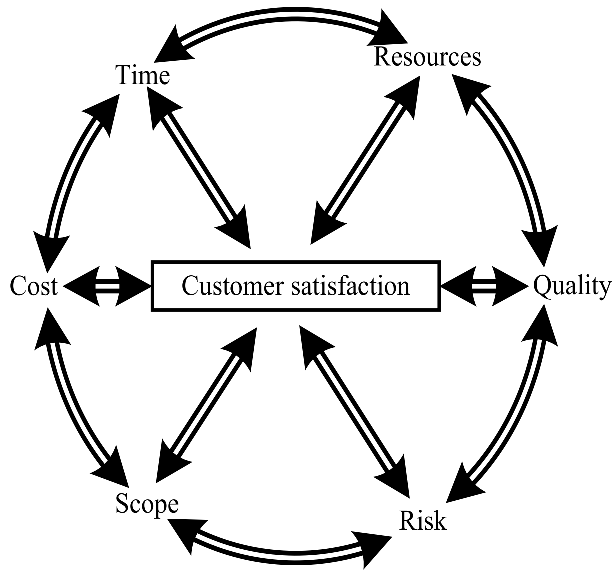

FIGURE 18. Agrifood Management Constraints.

agri-food production management enhances production efficiency, efficacy, service expansion, improved quality/ quantity of products, and customer satisfaction. Other benefits of this approach include better teamwork resulting from stakeholders' collaboration, a more significant competitive edge with other products, and effective risk management.

There are five stages in the agrifood production life cycle (see fig.19. The stages are initiation, planning, execution, monitoring, and closing.

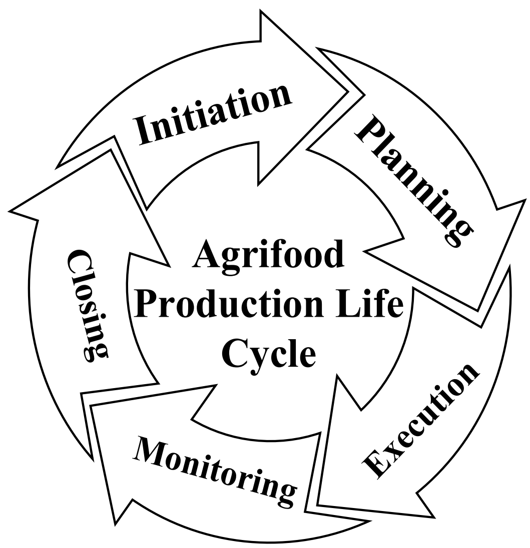

FIGURE 19. Phases in agri-food production life cycle.

1) INITIATION STAGE

Agri-food production initiation is a decision-making team's process to identify the project's feasibility and justification. It involves aligning stakeholders' expectations with the purpose, scope, and objectives of the production project [130].

2) PLANNING STAGE

Agri-food production planning is the process of defining, preparing, and coordinating all plan components and consolidating them into an integrated project management plan. This process creates a comprehensive document that establishes all production tasks and how to do them [130].

3) EXECUTION STAGE

The execution stage involves those processes performed to complete the project management plan's work to satisfy the project requirements. It entails coordinating resources, managing stakeholder engagement, integrating and executing the project's activities per the project management plan. This stage uses a large volume of total project resources, time, and budget. This stage can generate different change requests [130]. If approved, these change requests can trigger planning processes and modify project documents, baselines, etc.

4) MONITORING AND CONTROLLING STAGE

The monitoring and controlling stage consists of the procedures required to track, evaluate, and regulate the project's progress and performance; determine any areas where improvements to the strategy are necessary, and initiate the necessary changes. Monitoring is gathering project output data, creating performance metrics, and performance information monitoring and disseminating. Controlling is comparing actual performance with planned performance, analyzing variances, assessing trends to effect process improvements, evaluating possible alternatives, and recommending appropriate corrective action as needed [130].

5) CLOSING STAGE

The closing stage consists of processes performed to complete or close a project phase, or contract formally. It verifies the successful completion of all specified processes and tasks. In the context of digitized agri-food production, it marks the end of a farming cycle [130].

C. PROPOSED IMPLEMENTATION PHASES FOR AGRICULTURE 4.0 IN NIGERIA

The implementation of agriculture 4.0 in Nigeria should be in phases. We propose two approaches base on demographics and the type of food produced.

1) IMPLEMENTATION PHASE BASED ON DEMOGRAPHICS

In this section, we propose an implementation approach base on population and food consumption load centers. Five stages of implementation exist under this classification.

a: PHASE 1: PILOT CENTERS

The first set of digitized agriculture farming will be at Lagos, Kano, Port Harcourt, and Abuja. These centers should act as pilot centers, and their location selection will be based on their population and food demand. These centers should serve as proof of concept using carefully selected food crops. Economies of scale (leading to a low cost per product), freshness, and product quality will be competitive advantages over other existing products. The consumers' adoption of modern technology in e-commerce and mobile wallets will also be higher in these selected pilot centers.

b: PHASE 2: FOOD LOAD CENTERS

The second phase shall be based on food load centers, cities with larger populations, and more food demand. Table 6 summarizes the population of major cities in Nigeria as of 2020. The farmers shall implement lessons learned from pilot centers at these new locations.

c: PHASE 3: LEVERAGING THE AVAILABILITY OF SPECIAL NATURAL RESOURCES/INFRASTRUCTURES

The third phase shall leverage the availability of natural resources and endowments within Nigeria in locating new farms. There are regions within the country that are naturally endowed with good climatic and environmental features that favor certain food crops. If digital agriculture is introduced to such a region, it will improve optimization and improved capacity in such farming production. Table 7 shows the top 10 food crops and the household's percentage involved in its cultivation in Nigeria (source: NBS). Digitizing the production of these food crops in specific locations should be the next level of implementation.

d: PHASE 4: URBAN FOOD LOAD CENTERS

The fourth phase of implementation should be locating new farms close to urban centers. These centers already have better infrastructure and telecommunication coverage that farmers will need for agriculture 4.0.

e: PHASE 5: RURAL LOAD CENTER

The last phase of implementation will be the location of digitized agriculture in rural areas. This will include providing digital solutions to assist smallholder farmers in these regions to improve their income and livelihood. Rural locations will be in the last phase because of several perceived barriers to acceptance of the technology. Some of these perceived barriers include the knowledge gap, inadequate telecommunication coverage, technology gap, etc. The digitized agriculture farms' location in these locations will demonstrate proof and serve as a training center for smallholder farmers to facilitate acceptance.

2) IMPLEMENTATION PHASE BASED ON THE TYPE OF FOOD PRODUCED

The implementation of agriculture 4.0 can also be based on the type of food produced. The energy consumption for leafy greens (vegetables) is smaller than cereals and grains in greenhouse farming. The availability of electrical energy plays a crucial role in the implementation of digital agriculture. We shall consider five phases under the approach.

a: PHASE 1: VEGETABLE, LEAFY GREENS, AND GRASS (Livestock Feeds)

Vegetables and grass (livestock feed) could be the first phase of a greenhouse, vertical farms, and urban agriculture due

TABLE 6. Population of Main Cities in Nigeria.

S/No	City	Population	S/No	City	Population	S/No	City	Population
1	Lagos	9,000,000	25	Akure	420,594	49	Ila Orangun	179,192
2	Kano	3,626,068	26	Bauchi	316,149	50	Saki	178,677
3	Ibadan	3,565,108	27	Ikeja	313,196	51	Bida	171,656
4	Kaduna	1,582,102	28	Makurdi	292,645	52	Awka	167,738
5	Port Harcourt	1,148,665	29	Minna	291,905	53	Ijero-Ekiti	167,632
6	Benin City	1,125,058	30	Efon-Alaaye	279,319	54	Inisa	164,161
7	Maiduguri	1,112,449	31	Ilesa	277,904	55	Suleja	162,135
8	Zaria	975,153	32	Owo	276,574	56	Sapele	161,686
9	Aba	897,560	33	Umuahia	264,662	57	Osogbo	156,694
10	Jos	816,824	34	Ondo	257,005	58	Kisi	155,510
11	Ilorin	814,192	35	Ikot Ekpene	254,806	59	Gbongan	139,485
12	Oyo	736,072	36	Iwo	250,443	60	Ejigbo	138,357
13	Enugu	688,862	37	Gombe	250,258	61	Funtua	136,811
14	Abeokuta	593,100	38	Jimeta	248,148	62	Igboho	136,764
15	Abuja	590,400	39	Atani	230,000	63	Buguma	135,404
16	Sokoto	563,861	40	Gusau	226,857	64	Ikirun	134,240
17	Onitsha	561,066	41	Mubi	225,705	65	Abakaliki	134,102
18	Warri	536,023	42	Ikire	222,160	66	Okrika	133,271
19	Ebute Ikorodu	535,619	43	Owerri	215,038	67	Amaigbo	127,300
20	Okene	479,178	44	Shagamu	214,558	68	Lafia	127,236
21	Calabar	461,796	45	Ijebu-Ode	209,175	69	Gashua	125,817
22	Uyo	436,606	46	Ugep	200,276	70	Modakeke	119,529
23	Katsina	432,149	47	Nnewi	193,987			
24	Ado-Ekiti	424,340	48	Ise-Ekiti	190,063			

Source: Worldometer (https://www.worldometers.info/world-population/nigeria-population/)

TABLE 7. Share of major crops cultivated in Nigeria by family households.

S/No	Major Crops	Share of Family household growing them.
1	Maize	49.70%
2	Cassava	46.20%
3	Guinea Corn	29.60%
4	Yam	25.80%
5	Beans	20.90%
6	Millet	19.90%
7	Groundnut	17.60%
8	Rice	14.10%
9	Cocoyam	7.70%
10	Beni-seed	3.60%

Source: National Bureau of Statistics

to low energy consumption. Due to our Nigeria staple food structure, the vegetable market may not be too viable for digital agriculture; however, the cultivation of vegetables or grass as livestock feeds could solve our current herdsmen crisis in the country.

b: PHASE 2: TOMATOES AND GROUND FRUITS

The second phase is farming tomatoes and fruits of short plants. Planting trees like Oranges, mangos, etc., require more space for greenhouses. There are variants of these fruit trees that are smaller than traditional fruit trees. The energy consumption at this stage is about 2.5 times more than that of phase 1. These plants can be grown in open farms in regions that are currently favorable for their cultivation. Agriculture 4.0 will optimize the production process to increase profitability, yield, and environmental sustainability. In such open farms, this farming can be done as the first phase.

c: PHASE 3: RICE AND CEREALS

Rice and cereals are our most commonly consumed staple food. The energy required to produce this food in greenhouses is about 31 times more than in phase 1. However, these food crops can be grown in open farms employing digital technologies as phase 1 production. The primary motivation in using technology in these food productions is to leverage economies of scale, reduce cost, and improve yield. The Nigerian rice and cereals production section faces serious challenges resulting from inadequate technology adoption in production and processing. Substandard products with fraudulent labeling are very prevalent in this sector. The federal government of Nigeria banned importing foreign rice from allowing local content development in rice farming. This move led to rapid rice costs, as the locally produced rice struggle to sell at the same price as the illegally smuggled-in foreign rice.

d: PHASE 4: YAM, TUBERS, AND TREE-LIKE FRUITS

The costs of producing these food crops in greenhouses are currently too high to compete with conventional produce. The adoption of digital agriculture in open farms can ensure that these products appear in the first phase. High energy requirements and the need for a huge amount of soil make this agriculture produce unsuitable for greenhouses.

e: PHASE 5: CELLULAR AGRICULTURE

The production of food from cellular agriculture is a promising solution to the unsustainable environmental impact of farming. The use of modern cellular technology in the production of meat, dairy, eggs, gelatin, coffee, fish, silk, leather, and food in commercial quantities will be our last proposed phase of adoption.

D. ROLE OF STAKEHOLDERS FOR SUCCESSFUL IMPLEMENTATION OF AGRICULTURE 4.0 IN NIGERIA

The various stakeholders in the agricultural sector have significant roles to play to adopt agriculture 4.0 successfully. Conscious effort and collaboration of all stakeholders are necessary to achieve food sufficiency in Nigeria. In this subsection, we shall briefly consider the significant role and responsibilities of the following stakeholders: investors, input suppliers, farmers, processors, distributors, consumers, government, financial institutions, and research institutions in the successful adoption of agriculture 4.0 in Nigeria.

1) INVESTORS

Agriculture 4.0 implementation is a capital-intensive, strategic (long-term centered), and highly lucrative investment. The financial resources may not come from the government of Nigeria alone. Well-meaning Nigerians, international financial bodies, and agribusiness giants in developed countries should provide the necessary support in realizing this dream. This is particularly important considering Nigeria is Africa's largest country in terms of population. Nigerian's have demonstrated high purchasing power in the ongoing telecommunication revolution. Any financial investment in food production in Nigeria, if properly implemented, will undoubtedly yield a reasonable return with time. The benefits of agriculture 4.0 go beyond just financial returns on investment. Other benefits include attaining global food security, saving our environment from deforestation, aquatic and wildlife extinction, reducing desertification, and climate change. This will make the world a better place for the ones we care for the most – our children! The investment in agriculture 4.0 could be financial, technological, technical, experience, and collaboration (support). Investors are the foundation of any successful implementation of digital agriculture in Nigeria. They should realize that investment in agriculture 4.0 is long-term centered and a going concern. They should exercise patience for the industry to develop before expecting returns.

2) INPUT SUPPLIERS

Input suppliers should actively participate in the agri-food supply chain. They should ensure that quality inputs are supplied for the production process. They should communicate farmers' needs to input producers and collaborate with farmers during stakeholder engagement activities. When necessary, they should provide credit facilities to farmers in the form of inputs.

3) FARMERS

Farmers should realize that agriculture 4.0 is the future of farming. The earlier they embrace and accept digital technology in agriculture, the more their chances of survival in their future career. They should invest in self-development through training, seminars, workshop, and expert consultation. A good understanding of digital farming technology is necessary to ensure a profitable business model that can attract the required investment level. They should invest in modern smart machinery and avoid the importation of obsolete machinery. They should collaborate with all stakeholders and learn from experts. They should also realize that their investment in agriculture 4.0 is a going concern; the returns are not just for them alone but also for the children. They should understand the impacts of the traditional farming approach on our environment and its resultant contribution to climate change, deforestation, and environmental degradation. They should avoid shortcuts to profit and uphold high-quality products, safety, and sustainable agricultural practices as a new brand.

4) PROCESSORS

Locally made Nigerian agricultural products have shallow acceptance within and outside the country due to insufficient processing and packaging. Inadequate processing and packaging are also responsible for massive food spoilage in the country. When the quality of processed food cannot meet global acceptance standards, they are rejected for export. Nigerian elite within the country prefers imported food due to renowned hygiene, safety, and quality standards. For the successful implementation of agriculture 4.0, food products must be processed and packaged to internationally acceptable standards. Environmental sustainability, quality, safety, and hygiene must be our new food brands. Modern digital food processing and packaging technology should be employed in the agri-food supply chain.

5) DISTRIBUTORS

Distributors should ensure adequate storage and packaging of distributed food. They should collaborate with other stakeholders during engagement sections. They should provide sufficient promotional activities and advertisements to convey the risks of our traditional agricultural practices to our environment and the benefits of agriculture 4.0. They should ensure adequate market segmentation to address the needs of consumers. They should ensure that sustainability, quality, safety, and hygiene are communicated as the new brand to the final consumers.

6) CONSUMERS

In developed countries, final consumers are curious to know where their food is being produced. They are willing to pay a premium for fresh, high-quality, and sustainable products. They are also conscious of the effect of agriculture on our environment and the future of their children. It is our duty as Nigerians to follow the same line of thought. We can collectively ensure a better future, save more freshwater, combat climate change and desertification through a sustainable lifestyle.

7) GOVERNMENT

The government should realize the potential of agriculture 4.0 in significantly solving food security, climate change, desertification, and natural resource depletion problems. The adoption of agriculture 4.0 can increase productivity, export food products, and suitable employment for Nigerian citizens. The government should see the need for a shift in food production from a traditional, unsustainable approach to an innovative and knowledge-based economy to maintain our position as the giant of Africa indeed. In summary, the role of government in the adoption and implementation of agriculture 4.0 [131] in Nigeria includes

- create and ensure safety, security, and a conducive environment for business investment to thrive.
- Ensure economic and political stability for investment in agriculture.
- Engage in active consultation at the national and international level with global leaders in agriculture 4.0 to attract investments.
- Provide policy framework, incentives, and regulations towards the smooth implementation of agriculture 4.0.
- Ensure harmony in food safety, quality, and standards within the country.
- Enhance domestic food testing capabilities.
- Foster collaboration among stakeholders to achieve scale, efficiency, and agility across the agri-food supply chain.
- To ensure the same priority level is given to security, health, and agriculture 4.0 in financial and budgetary allocations.
- Rejuvenate and ensure that agricultural research centers are functional in providing solutions to the agri-food supply chain problems.
- Ensure that young and bright minds receive the scholarship to study modern agriculture technology in developed countries.

8) FINANCIAL INSTITUTIONS

The Central Bank of Nigeria (CBN) is the regulatory body for all banks in Nigeria. The government controls all financial sector activities (including commercial, agricultural, mortgage banks, etc.) through the CBN. Financial institutions should provide credit facilities for the agri-food sector. Access to credit facilities at a low-interest rate will increase food production capacity [132]. International financial institutions like World Bank have a significant role in adopting and implementing agriculture 4.0 in Nigeria. They should give a special incentive (subsidized interest rates) to farmers and investors going into digital agriculture. One constraint why financial institutions hesitate in granting credit facilities to farmers is the perceived risk in farming operations and the lack of credible data. Agriculture 4.0 can provide the necessary data and projections to enable third-party insurance companies to guarantee credit facilities in the agri-food supply chain.

9) RESEARCH INSTITUTIONS

Research institutions have a very vital role to play in the successful implementation of agriculture 4.0. The present deplorable state of agriculture in Nigeria can be directly traced to inadequate technical research support in the early 1960s after independence. Our fathers did not lack the physical strength to do the farming operation; however, insufficient technology and scalability of our farming operations were the reason for our present food production state. The government needs to rejuvenate the 69 agricultural research institutes in Nigeria and position them as active stakeholders in the agri-food project. They should give research incentives (grants) to thriving research that solves the real problems facing our agricultural digitization efforts.

V. DISCUSSION, LIMITATIONS, AND THREATS TO VALIDITY

In this section, we shall treat the discussion, the limitations of our study, and how we minimized threats to this study's validity.

A. DISCUSSION

Agriculture 4.0 is undoubtedly the best solution to food security amidst growing population, insecurity, environmental challenges, and climate change. With digital agriculture, we can ensure continuous food production relatively close to food load centers in pandemics or lockdown. Building self-sustaining cities with a sustainable lifestyle are desirable to combat the global challenges facing our world. It is more realistic for the Nigerian government to provide security and financial support to few commercial farming locations than for millions of smallholder farmers.

Adequate, cheap, and sustainable energy, the availability of ICT, and modern infrastructure are crucial to the successful implementation of agriculture 4.0. The cost of implementing digital agriculture increases significantly with the cost of energy. The current energy crisis in Nigeria is an issue that needs an urgent resolution to pave the way for sustainable economic development and growth. Adequate and reliable ICT infrastructure is also essential for the implementation of digital agriculture. These infrastructures (including the right access road, railways for transportation of goods) should be available in urban and rural areas.

Security is another essential factor for any level of development and growth to occur in Nigeria. The ongoing Boko-Haram insurgence, the kidnapping of expatriates in the Niger Delta, armed robbery in federal highways, and herdsman/farmer crashes in many states of the federation impede agriculture, growth, and country development. Nigeria cannot implement agriculture 4.0 amidst extreme hunger, poverty, and underdevelopment prevalent in rural areas. Violence, insurgency, and insecurity are critical foundational requirements for development and investment in any part of the world.

B. LIMITATIONS

We acknowledge the following limitations in our study; We recognize the following limitations in our study

1) That our proposed framework is more centered on crop production. Other forms of agriculture like fishery, livestock farming, and forestry may significantly vary from our proposed framework.
2) That only research is limited to only publications in the English language. We are aware of the valuable

wealth of knowledge in other languages, which may be missing in this study.

3) That our research questions, search selection protocol may not cover all significant and vital English language publications. However, we took great care to avoid this from happening. However, we acknowledge that we may not include the possibility of essential works in this field in this study.
4) Our study scope was for publication between 2015 to 2020 in selected digital libraries. There may be vital studies that are outside this scope, which we might have omitted.

C. THREATS TO VALIDITY

The following are some measures we put in place to mitigate the threats to the validity of this study.

- We had a well-defined methodology and research protocol in place from the beginning.
- We used well-defined digital libraries (databases) representing the geographical disparity of authors and opinions.
- We formulated specific research questions that guide our search and selection processes.
- We used well-defined search strings and searched periods (2015 – 2020) to ensure that other researchers can reproduce our search processes.
- We removed duplicate studies and did a reference check to ensure that we did not omit essential studies.

Below are some specific approaches to mitigate threats to the validity of our study.

- **Construct validity:** We acknowledge that our six research questions may not completely cover all about food security and agriculture 4.0 in the context of this study. Our approach is to identify the problems and challenges facing food security in Nigeria and propose a conceptual framework for adopting agriculture 4.0.
- **Internal validity:** To exhaustively identity articles on food security and agriculture 4.0, we conducted searches in six different electronic databases. We aimed to include publications from authors with various opinions and backgrounds in our primary source studies. We also did snowball as an alternative to reducing the possibility of omitting relevant publications.
- **External validity:** We selected publications within a specified period (2015 – 2020) using our stated search strings. We also excluded publications with ambiguity and unexplained methodology.
- **Conclusion validity:** We designed a research protocol that guided our data extraction strategy and format. Two renowned authors proposed the review protocol, and my mentors did the review. We used a data extraction form to ensure consistency in our data extraction process.

VI. CONCLUSION AND FUTURE WORKS

The use of digital technologies in food production is a viable option for food security attainment in a country that is facing serious insecurity challenges, population growth, climate change, natural resource depletion, massive food wastage, and restrictions associated with pandemics like Covid-19. We set out to understand the current state of agriculture in Nigeria, the factors militating against food security, the meaning of agriculture 4.0, and how it can help solve Nigeria's food security problems. As we can see from this study, agriculture in Nigeria is performing far below expectations. With about 36% of Nigeria's active labor force involved in agriculture, we are still a net importer of food. More than 80% of farmers in Nigeria are smallholder farmers who still practice traditional farming without adopting modern technologies. These smallholder farmers are responsible for the production of about 90% of Nigeria's local food. Nigeria is also experiencing massive food waste, poor food packing, and loss of economic value to these smallholder farmers during the peak harvest period due to adequate infrastructure (roads, railways, cold chain logistics, storage facilities, ICT), poor agricultural product processing, and inability to meet globally acceptable standards.

Agriculture 4.0 is the fourth industrial revolution in agriculture that involves digitizing the agricultural food production process through precision agriculture and the agri-food supply chain. This study analyzed PA's three components: guidance, navigation and control, advanced imaging, and yield mapping. We also reviewed the six aspects of supply value chain improvement, including rental services, linking platforms, e-extension services, monitoring platforms, e-commerce services, and warehouse receipt systems. We identified ten enabling technologies for agriculture 4.0: IoT, big data/cloud computing, blockchain technology, AI, robotics, autonomous vehicles, additive manufacture, AR/VR, sustainable packaging, cellular agriculture, and others. Next, we highlighted the obstacles to the adoption of agriculture 4.0 in Nigeria.

Our proposed implementation framework for agriculture 4.0 in Nigeria highlighted the primary considerations during each stage of farming inputs, farming scale, farming approach, farming operation, food processing, food preservation/storage, distribution and logistics, and the final consumers. We analyzed the food production life cycle from a project management point of view. We highlighted the various tasks associated with each of the five stages of the agricultural food production life cycle: initiation, planning, execution, monitoring, and closing. We proposed a five-phase implementation strategy for adopting agriculture 4.0 in Nigeria based on demographics and the type of food produced in greenhouses. Finally, we highlighted the various stakeholders' roles (investors, input suppliers, farmers, processors, distributors, consumers, government, financial institutions, and research institutions) in a successful implementation project for agriculture 4.0. It is more attainable for the government and all stakeholders to focus on digitized commercial food production in few strategic locations based on available data rather than spreading the resources to millions of smallholder farmers. It will be more effective to provide security and financial support at these few locations than meet these needs at millions of geographically dispersed locations.

In the global context, Nigeria is the giant of Africa (in terms of demographics). The benefits of agriculture 4.0 in Nigeria will significantly impact SDG 2 (zero hunger), SDG 3 (good health and well-being), and SDG 8 (decent work and economic growth) of #Envision 2030 of the United Nations.

The adoption of agriculture 4.0 in other specific agriculture forms like livestock farming, fishery, and forestry are open areas for future work. A framework for a particular crop like rice, cereals, etc., is also available for future research. There is a need for the integration of renewable energy in agriculture 4.0 to make it truly sustainable. Future research should target bringing CO_2 emissions to zero as a technique of combating climate change and ensuring food security.

In our future work, we shall develop an implementation framework of a sustainable commercial greenhouse for livestock feeds to solve the herdsmen-farmers crisis in Nigeria.

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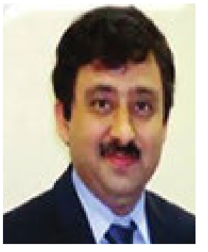

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