Heliyon 10 (2024) e31611

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Digitalization of rice value chain in Nigeria with circular economy inclusion for improved productivity – A review

Michael Mayokun Odewole [a,*], Mayowa Saheed Sanusi [a], Musliu Olushola Sunmonu [a], Suleiman Yerima [b], Dare Mobolaji [c], Joshua Olanrewaju Olaoye [d]

[a] *Department of Food Engineering, University of Ilorin, Ilorin, Nigeria*
[b] *Faculty of Computing Engineering and Media, De Montfort University, Leicester, England, UK*
[c] *Department of Computer Science, University of Ilorin, Nigeria*
[d] *Department of Agricultural and Biosystems Engineering, University of Ilorin, Ilorin, Nigeria*

ARTICLE INFO

Keywords:
Digital technology
Value chain
Rice
Circular economy
Agric-food sector

ABSTRACT

Agriculture is a primary sector of production that is important for providing basic raw materials for many sectors. There seemed to be more people practicing it traditionally, and this situation is limiting the buoyancy of agricultural productivity. Traditional agriculture cannot fully thrive in the 21st century. This is because the global human population is currently growing at an alarming rate that is much higher than the agricultural productivity requirements to strike a balance, especially between food demand and supply. Hence, there is a need to take advantage of technology and incorporate it into agriculture with a view to bridging the gaps created by traditional agriculture. In this review paper, agricultural productivity information as it relates to the human population is presented. Also presented was background information on digital technology and its connections to agriculture through the use of some existing digital technology devices for improved productivity. Furthermore, matters relating to the rice value chain, with specific attention to Nigeria, were given extensive consideration. The circular economy (CE) approach was presented as a means of converting the three (3) major rice value chain by-products or wastes (straw, husk, and bran) to other value-added products. The CE will protect the environment and make it more friendly. Also, it will improve productivity, increase income, and create better living conditions for those in the rice value chain in Nigeria.

1. Introduction

Agriculture is an important contributor to the economic prosperity of both developed and developing nations [1]. Also, it is the sector providing raw foods and agro-based raw materials to human beings and industries. The world population will rise above 9.8 billion by the year 2050 [2,3], with an annual growth rate of about 1.1 % [4]. The projected population explosion is posing a serious threat to the provision of food to match the alarming population growth projection. Consequently, this has led to a growing tension between food demand and supply worldwide [5]. In Nigeria, agriculture contributes about 24 % to the national Gross Domestic Product (GDP), with the involvement of about 70 % of Nigerians [6–8]. Nigeria has the highest population in Sub-Saharan Africa [7],

* Corresponding author.
E-mail address: odewole.mm@unilorin.edu.ng (M. Mayokun Odewole).

https://doi.org/10.1016/j.heliyon.2024.e31611
Received 7 January 2024; Received in revised form 16 May 2024; Accepted 20 May 2024
Available online 21 May 2024

and the population keeps growing, with the aftermath effects of an increase in demand for food and the escalation of hunger. In the space of 21 years (2000–2021), the hunger index of Nigeria declined from 39.5 to 28.3 points [9]. These indices signified a respective move from an alarming situation to a more serious situation. Hence, there is a need to pay urgent attention to the food systems, with a view to averting famine and also for the achievement of goal 2 of the Sustainable Development Goals (SDGs) of the United Nations (UN).

Food systems are the ways humans organize themselves, in space and time, to obtain and consume their food [10]. Globally, food systems are experiencing rapid changes caused by extrinsic and intrinsic factors. Among the extrinsic factors are climate change and chain organization, whereas intrinsic factors include innovation and a reduction in the number of farmers [4]. According to FAO [11], the future of food and agriculture from a global perspective rest on two pivots: knowing whether the existing food systems will sustainably and efficiently feed everyone beyond 2050 and also meeting the non-food demand for agricultural products. Globally, about 2 billion people are experiencing food insecurity. Approximately 690 million people and 340 million children are malnourished and suffering from micronutrient deficiencies, respectively [12]. The use of advanced technologies in agriculture is a means of substantially harnessing the benefits of intensifying agriculture and food security [12].

Rice (Oryza sativa) is a major food for about 50 % of the world population and is usually cultivated by peasant farmers on plots of not up to 1 ha [13]. It is supporting the livelihoods of 3.5 billion consumers [14]. The origin of rice cultivation has been traced to China [15,16]. Oryza sativa is the common species of rice; it has indica and japonica as sub-species, with 13 % japonica and the bulk of indica making up the higher percentage of the global rice production [13]. The African rice is a special variety botanically known as Oryza glaberrima [17]. Some of the improved varieties of rice that are grown in Nigeria are: NERICA 8, FARO 52, FARO 60, FARO 61, and FARO 44 [18]. There are four broadly defined ecosystems that can support the growth of rice: irrigated land, rain-fed lowland, upland, and deep-water rice. Irrigated rice, lowland rice, and upland rice account for 50, 35, and 9 % of global rice production, respectively [13]. About 90 % of the global rice crop is grown in Asia [19,20]. India and China are the highest producers of rice globally, both providing more than 50 % of the global rice supply [19,20], although Thailand (the 5th highest producer) exports the highest quantity of rice in the world [21]. Rice is the most consumed crop globally and ranks third in terms of cultivation. Also, the total global trade value of rice was $28.4 billion in 2021, and it would reach about 700 million metric tons in 2025 [14].

In Nigeria, rice is one of the major cereal crops used as food by all tribes, and it has economic values and creates sustainable food security [22]. Ilu [23] reported rice as the fourth largest cereal crop grown in Nigeria and listed it as the second most important food security crop in Nigeria. It is an important food commodity and generates income for small-scale farmers in rural areas. About 80 % of the rice crop is sold to generate income to purchase other foods. Rice is cultivated in almost all agro-ecological zones of the country, with about 2.8 million metric tons of annual production capacity [21]. Rain-fed lowland, rain-fed upland, irrigated lowland, and deepwater rice contribute 50 %, 30 %, 16 %, and 4 %, respectively, to rice production systems in Nigeria [24]. In the 1960s, the cultivation of rice was less than 150,000 ha. However, in 2011, there was an appreciable increase in rice cultivation (2.17 million hectares), but the production increase experienced did not meet the consumption needs of Nigerians, and this resulted in the annual importation of about 2.5 million metric tons [21]. Nigeria is both Africa's leading producer and the leading consumer of rice. Also, Nigeria occupies the second position in rice importation worldwide, with about 6 % of the global rice trade [23]. The growing demand for rice in Nigeria will reach 36 million metric tons by 2050 [8]. In 2007, six (6) states in Nigeria (Niger, Kaduna, Benue, Taraba, Ebonyi, and Kwara) produced about 1.9 million metric tons of paddy, which was more than 60 % of total domestic output [23]. The Agricultural Transformation Agenda (ATA) of 2012, launched in Nigeria, focused on making Nigeria self-sufficient in rice production by 2015. This seemed not to have been achieved, with evidence from a report that 1.26 % of the Nigerian budget for 2017 was on rice importation [17]. The ATA discouraged rice importation through increased tariffs on imported rice, the importation of 100 new rice mills operated by the private sector, and the formation of rice production groups close to the new mills for the production of paddy [21].

Currently, there is a global effort to reduce poverty and food prices through the formulation of formidable agricultural policies [25–27]. Practical steps through publicity and the supply of necessary inputs to small-scale farmers to boost the production of rice in Nigeria are being intensified [17]. Around 2007–2022, agriculture contributed to the economic growth of Nigeria by 27 %, while manufacturing (a sector that encompassed agricultural product processing—a part of the rice value chain) had an almost insignificant value of 1 % [21,28]. The focus of this review paper is to present the extent to which, the concept of digital technology in agriculture has been adopted for the improvement of activities (including the circular economy) and productivity of the rice value-chain in Nigeria.

2. Conceptual framework

The concept of paper refinement strategy was used to search 110 published works of literature in Agricultural Value Chain (AVAC), Agricultural Applications (Agri Apps), Agricultural Internet of Things (Agri IoT), Digital Inclusion in Agriculture, Agricultural Technologies, Rice, Rice Value Chain and Circular Economy aspects. Out of the 110 published works of literature, 81 most relevant were selected and used to prepare this review paper. The selected related works of literature were within the last 28 years to date (1996–2024), but only one literature was for 1996. Others beyond 28 years were filtered and dropped.

2.1. Digital agriculture

Izuogu et al. [29] used two terms to explain the concept of digital agriculture: digitization and digitalization. Digitization is the non-theoretical change of analog information into digital messages. Digitalization is the mental, social, and economic process of taking up improved technologies. Migrating to the use of information communication technologies ensures improvements in the aspects of generating, collecting, exchanging, aggregating, combining, analyzing, accessing, searching, and presenting digital contents. All the aforementioned activities lead to the development of useful applications and services [30]. Digital agriculture is a food system that makes use of information and communication technology (ICT) at all levels of agricultural production and its ecosystem [31]. Furthermore, digital agriculture can also refer to any of the following terms: smart agriculture, smart farming, or digital farming [32]. Smart agriculture (Fig. 1) enables farmers to have access to various tools (internet of things—IoT, cloud computing, drone technology, software applications, wireless sensor networks, artificial intelligence-powered tools, and digital analytics solutions) to address several agricultural and food production issues [33,34]. Additionally, smart agriculture incorporates the use of data from diverse sources and insights obtained through research efforts and agri-food operations. It can structure the information in diverse ways and lead to making decisions that enhance agricultural productivity [35]. The global agreement on the definition of digital agriculture focused basically on the multiplication of data, parts played by artificial intelligence, connectivity, and automation. However, this global agreement did not consider genomics, which involves the collection of data in the laboratory [4].

Digital technology was first used in agriculture about five (5) decades ago, and the term "digital agriculture" came into existence in the early part of the 21st century [4]. The use of digital technology in agriculture has led to the generation of large volumes of highly non-homogeneous data, or big data [36], from different sources (Fig. 2). It can achieve the required innovations in digital agriculture with the availability of the following: abundant data, computing capacities leading to the implementation of artificial intelligence (AI) and new methods of modeling, and interfaces for connectivity and exchange of information [4]. Yalmaev et al. [37] reported smart farms, smart warehouses, smart herds, smart greenhouses, smart processing, and others as the most important technologies in the digitization of agriculture. Digital technology in agriculture aids diversification of the service economy, increases the capacity of farmers for action, accelerates agricultural transformation, and makes agriculture more appealing to the youth. It also creates systems that will support food security, profitability, sustainability, and improve value chains at all levels of production [2,4]. An appropriate level of intensive application of digital agriculture operations can lead to increased economic and better environmental performance [38]. This can be achieved through an increase in productivity and a reduction in environmental burden and the cost of resources.

Digital technology development in the agri-food value chain has multidisciplinary dimensions [4]. It affords all the stakeholders in agriculture to be part of beneficial changes; it reduces the role of middlemen, expands market opportunities, improves the links between extension and research centers, and makes the agricultural system and productivity highly efficient [4,29,40]. The incorporation of digital farming into agricultural development enhances industrial integration and innovation, and supports the revitalization of rural areas [41–44]. In connection with the SDGs, digital agriculture is potentially positioned to release economic benefits for the betterment of all stakeholders in agriculture. The benefits can be achieved through an increase in productivity, efficient cost management, and increased market opportunities. In addition, there exist social, environmental, and cultural benefits [2]. Three factors affect digital agriculture [2]. These are individual (users of digital tools), institutional (stakeholders responsible for the creation of an enabling environment for digital agriculture), and technological (consideration of the suitable type of digital technology to be provided). Also, it has the constraints of cost, relevance, user friendliness, risk, and trust (Fig. 3). Sulimin et al. [45] reported the three general stages of the development and introduction of digital technologies in agriculture. These are: pilot technologies (state of initial introduction and monitoring), market saturation (the attainment of critical mass of the technologies and standards in agriculture), and integration (proper spreading of well-established standards and solutions).

There is global change in world agricultural production due to global climate change, growth, and changes in consumption patterns associated with an increase in population and well-being [45]. According to USAID [30], there was a world food crisis in 2007–2008, which led to the sharpest increase in food prices for the first time in 30 years. The food crisis caused food riots in many parts of the world and later drew the attention of the world to the importance of agriculture. This further led the Food and Agriculture Organization (FAO) to postulate that developing countries (Nigeria included) will have to double food output (70 % rise in food production) by 2050 to reasonably close the food demand gap. Agricultural activities have advanced beyond food and plant production to include the processing, marketing, and distribution of crops and livestock products in the past 20 years [24]. Digital transformation in

Fig. 1. Components of Digital or Smart Agriculture. Adapted from Abbasi et al. [33].

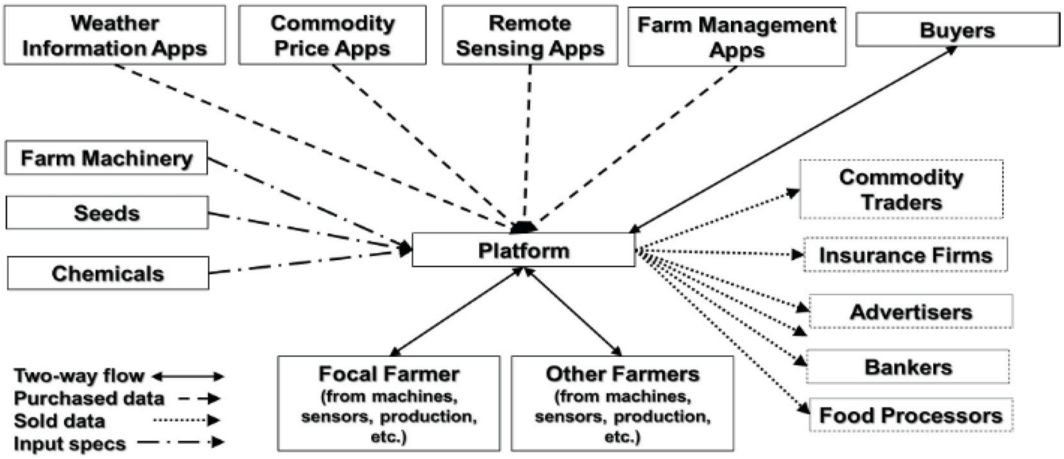

Fig. 2. Data Flow for Digital Agriculture. Adapted from Kenny et al. [39].

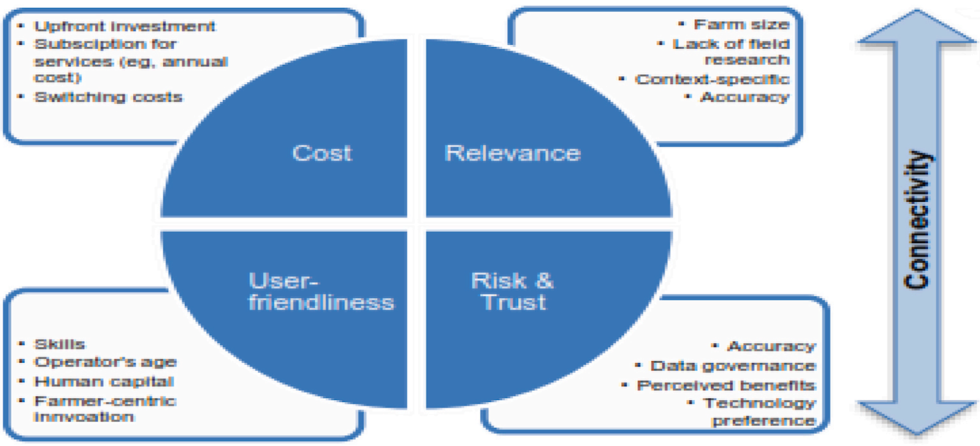

Fig. 3. Digital Agriculture Constraints. Adapted from McFadden et al. [30].

agriculture can deliver substantial social, economic, and environmental benefits through the use of mobile applications [2]. One of the challenges caused by the COVID-19 pandemic was social distancing; this led to the rapid development and use of digital tools in Nigeria by extension personnel [46]. The benefits of having access to digital technology for smallholder farmers and other rural business owners are numerous. The benefits are in the areas of the provision of useful information and links to suppliers, the harnessing of workforce talent by the users, building strategic partnerships along the value chain, accessing support services (legal services, finance, and training), and reaching markets and customers [2].

2.2. Existing digital technologies in the agric-food sector

Highlights of some existing digital technologies in the agric-food sector [2, 30] are stated below:

(i) **EMA-i**: This App was developed by FAO for animal health workers. It reports early occurrence of diseases of livestock. The reports captured by the App will assist in taking timely corrective actions before detected diseases spread beyond control or before larger resources will be needed for the control of the diseases. Also, the reports may be useful in future for planning livestock diseases preventive control regimes.

(ii) **Dino Agrobot**: The robot is a digital tool used by vegetable farmers to perform a high-level precision weeding. The use of this robot ensures better working conditions, reduction of time loss during field operation and high profitability.

(iii) **MyCrop**: It is an e-commerce platform that supplies farmers with vital information. The use of the information supplied leads to increase in productivity, improvement of standard of living and increase in profitability.

(iv) **Smart Brain**: This is an AI driven technology in piggery. It uses facial appearance, body temperature and voice of pigs to ascertain their health status. Also, this technology can use the sleeping pattern, eating habits and posture of female pigs while standing to detect pregnancy.

(v) **Walmart Tracker**: It is a blockchain platform for monitoring bagged spinach and lettuce head. It gives real-time information on the level of contamination of the bagged vegetables as they move from where they are originated (suppliers) to their desired destinations.
(vi) **Automated Heat Detector**: This technology uses data collected from dairy herd over time to identify cows that are ready to be submitted for artificial insemination. It also detects animals that experienced abortion and resumed another heat cycle.
(vii) **Crop Sensors**: They are digital tools that are used for improving the conditions of crops. They work by measuring various parameters of crops (yield, leaf area, quality, development stage, diseases and pest infections, level of nutrients and others). The outputs of the measurements are used for taking decisions or steps that will improve the conditions of crops.
(viii) **Digital Pasture Management Tools**: These are set of digital tools equipped with meters, sensors and probes. They are used for precisely measuring the temperature and other parameters that affects the health of animals.
(ix) **Milking Robot**: It is a complex digital device that milks cows automatically, instead of doing it manually. It has a means of detecting the precise time to milk cows. This is achieved based on the previous milking time and other important information already collected and stored in the memory of the device and its accessories on the cows.
(x) **Satellite/Drones**: It is a remote sensing digital tool with different wavelengths and resolutions. It is used for aerial viewing or properly taking aerial images of farms or locations where other agricultural related activities are taking place. Images taken are used for decision making after interpreting them.

3. Rice value chain in Nigeria

The value chain is the description of all the required activities, from the conception of a product to its delivery to end users and beyond [47]. Also, it is the process of augmenting the existing value of products by diversifying their outputs through strategic product processing, upgrading, and marketing for the delivery of added value to customers [48]. Similarly, the value chain is the full range of activities that are required to bring a product or service from its conception to its end use [49]. The value chain is both an analytical and an operational model consisting of relevant stakeholders responsible for product or service delivery. Hence, the agricultural value chain (Fig. 4) is simply the people and activities that bring a basic agricultural product from the field to consumers [49]. Furthermore, value chain analysis is a useful analytical tool that helps to understand the overall direction of industrial reorganization, identify agents of change, and leverage points for policy and technical interventions [50]. The value chain serves some of the following purposes: it provides an important means to understand business-to-business relationships; it serves as a mechanism for increasing efficiency and productivity; it increases market links; and it adds value to products and services [51]. The value chain is needed for the growth and equity dimension of the modernization of agric-food systems [51], and it exists when all the stakeholders along the chain act in ways that will maximize value generation in the chain [23]. The major drawback to achieving rice value chains across the world is climate change, which has led to erratic rainfall patterns, overflooding of arable land, and drought [52,53].

The value chain for rice produced in Nigeria is presently controlled by a largely fragmented production and milling industry, with limited attention to creating new investments in either production or processing [39]. The presence of multiple participants in the traditional value chain is greatly reducing the expected accrued benefits. On the other hand, the private sector-driven model (e.g., Olam and Veetee rice mills) can compete with imported rice and contribute to a more efficient value chain that improves food security in Nigeria. Also, the public-private partnership idea of “Lake Rice,” which is primarily an agro-business partnership between Lagos and Kebbi states (Lake: La-Lagos and Ke-Kebbi); the Imota rice mill in Lagos State; and others are good initiatives that can reduce the importation of rice in Nigeria. This will go a long way in taking Nigeria many steps forward in achieving self-sufficiency in rice production, creating more employment opportunities, revamping other industries associated with rice production, and increasing the country’s GDP if well managed and sustained.

According to Tinsley [13], the rice value chain in a typical Nigerian community is divided into three primary components: production, processing, and marketing, with many interlinks (mainly transportation) between them. Generally, the following links exist in the rice value chain in Nigeria: Farmers to village buyers (bulk purchase of paddy) to traders and transporters to processors to wholesale market to retail market. Consumers usually buy from retailers. It is important to note that, there are some instances in which

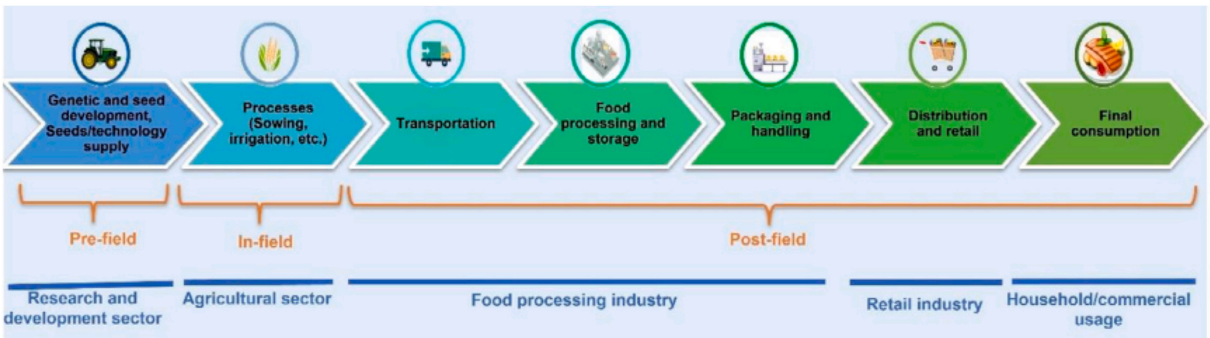

Fig. 4. Agriculture Value Chain. Adapted from Abbasi et al. [33].

the aforementioned links of the value chain may not be strictly followed as presented. In these situations, some actors in-between the links are bypassed, and two or more activities are eliminated or handled by a single actor. Sometimes, farmers (producers) may sell directly to processors or consumers or marketers. Likewise, it is possible for traders to sell directly to processors or wholesale marketers or retail marketers or consumers. Processors can also sell directly to retail marketers without involving wholesale marketers. Lack or poor accessibility to some actors, cost and time saving strategies, inadequate facilities, shortage of some value chain actors, lack of market dynamics information and deliberate attempt to eliminate the bad influence of middlemen are some of the reasons for bypassing some actors along the value chain. Production involves the following activities: land preparation for the establishment of crops, selection of variety and quality of seeds to be planted, planting, fertilizer application, crop protection, harvesting, threshing, drying (on-field drying to a level that can take place after harvesting and before threshing), and winnowing and on-farm storage (at a safe moisture content of about 14 %). Processing starts with parboiling (a combination of soaking and heating), drying, milling to remove husks and bran (single stage or double stage), and destoning. Marketing is the final component of the value chain. The processed rice is sold under wholesale or retail arrangements to consumers or other traders. About six (6) hectares of land are needed for a Nigerian rice farmer to be regarded as a full-time farmer in the rice value chain. In another development, quality improvement along the value chain could be accompanied by an increase in production and processing costs. However, the financial burden will be passed on to consumers (most of whom are low-income earners), who may not be able to easily afford the cost. Also, it was observed that the price of local rice per kilogram in the Kano open market in 2009 was almost the same as small packages of rice in the major USA supermarkets; therefore, rice was reported to be relatively expensive in Nigeria.

3.1. Importance of digitalization of rice value chain on productivity

The importance of digital technology application to foods value chain (rice inclusive) cannot be over emphasized. It has the tendency to enhance the efficiency of the rice value chain [54]. It helps to know the origins of foods, their true varieties and actors, as well as tracking of activities and fraud minimization along the value chain [55]. Also, it increases transparency, data collection for decision making and visibility. Its aids efficient use of available resources, and supports circular economy activities [56]. More specifically, in recent times, it has made global rice trading to be faster, simpler, and with better accessibility to rice value chain actors [57]. Furthermore, digital technology can cause significant increase in rice yield with little involvement of human efforts. This supports social, environmental and economic aspects of sustainability of the rice sector of agric-food operations. In addition, there is higher possibilities of product cost reduction and decrease in the quantities of wastes generated [58].

3.2. Empirical studies on rice value chain in Nigeria

There are some empirical studies on rice value chain in Nigeria. These studies were found in Ilu [23], and the respective author(s) and major findings are highlighted below:

Onyenwaku [59]: The northern states in Nigeria had a comparative advantage over the southern states in the land needed to produce most grains (including rice). Akande [60]: Nigeria had a comparative advantage in the production of rice. Longtau [61]: There was a near-total collapse of large- and medium-scale rice schemes. Also, very low levels of use of modern inputs due to institutional failure deprived rice farmers of the needed support systems. Chuma [62] identified Nigeria as the largest importer of rice in the world, and it led to a shrinkage of domestic rice markets. It was concluded that a significant reduction in production at the farm level would improve the standard of local rice. The majority (95 %) of rice farmers in Nigeria operated on small-scale farms (0.5–1.5 ha). Poor seed quality, low fertilizer use, limited irrigation area, and the use of traditional cultural practices led to low rice yields. Erenstein et al. [63]: Provision of an enabling environment that would allow access to markets (for inputs, outputs, and information) would make rice production in Nigeria more attractive and competitive. Kebbeh et al. [64]: Better utilization of existing infrastructure can to the achievement of significant rice production gains. Erenstein et al. [65]: The sustainable way forward for the Nigerian rice sector is to allow significant competition to exist (in both price and quality) between local rice and imported rice. USAID [30]: Total sales of rice in Nigeria were above $5 billion per year, and $3 billion out of the said sales were from imports. The aforementioned indicated a significant rice market in Nigeria.

Furthermore, a group of researchers conducted the following studies on the rice value chain (processing aspect) from 2017 to 2023, with a focus on local varieties of rice in Nigeria: evaluation of the physical, milling and cooking properties of new rice (oryza sativa L.) varieties in Nigeria [66]; comparative studies of the effect of processing on cooking and sensory properties of selected rice varieties [67]; multi-objective optimization of parboiled rice quality attributes and total energy consumption [68]; modelling and optimizing the impact of process variables on brown rice quality and overall energy consumption [69]; rice parboiling using a dual-powered parboiler: evaluation of energy consumption patterns and milling quality [70]; evaluation of rice milling quality and energy requirement via a developed vibratory rice grader [71]; evaluation of energy consumption patterns in rice processing using Taguchi and artificial neural network models [67]; impacts of soaking time and steaming time on proximate, vitro-starch digestibility and amylose content of short, medium and long rice grain type [72]; influence of oscillatory motion of a rice dehydrator on energy consumption and milling quality of rice [73].

3.3. Circular economy in the rice value chain

Nattassha et al. [74] reported circular economy (CE) as a system in which the wastes of one process are not discarded directly but instead become resources for other means. CE is sometimes referred to as the “reduce, reuse, recycle” model of materials [75].

Agric-food sectors generate a lot of waste that is most often a menace to the environment via pollution and contamination. This situation is gradually reducing the eco-friendly nature of the environment as well as causing serious economic losses. Conventionally, the popular and age-long "take-make-waste" or "take-make-dispose" [75] life cycle of agric-food materials, which is a linear model, does not take into consideration other values that can be harnessed from agricultural by-products. Once agricultural raw materials are used or some parts not needed for specific purposes are separated, they are not considered as another form of raw material for producing other value-added products, but rather as waste or used for less beneficial purposes. These wastes are even sometimes not properly disposed, hence creating more harm than good to the environment. The concept of CE is a non-linear model waste management system (waste-to-wealth) that has the potential to address the identified challenges of the aforementioned linear model if properly implemented. According to Illankoon et al. [76], CE addresses optimization of the use of available resources. It is also a means of achieving equilibrium among the economy, the environment and the society through supporting of closed manufacturing processes. In addition, CE takes the following into consideration: sustainable production practices at corporate-level, more awareness on the responsibilities of producers and consumers, exploration of the use of renewable materials and technology; and adoption of appropriate, consistent and clear policies and systems. The objectives of CE could be achieved through the manipulation or imposition of 9Rs (Fig. 5). It was reported that the primary objective of CE was to achieve maximum efficiency in resource use while keeping the production of waste and pollutants to a minimum [75].

3.4. Rice wastes

Agricultural wastes are biomass residues and can be classified into two (2) categories: crop residues and agro-industrial residues [77]. Rice wastes are both crop and agro-industrial residues. Rice currently generates a high quantity of unavoidable wastes (Fig. 6) that are primarily from rice straw, rice husk, and rice bran [14,76]. Rice bran and rice husk account for about 0.05–0.1 kg and 0.28 kg of waste, respectively, per 1 kg of harvested rice [78]. Rice husk is mostly used as a heat source for paddy parboiling [79] and can also be explored for producing biofertilizer through composting [80]. Rice bran is one of the raw materials for making animal feeds [81]. The straws from rice are most often subjected to open burning during land preparation, used as mulch, or allowed to decay and insignificantly add to the fertility of the soil. Food loss (associated with rice grains during handling and processing), waste, and environmental degradation along the rice value chain are of increasing concern. Rice paddies contribute about 19 % and 11 % of methane and nitrous oxide emissions, respectively; these are parts of 43 % of greenhouse gas (GHG) emissions [21].

Illakoon *et al.* [76] reported that there was an increase in global rice production and harvested areas from 2000 to 2018 (Fig. 7). Similarly, there was also a progressive increase in rice consumption from 2000 to 2022 (Fig. 8). Considering the huge volume of waste and by-products generated along the rice value chain, the sub-sector has a high potential for generating different value-added products. However, there is a need to properly look into issues relating to the supply of waste and by-products, appropriate technologies for treating them, and cost-effective methods of converting them to other value-added products [76].

3.5. Compositions of rice wastes and conversion to value-added products

The composition of the aforementioned three (3) main wastes along the rice value chain are presented in this section in line with the information found in Illankoon et al. [76]:

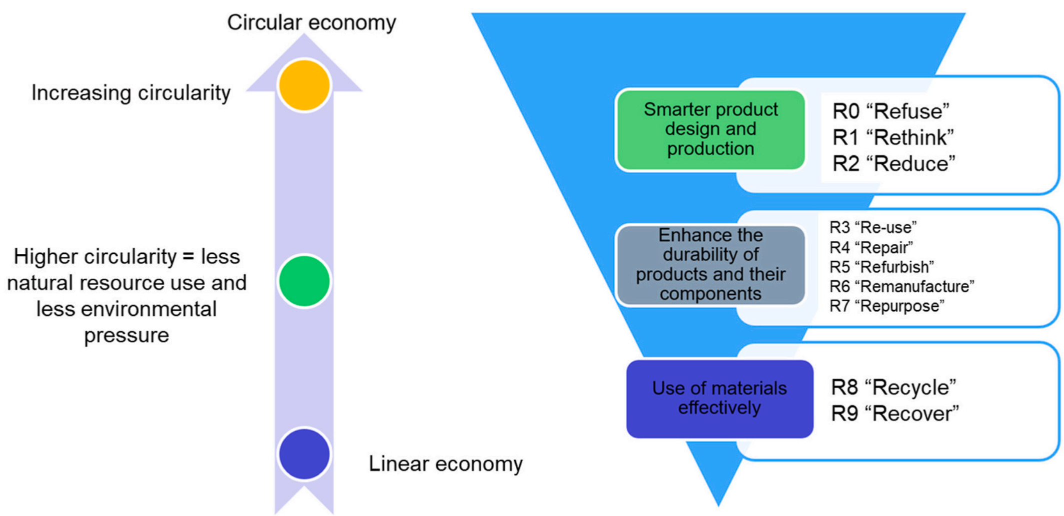

Fig. 5. A Typical Circular Economy System. Adapted Illakoon et al. [76].

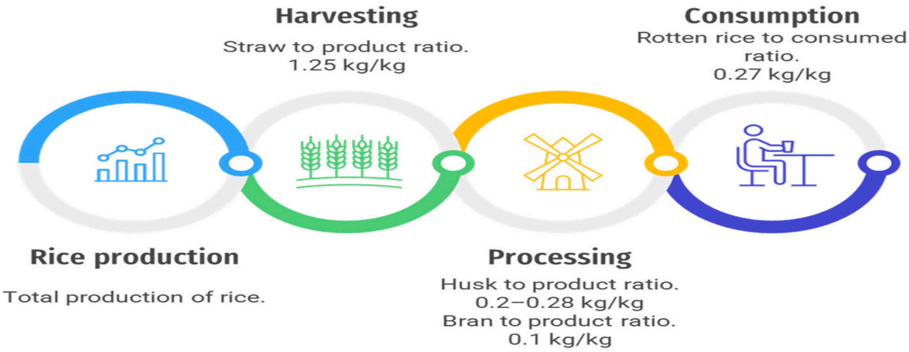

Fig. 6. Rice Value Chain Wastes. Adapted from Illakoon et al. [76].

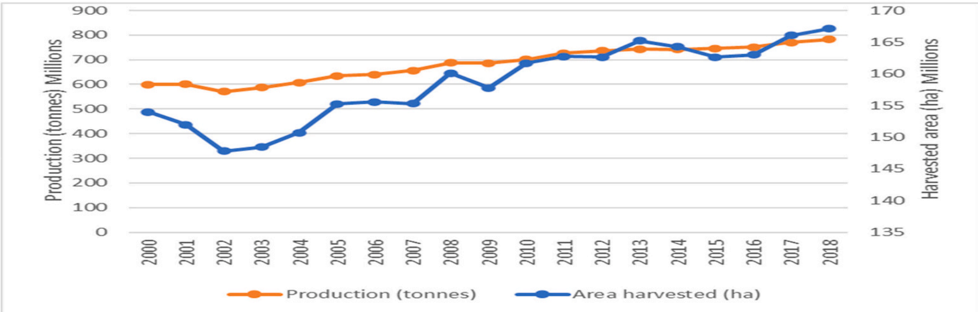

Fig. 7. Global Rice Production and Harvested Areas Trends. Adapted from Illakoon et al. [76].

Fig. 8. Global Rice Consumption Trend. Adapted from Illakoon et al. [76].

3.5.1. Rice straw

Rice straw is the vegetative part of the rice plant. It consists of the stem, leaves, and pods. The straw is the major by-product obtained after threshing harvested rice stands. It contains lignin, cellulose, silicates, waxes, and minerals. The silica concentration in rice straw is high, but its lignin content is lower than that of the straws of other cereals. Rice straw can be converted basically to fertilizer, energy, animal feed, and other beneficial uses (Fig. 9). Subjecting rice straw to pyrolysis will yield bio-oil, biochar, and syngas. In addition, it is used for producing biogas via anaerobic digestion. Furthermore, rice straw is a raw material for making polypropylene composite, rice-straw cement bricks for load-bearing walls, and cheaper cement bricks with better mechanical, thermal insulation, and fire resistance properties. Also, rice straw is used in the following areas: making ceiling panels, bulletin boards, fiber boards, lactic acid, many kinds of enzymes, silage for feeding animals, and low-cost adsorbents for purifying contaminated water. Moreso, it can be used as a soil conditioner to replace organic matter, as a growth medium for mushrooms, and to enhance soil characteristics.

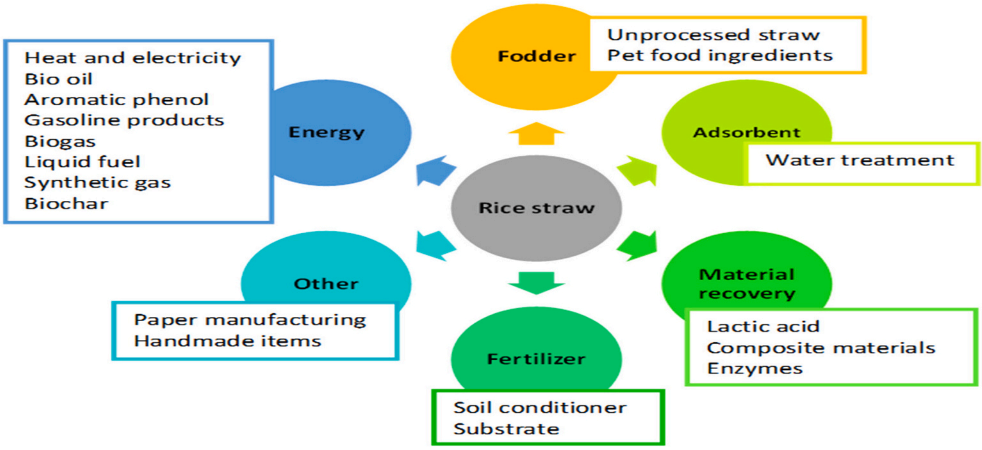

Fig. 9. Products from Rice Straw. Adapted from Illakoon et al. [76].

3.5.2. Rice husk

Rice husk is the first hard covering on threshed rice grains. The hard covering (husk) is the layer that encapsulates brown rice grains. Rice husk is obtained after the milling operation known as dehusking (the removal of rice husk). The rice obtained after dehusking is referred to as brown rice. Therefore, rice husk is one of the main by-products of rice milling operations. It can be used to produce various value-added products (Fig. 10). It is also referred to as rice hull or rice chaff. Rice husk contains lignin, cellulose, and hemicellulose as its main organic compounds. Also, it has a considerably high calorific value (16720 kJ/kg), and about 20–30 % of its mass is made up of minerals (calcium, sodium, silica, iron, manganese, magnesium, and potassium). Rice husk is good for water treatment, using activated carbon to adsorb heavy metals from industrial effluents. Biochar can also be produced from rice husks. Imposing a pyrolysis process on rice husks will produce rice husk pellets, which are an alternative energy source for small-scale power plants. Biodiesel can also be produced from rice husks through pyrolysis and gasification processes. Rice husk in combination with starch or gum Arabic will give briquettes better burning efficiency than timber. Rice husk mixed with charcoal or sawdust will yield high-grade fuel. Rapid pyrolysis and catalytic treatment of rice husk produce boiler fuel oil. Ash from risk husks is used to produce the following value-added products: high-quality silica, heavy metal adsorbent, contaminants removal from biodiesel, paper coatings that enhance printing quality, cement of better quality, and reinforcing fillers for different rubbers. Rice husk can also improve the quality of epoxy paints.

3.5.3. Rice bran

It is the immediate outer layer over the white rice grain. The removal of the bran from the surface of brown rice (obtained after dehusking) through the milling process will give white rice. Several beneficial products can be derived from rice bran (Fig. 11). Rice bran is rich in fiber, carbohydrate (cellulose and hemicellulose), and lipids (about 14–18 % oil). It also has substantial proteins and minerals. Rice bran oil can be obtained from rice bran. The rice bran oil can be subjected to a transesterification process to produce biodiesel. Bioethanol can be synthesized from rice bran. Lactic acid and water pollutants can also be produced from rice bran. Hydrogen, an excellent substitute for conventional fossil fuels, can be produced from rice bran via the fermentation process. Fermentable sugars are viable products that can be derived from rice bran via enzymatic hydrolysis. Also, rice bran is a fiber-rich raw material for making animal feed.

4. Conclusions

The full use of traditional methods in the agric-food sector can no longer be on par with the rate at which the human population is growing globally. The tension between food demand and supply can be substantially resolved with the use of digital technology in the agric-food sector. The use of digital technology will, to a large extent, bridge the existing gaps in the rice value chain. The major by-products from rice processing (straw, husk, and bran), which are wrongly considered as wastes in most cases or underutilized, can be converted to other value-added products through the circular economy (CE) approach. The CE will protect the environment and make it more friendly. Also, it will improve productivity, increase income, and create better living conditions for those in the rice value chain in Nigeria. This review paper revealed that many activities of the rice value chain in Nigeria needs more digitalization attention, in order to improve productivity.

Funding statement

The Project is Funded by Innovate UK. Project Number: 10048517; KTP Reference: 13464.

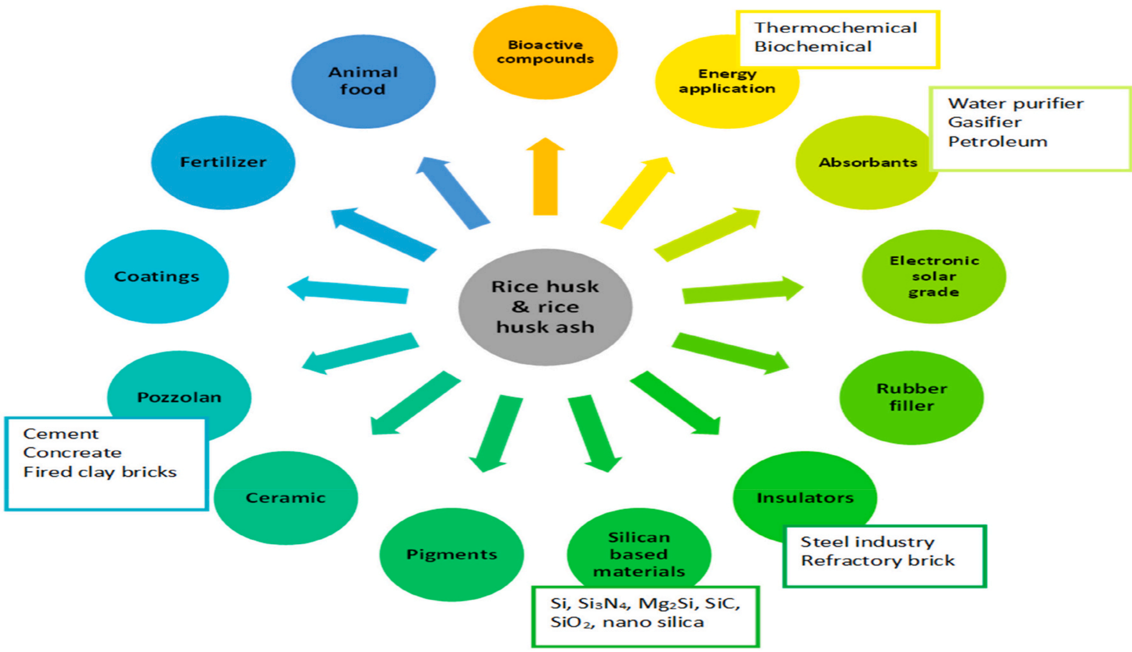

Fig. 10. Products from Rice Husk. Adapted from Illakoon et al. [76].

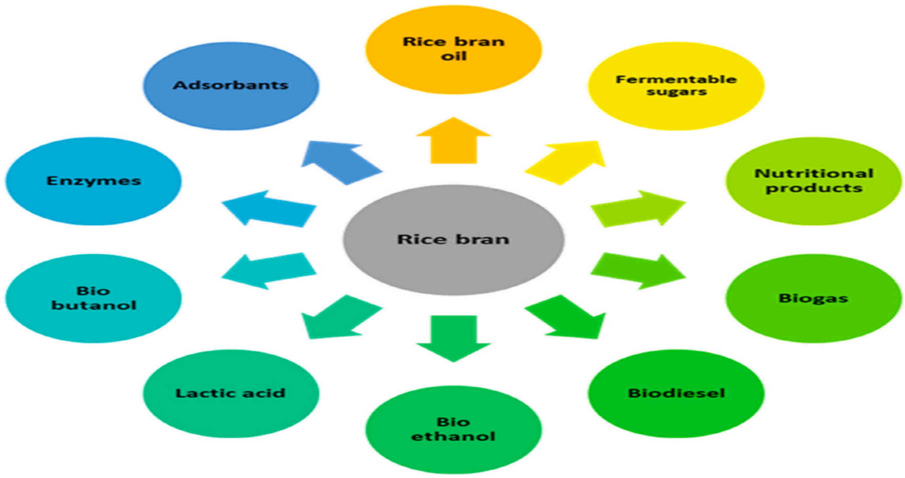

Fig. 11. Products from Rice Bran. Adapted from Illakoon et al. [76].

Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Michael Mayokun Odewole: Writing – review & editing, Writing – original draft, Conceptualization. **Mayowa Saheed Sanusi:** Conceptualization. **Musliu Olushola Sunmonu:** Supervision, Funding acquisition. **Suleiman Yerima:** Visualization, Validation, Resources. **Dare Mobolaji:** Software, Resources. **Joshua Olanrewaju Olaoye:** Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Musliu Olushola Sunmonu reports financial support and article publishing charges were provided by Innovate UK. Musliu Olushola Sunmonu reports a relationship with Innovate UK that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

African Agriculture Knowledge Transfer Project (AAKTP); University of Ilorin, Ilorin, Nigeria; De Montfort University, Leicester, England and Microscale Embedded Limited, Abuja, Nigeria.

References

[1] T. Talaviya, S. Dhara, P. Nivedita, Y. Hiteshri, S. Manan, Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides, Artificial Intelligence in Agriculture 4 (2020) 58–73, https://doi.org/10.1016/j.aiia.2020.04.002.
[2] M. Trendov, V. Samuel, Z. Meng, Digital technologies in agriculture and rural areas: status report, Digital technologies in agriculture and rural areas: Status Rep. (2019).
[3] Food and Agriculture Organization –FAO, The State of Food and Agriculture Leveraging Food Systems for Inclusive Rural Transformation, 2017, pp. 1–181, 978-92-5-109873-8pp.
[4] V. Bellon-Maurel, L. Brossard, F. Garcia, N. Mitton, A. Termier, S. Barbier, Agriculture and Digital Technology: Getting the Most Out of Digital Technology to Contribute to the Transition to Sustainable Agriculture and Food Systems, vol. 10, 2022, pp. 1–185.
[5] L.R. Brown, Full Planet, Empty Plates: the New Geopolitics of Food Scarcity, WW Norton & Company, 2012.
[6] National Bureau for Statistics (NBS), Annual collaborative survey of socioeconomic activities in Nigeria, Main statistical report 1 (2021).
[7] World Bank Group, Population Total for Nigeria (2021). www.data.worldbank.org. (Accessed 15 June 2023).
[8] Federal Ministry of Agriculture and Rural Development (FMARD), Agricultural Transformation Agenda: Repositioning Agriculture to Drive Nigeria's Economy, Presentation by the Minister of Agriculture and Rural Development, Abuja, 2012.
[9] Global Hunger Index – GHI, Hunger and food systems in conflict Settings, Boon: Welthungerhilfe; Dublin: Concern Worldwide (2021).
[10] L. Malassis, H. Nourrir les, Dominos – Flammarion (1994) 110. Paris.
[11] Food and Agriculture Organization – FAO, The Future of Food and Agriculture: Alternative Ways to 2050, FAO, Rome, 2018, p. 202.
[12] A. Tzachor, D. Medha, K. Brian, A. Shahar, O.E. Seán, Responsible artificial intelligence in agriculture requires systemic understanding of risks and externalities, Nat. Mach. Intell. 4 (2) (2022) 104–109, https://doi.org/10.1038/s42256-022-00440-4.
[13] R. Tinsley, Rice Value Chain Analysis–Sokoto State Nigeria (NIG 244), 2012, pp. 1–45. (Accessed 20 November 2023).
[14] PACE-Platform for Accelerating the Circular Economy, Recapturing Resources for Circular Food Production: Why Focus on Rice? Applying Circular Principles to the Rice Value Chain Is Urgent Given Changing Climates and a Growing Demand-Supply Gap for Rice, 2023. https://pacecircular.org/node/560.
[15] D.R. Harris, Origins and Spread of Agriculture and Pastoralism in Eurasia, vol. 565, Psychology Press, 1996. ISBN 1-85728-538-7.
[16] J. Molina, S. Martin, G. Nandita, M. Jonathan Flowers, Samara Rubinstein, Andy Reynolds, Pu Huang, et al., Molecular evidence for a single evolutionary origin of domesticated rice, Proc. Natl. Acad. Sci. USA 108 (20) (2011) 8351–8356, https://doi.org/10.1073/pnas.1104686108.
[17] I.O. Eshiett, O.E. Eshiett, G.O. Uwhubetine, Customer Perception of rice value chain in Nigeria, J. Enterpren. Bus. Innovat. 2 (2) (2021) 24–55.
[18] M.S. Sanusi, A. Rahman, Evaluation of energy consumption pattern in rice processing using Taguchi and artificial neural network approaches, Agricultural Engineering International: CIGR Journal 24 (2) (2022).
[19] S. Muthayya, D.S. Jonathan, M. Scott, F.M. Glen, An overview of global rice production, supply, trade, nd consumption, Ann. N. Y. Acad. Sci. 1324 (1) (2014) 7–14, https://doi.org/10.1111/nyas.12540.
[20] H. Bhandari, Global rice production, consumption and trade: trends and future directions, in: Proceedings of the Korean Society of Crop Science Conference. The Korean Society of Crop Science, 2019, p. 5, 5.
[21] United States Agency for International Development-USAID, Nigeria Rice Value Chain Analysis-Prepared Chemonics International, 2012. Washington, DC, USA.
[22] M. Maertens, V.V. Katrien, Contract-farming in staple food chains: the case of rice in Benin, World Dev. 95 (2017) 73–87, https://doi.org/10.1016/j.worlddev.2017.02.011.
[23] I.Y. Ilu, Value Chain Analysis of Rice (Oryza Sativa) in Kano River Irrigation Project (Krip) Kano State, Nigeria, Ahmadu Bello University, Zaria, Nigeria, 2015. An unpublished Ph. D Thesis.
[24] S. Kaushal, S. Kumar, S. Tabrez, Artificial intelligence in agriculture, Int. J. Sci. Res. 11 (5) (2022) 1682–1688, https://doi.org/10.21275/SR22524180634.
[25] Sebastian Garmann, Does globalization influence protectionism? Empirical evidence from agricultural support, Food Pol. 49 (2014) 281–293, https://doi.org/10.1016/j.foodpol.2014.09.004.
[26] C.L. Dupraz, P. Angèle, Food sovereignty and agricultural trade policy commitments: How much leeway do West African nations have? Food Pol. 38 (2013) 115–125, https://doi.org/10.1016/j.foodpol.2012.11.005.
[27] O. Obi-Egbedi, O.O. Victor, A. Alarudeen, Y. Sulaiman, Effect of rice trade policy on household welfare in Nigeria, Eur. J. Bus. Manag. 4 (8) (2012) 160–170.
[28] V.M. Manyong, Agriculture in Nigeria: Identifying Opportunities for Increased Commercialization and Investment, IITA, 2005.
[29] C.U. Izuogu, C.N. Loveday, O.O. Michael, C.K. Philomina, C.A. Gillian, D.A. Gabriel, A review of the digitalization of agriculture in Nigeria, Journal of Agricultural Extension 27 (2) (2023) 47–64, https://doi.org/10.4314/jae.v27i2.5.
[30] J. McFadden, C. Francesca, G. Terry, A. Jesús, The digitalization of agriculture: a literature review and emerging policy issues. https://doi.org/10.1787/18156797, 2022.
[31] V. Bellon-Maurel, H. Christian, L'innovation technologique dans l'agriculture, Géoéconomie 3 (2016) 159–180.
[32] G. Aceto, P. Valerio, P. Antonio, A survey on information and communication technologies for industry 4.0: state-of-the-art, taxonomies, perspectives, and challenges, IEEE Communications Surveys & Tutorials 21 (4) (2019) 3467–3501, https://doi.org/10.1109/COMST.2019.2938259.
[33] R. Abbasi, M. Pablo, A. Rafiq, The digitization of agricultural industry–a systematic literature review on agriculture 4.0, Smart Agricultural Technology. 2 (2022) 100042, https://doi.org/10.1016/j.atech.2022.100042.
[34] J. Zha, Artificial intelligence in agriculture, J. Phys. Conf. 1693 (1) (2020), https://doi.org/10.1088/1742-6596/1693/1/012058.
[35] J. Baerdemaeker, Artificial intelligence in the agri-food sector: applications, risks and impacts. The study, Panel for the Future of Science and Technology; EPRS| European Parliamentary Research Service 91 (2023). Scientific Foresight Unit (STOA): Strasbourg, France.
[36] V. Bellon-Maurel, I. Irstea, N. Pascal, T. Alexandre, G. Frédérick, Le Big Data en agriculture, Big Data: économie et regulation 77 (2018).
[37] R.A. Yalmaev, A.S. Ekaterina, O.I. Bundina, Agriculture digitization: trends and Problems'review, in: European Proceedings of Social and Behavioural Sciences, EpSBS, 2020, pp. 2643–2648.
[38] J.O. Olaoye, Digitizing agricultural operations for sustainable environment, in: A Lead Paper Presented in the Proceedings of the 4th International Soil Tillage Research Organization ISTRO-Nigeria 2023 Symposium Held on the 11th Day of July 2023 at African University Science and Technology, Km 10 Airport Road, Galadimawa, Abuja with the Theme Tillage for Sustainable Environment, 2023, pp. 22–38.
[39] K. Martin, H. Serhan, G. Trystram, Digitalization and Platforms in Agriculture: Organizations, Power Asymmetry, and Collective Action Solutions, 2020. http://pub.etla.fi/ETLA-Working-Papers-78.pdf.

[40] J. Kim, S. Parmesh, C.G. Joanne, P. Ashesh, Scaling up Disruptive Agricultural Technologies in Africa, World Bank Publications, 2020, https://doi.org/10.1596/978-1-4648-1522-5.
[41] L. Klerkx, J. Emma, L. Pierre, A review of social science on digital agriculture, smart farming and agriculture 4.0: new contributions and a future research agenda, NJAS - Wageningen J. Life Sci. 90 (2019) 100315, https://doi.org/10.1016/j.njas.2019.100315.
[42] X. Leng, T. Guangji, The digital economy empowers the sustainable development of China's agriculture-related industries, Sustainability 14 (17) (2022) 10967, https://doi.org/10.3390/su141710967.
[43] B.C. Runck, J. Alison, A.T.S. Kevin, C. Connie, G.P. Philip, C.W. James, Digital agriculture platforms: Driving data-enabled agricultural innovation in a world fraught with privacy and security concerns, Agronomy journal 114 (5) (2022) 2635–2643, https://doi.org/10.1002/agj2.20873.
[44] Y. Zhu, Z. Yan, P. Huilan, Does agricultural mechanization improve the green total factor productivity of China's planting industry? Energies 15 (3) (2022) 940, https://doi.org/10.3390/en15030940.
[45] V.V. Sulimin, V.V. Shvedov, M.I. Lvova, Digitization of agriculture: innovative technologies and development models, IOP Conf. Ser. Earth Environ. Sci. 341 (1) (2019), https://doi.org/10.1088/1755-1315/341/1/012215.
[46] L.K. Fatty, Agricultural Extension Services Delivery and Post-harvest Losses of Horticultural Crop Produce in West Coast Region of the Gambia (Doctoral Dissertation), 2019.
[47] R. Kaplinsky, R. Jeff, Integrating SMEs in Global Value Chains: towards Partnership for Development, Unido, Vienna, 2001.
[48] M. Demont, Reversing urban bias in African rice markets: a review of 19 national rice development strategies, Global Food Secur. 2 (3) (2013) 172–181, https://doi.org/10.1016/j.gfs.2013.07.001.
[49] Farm Radio International, (n. d). An Introduction to Agricultural Value Chains. Project supported by the Canadian International Development Agency. (2023) https://idl-bnc-idrc.dspacedirect.org/bitstream/handle/10625/52685/IDL-52685.
[50] United Nations Industrial Development Organization (UNIDO), Agricultural Value Chain Analysis and Development: the UNIDO Approach, A staff working paper, Vienna, 2009.
[51] C.M. Webber, L. Patrick, Building Competitiveness in Africa's Agriculture: a Guide to Value Chain Concepts and Applications, World Bank Publications, 2009.
[52] P.M. del Villar, L. Frédéric, West African rice development: beyond protectionism versus liberalization? Global Food Secur. 5 (2015) 56–61, https://doi.org/10.1016/j.gfs.2014.11.001.
[53] I. Niang, O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, P. Urquhart, Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects (2017).
[54] C.U. Uneze, H.I. Egor, N.J. Otaokpukpu, Digitilization in agricultural cooperatives: a perspective from members in rice value chain of Anambra State, Nigeria, J. Agribus. Rural Dev 1 (71) (2024) 93–101, https://doi.org/10.17306/J.JARD.2024.01800.
[55] A.Z. Ibrahim, The digitalization approach in the paddy sector to achieve the self-sufficiency level in Malaysia, 2023, E3S Web of Conferences 440 (2023) 02004, https://doi.org/10.1051/e3sconf/202344002004. ICEnSO 202.
[56] A. Neri, M. Negri, E. Cagno, S. Franzo, V. Kumar, T. Lampertico, C.A. Bassani, The role of digital technologies in supporting the implementation of circular economy practices by industrial small and medium enterprises, Bus. Strat. Environ. 32 (2023) 4693–4718, https://doi.org/10.1002/bse.3388, 2023.
[57] F. De Breuck, How digitalized rice trading is improving global food security, Blockchain Byline article (2021) 1–2. http://www.fujitsu.comerror/.
[58] A. Sridhar, M. Ponnuchamy, P.S. Kumar, A. Kapoor, D.N. Vo, G. Rangasamy, Digitalization of the agro-food sector for achieving sustainable development goals: a review, Sustainable Food Technol (1) (2023) 783–802, https://doi.org/10.1039/d3fb00124e, 2023.
[59] C.E. Onyenwaku, O. Ogunfowora, A.O. Falusi, An inter-regional programming model for agricultural planning in Nigeria, Indian J. Agric. Econ. 37 (1982) 483–493, 902-2018-1893.
[60] S.O. Akande, G. Akpokodje, Rice prices and market integration in selected areas in Nigeria: a study report, in: The Nigerian Rice Economy in a Competitive World: Constraints, Opportunities and Strategic Choices, Nigeria Institute of Social and Economic Research (NISER), Ibadan, 2003.
[61] S.R. Longtau, Multi-agency partnerships in west African agriculture. A review and description of Rice Production System in Nigeria, Ecosystem Development Organization (EDO) (2003).
[62] B.A. Chuma, C. Marc, K. Alain, R. Arisoa, S. Kalimuthu, S. Sabine, V. Isaac, A. Folkard, Altitude, temperature, and N Management effects on yield and yield components of contrasting lowland rice cultivars, J. Agron. Crop Sci. 206 (4) (2020).
[63] O. Erenstein, L. Frederic, S.O. Akande, S.O. Titilola, G. Akpokodje, O.O. Ogundele, Rice Production Systems in Nigeria: A Survey, Côte d'Ivoire: West Africa Rice Development Association, Abidjan, 2003.
[64] M. Kebbeh, S. Haefele, S.O. Fagade, C.D.I. Abidjan, Challenges and opportunities for improving irrigated rice productivity in Nigeria, West Africa Rice Development Association (WARDA) Bouake, Cote d'Ivoire (2003).
[65] O. Erenstein, L. Frederic, O. Olu, K. Mohamed, Operationalizing the Strategic Framework for Rice Sector Revitalisation in Nigeria. Project Report-The Nigerian Rice Economy in a Competitive World: Constraints, Opportunities and Strategic Choices, WARDA-The Africa Rice Centre., Abidjan, 2004, pp. 11–35.
[66] Rice Knowledge Bank, Milling (2017). http://www.knowledgebank.irri.org/step-by-stepproduction/postharvest/milling. (Accessed 7 September 2023).
[67] M.S. Sanusi, R. Akinoso, N. Danbaba, J.B. Hussein, Comparative studies of the effect of processing conditions on cooking and sensory properties of selected rice varieties, Afr. J. Food Nutr. Sci. 22 (10) (2022) 21785–21806, https://doi.org/10.18697/ajfand.115.20855.
[68] M.S. Sanusi, R. Akinoso, Multiobjective optimization of parboiled rice quality attributes and total energy consumption, Nigerian Journal of Technological Research 15 (3) (2020) 24–33, https://doi.org/10.4314/njtr.v15i3.4.
[69] M.S. Sanusi, R. Akinoso, Modelling and optimising the impact of process variables on brown rice quality and overall energy consumption, Int. J. Postharvest Technol. Innovation 8 (1) (2021) 70–88, https://doi.org/10.1504/IJPTI.2021.116075.
[70] M.S. Sanusi, M.O. Sunmonu, S.A. Olaleye, I.B. Adedeji, H.O. Adeniyi, A. Eniola, Rice parboiling using a dual-powered parboiler: evaluation of energy consumption patterns and milling quality, Acta Period. Technol. 53 (2022) 63–74, https://doi.org/10.2298/APT2253063S.
[71] M.S. Sanusi, M.O. Sunmonu, J.B. Hussein, S.A. Olaleye, I.B. Adedeji, G.O. Hamzat, I.T. Popoola, Evaluation of rice milling quality and energy requirement via a developed vibratory rice grader, Algerian Journal of Engineering and Technology 7 (2022) 19–26.
[72] M.S. Sanusi, J.B. Hussein, Impacts of soaking time and steaming time on proximate, vitro-starch digestibility and amylose content of short, medium and long rice grain type, Carpathian Journal of Food Science and Technology 15 (1) (2023) 68–77, https://doi.org/10.34302/crpjfst/2023.15.1.6.
[73] M.S. Sanusi, S.O. Alasi, A.A. Tajudeen, K.A. Aminu-Adana, O.L. Oke, T.B. Olaniran, Influence of oscillatory motion of a rice dehydrator on energy consumption and milling quality of rice, UNIOSUN Journal of Engineering and Environmental Sciences 5 (1) (2023) 115–123, https://doi.org/10.36108/ujees/3202.50.0101.
[74] R. Nattassha, H. Yuanita, M.S. Togar, S. Manahan, Understanding circular economy implementation in the agri-food supply chain: the case of an Indonesian organic fertiliser producer, Agric. Food Secur. 9 (2020) 1–16.
[75] E.K. Boon, W.A. Samuel, Circular economy and its relevance for improving food and nutrition security in Sub-Saharan Africa: the case of Ghana, Materials Circular Economy 2 (2020) 1–14.
[76] W.A.M.A.N. Illankoon, C. Milanise, M.C. Collivignarelli, S. Sorlini, Value chain analysis of rice industry by Products in a circular economy Context: a review, Waste 1 (2) (2023) 333–369, https://doi.org/10.3390/waste1020022.
[77] R. Yevich, A.L. Jennifer, An assessment of biofuel use and burning of agricultural waste in the developing world, Global Biogeochem. Cycles 17 (4) (2003), https://doi.org/10.1029/2002GB001952.
[78] Rice Knowledge Bank, Milling (2017). http://www.knowledgebank.irri.org/step-by-stepproduction/postharvest/milling. (Accessed 7 September 2023).
[79] M. Ahiduzzaman, I.A.K. Sadrul, Energy utilization and environmental aspects of rice processing industries in Bangladesh, Energie 2 (1) (2009) 134–149.
[80] S.L. Lim, T.Y. Wu, E.Y.S. Sim, P.N. Lim, C. Clarke, Biotransformation of rice husk into organic fertilizer through vermicomposting, Ecol. Eng. 41 (2012) 60–64.
[81] M.K. Sharif, M.S. Butt, F.M. Anjum, S.H. Khan, Rice bran: a novel functional ingredient, Crit. Rev. Food Sci. Nutr. 54 (6) (2014) 807–816.