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Understanding the impacts of the COVID-19 pandemic on sustainable agri-food system and agroecosystem decarbonization nexus: A review

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\textbf{A R T I C L E  I N F O}

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\textbf{A B S T R A C T}

The existing finite natural resources have witnessed unsustainable usage in the past few years, especially for food production, with accompanying environmental devastation and ecosystem damage. Regrettably, the global population and consumption demands are increasing ceaselessly, leading to the need for more resources for food production, which could potentially aggravate the sustainability and ecosystem degradation issues, while stimulating drastic climate change. Meanwhile, the unexpected emergence of the COVID-19 pandemic and some implemented measures to combat its spread disrupted agricultural activities and the food supply chain, which also led to a reduction in ecosystem carbonization. This study sets out to explore policy framework and selected feasible actions that are being adopted during the COVID-19 pandemic, which could potentially reduce the emissions even after the pandemic to promote a resilient and sustainable agri-food system. In this study, we reviewed 27 articles that focus on the current state of the agri-food system in light of the COVID-19 pandemic and its impact on the decarbonization of the agroecosystem. This review has taken the form of a systematic methodology in analyzing the adoption and implementation of various measures to mitigate the spread of COVID-19 on the impact of the agri-food system and reduction in ecosystem degradation. Up to 0.3 Mt of CO\textsubscript{2} reduction from the agri-food system alone was reportedly achieved during the first 6 months of the pandemic in 23 European countries. The various adopted measures indicate that the circular economy approach is a panacea to achieve the needed sustainability in the agri-food system. Also, it dictates a need for a paradigm change towards improvement on localized food production that promotes sustainable production and consumption.

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1. Introduction

The exceedingly dramatic surge in global population has generated a triple demand for meeting the food, water, and energy needs of people, thereby increasing pressure on the environment, and stimulating drastic restrictions, and suspension of carbon-intensive activities (Le Quéré et al., 2020; Markard and Rosenbloom, 2020; Nogueira et al., 2021). These restrictions and some other implemented measures have greatly caused disruptions in agricultural activities and the food supply chain (Gupta et al., 2019; de Paulo Farias and dos Santos Gomes, 2020; Adelodun et al., 2021a), thereby resulting in the reduction of ecosystem carbonization and emissions along the supply chain (Sembiring, 2020; Liu et al., 2020).

This new development, though sadly to experience the pandemic, presents an opportunity that could be explored to address the long issue of global emissions and climate change agenda along with the transition to sustainable production and consumption, even after the pandemic (Rasul, 2021; Ghennai and Bettayeb, 2021; Markard and Rosenbloom, 2020). Before the pandemic, the world was neck-deep in carbon-intensive activities of production and consumption, making it difficult to realize the set goal of emissions reduction and decarbonization agenda. However, several measures implemented to combat the COVID-19 spread have shown the feasible transformation in energy supply, food supply chain and transportation, and agri-food system that could drive the decarbonization and climate agenda. It was speculated that the global CO₂ would experience about a 5% reduction due to various measures attributed to the COVID-19 pandemic (Storrow, 2020). Although this figure is below the 7% reduction annual plan required to achieve the 1.5 °C targets, the perceived success achieved through the various implemented COVID-19 measures can be integrated with other earlier plans before the pandemic to addressing the climate change issue.

This study, therefore, reviews the gains of the various measures adopted to mitigate the spread of COVID-19 on the agri-food system, including the supply chain, and the decarbonization of the agro-ecosystem. The study sets out to explore policy framework and selected feasible actions that are adopted during the COVID-19 pandemic that could potentially reduce the GHG emissions even after the pandemic to promote a resilient and sustainable agri-food system. Furthermore, the adoption of circular economy in agri-food system towards achieving sustainable agri-food system and agroecosystem decarbonization is extensively explored.

2. Methodology

This study has taken a thorough look at the impact of the adoption and implementation of various measures to mitigate the spread of the COVID-19 pandemic on the agri-food system and reduction in agro-ecosystem degradation. The impact of transitioning to a circular economy from the conventional linear system in the agri-food sector was also considered. The review process employed a systematic approach using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model presented by Liberati et al. (2009), by considering relevant literature that addressed the monitoring of impact assessment of COVID-19 pandemic mitigation measures on agri-food production systems about decarbonization and climate change. At first, the literature search based on abstracts and titles was thoroughly conducted by identifying four hundred and fifty-one (451) relevant
peer-reviewed literature consisting of review and original articles, conference proceedings, and book chapters from Scopus (www.scopus.com) and Web of Science (www.webofknowledge.com) databases published up to May 23, 2021, and in the English language when the search keyword – “sustainable agri-food system” was used, and after removing the duplicated articles from both databases.

A further search and screening of the large volume of the indexed documents using germane keywords like “agri-food systems”, “agro-ecosystems”, “adoption”, “transition”, “research and innovation”, “agri-food supply chains”, “COVID-19 impacts”, “environmental effects”, “precision farming”, “COVID-19 lockdown”, and “circular economy”, while combining them with Boolean search words like “OR”, “AND”, yielded fifty-seven (57) articles. The selected full-text articles were filtered and streamlined to twenty-three (23) “recently” published papers, based on relevance to subject matter, defined scope of the study, and thoroughly studied to arrive at major themes that are representative of a full overview of the scope of the study. Four (4) more articles of interest were additionally included from citations within the initially identified papers to make a total of twenty-seven (27) papers that are finally considered for the study. The excluded papers include studies that provide no information on both direct and indirect gains from mitigation measures of COVID-19 spread on the agroecosystem to achieve a sustainable agri-food system. The detailed PRISMA flow diagram of the literature search is presented in Fig. 1. The geographical coverage of the review extensively covers Asia, Australia, Europe, North America, and South America. Fig. 2 shows the spatial distribution of the reviewed articles. The spatial global map of published papers on the efforts to mitigate the impact of COVID-19 on the agri-food system and the spread of the pandemic shows that there is a huge gap in the research efforts among the countries that are highly impacted by the pandemic. Although the USA and India indicated the high intensity of COVID-19 impact, China and Italy were currently found to have more research efforts to mitigate the relative impact of the pandemic on the agri-food system. This could be attributed to the fact that China was pointed to as the origin of the COVID-19 pandemic, hence, more research efforts were instituted.

Themes discussed in this study include research, policy, and innovation contributions on the impact of mitigation measures pursued to prevent the spread of COVID-19 on agri-food system vis-à-vis GHG emissions reduction and decarbonization in agroecosystem and food supply chain during the pandemic, food wastage – a threat to decarbonization and circular economy practice, uncertain future of the linear economy in agri-food system, and circular economy in agri-food system as a solution tool to GHG emissions mitigation and decarbonization agenda. The author-inspired model on nutrient and material flows within subsystems of a typical agri-food system was also presented.

3. Impacts of COVID-19 pandemic on agri-food system

The emergence of the novel coronavirus (SARS-CoV-2) that was first reported in Wuhan, China in late December 2019, has rapidly spread across the world with the greatest mortality effects reported in the United States, Brazil, Mexico, India, the United Kingdom, Italy, and France (Wordometer, 2021), some of which are among the G7-countries that have significant roles in the world economy, agri-food system, and value chains (Sarkodie and Owusu, 2020; Giudice et al., 2020;
According to Farzanegan et al. (2020), countries with higher levels of globalization have been greatly affected by the pandemic. COVID-19 has also significantly altered agri-food systems and food consumption dispositions in the short term and future predictions have it that this may extend beyond (Borsellino et al., 2020).

In another study, Giudice et al. (2020) carried out a pilot study on the interconnection between COVID-19 and the food system using a ‘theme popularity’ metric for six institutional accounts on the social media platform of Twitter and concluded that the change responses in popularity over three phasic periods – pre-pandemic, lockdown period, and post-lockdown were significant. The major change in popularity was reportedly recorded to food system parameters of food safety, food security, and sustainable food system (Giudice et al., 2020). During the pre-pandemic survey, respondents favored food safety above others; for the lockdown period, food security was the most dominant theme; while during post-lockdown, the media shifted to food sustainable management (Giudice et al., 2020). As much as this does not hold a conclusive stand, however, it is an important reason to support the linkage that exists between the pandemic and agri-food systems. The achievement of

Fig. 2. Spatial distribution of reviewed articles and the spread of COVID-19 cases (NA: Not applicable for other countries except with legends).

Oteros-Rozas et al., 2019). According to Farzanegan et al. (2020), countries with higher levels of globalization have been greatly affected by the pandemic. COVID-19 has also significantly altered agri-food systems and food consumption dispositions in the short term and future predictions have it that this may extend beyond (Borsellino et al., 2020).

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some of the goals of the United Nations on Sustainable Development is centered on sustainable food systems, which include food security, food nutrition, and sustainable consumption and production. Moreover, the COVID-19 has shown how crucial food safety is within the food systems on human health (Adelodun et al., 2021a; Galanakis, 2020). Rizou et al. (2020) summarized the safety measures to be adopted in the food sector in the era of COVID-19 pandemic against the foodborne transmission, which include worker’s health, personal hygiene, disinfection of surfaces, and clean food processing environment, with more emphasis on the consumption stage of the supply chain due to the involvement of more people.

The current status quo in the food industry relating to the COVID-19 has indicated the importance of sustainable and resilient approaches in the food systems to ensure future food security and food provision (Galanakis, 2020; Rasul, 2021). The micro, small, and medium-sized enterprises play an important role in the agri-food system to ensure the achievement of sustainable development goals of food and nutrition security, especially in low- and medium-income countries (Nordhagen et al., 2021). This sector is responsible for the supply of about 80% animal-based food including meat and dairy products and over 85% of fruit and vegetables in sub-Saharan Africa, with 72–83% of the total food consumption in India (Herrero et al., 2017; Reardon et al., 2020). However, this sector has been greatly affected by the COVID-19 pandemic (Nordhagen et al., 2021). The unavailability of essential raw materials required for food production and the reduction of labor availability of up to 25% have been reported as potential factors that could contribute to a food shortage (Rasul, 2021; Huff et al., 2015). The role of bioactive ingredients of food and other essential functional food supplements is critical to provide essential nutrition and y diets that can serve as an alternative to resources consuming food (Galanakis, 2020; Galanakis et al., 2020). Moreover, the consumption of foods rich in vitamins and associated supplements such as vegetables like spinach, carrots, and sweet potatoes or fruits like kiwifruits, broccoli, and citrus, and supplemental vitamins D and E, which are immune system boosters could reduce the vulnerability to various viral infections including the COVID-19 and also provide supports to hasten the repair of worn-out body tissues (Galanakis, 2020; Huang et al., 2018; Carr and Maggini, 2017). Thus, the reduction in the production and waste of food items that are often responsible for the degradation of the environment, which was intensively experienced during the peak of the pandemic could be beneficial to the decarbonization target in the agri-food systems (Adelodun and Choi, 2020; Yetkin Özbük et al., 2021). The various mitigation strategies that would not hamper the existing food insecurity in many parts of the world while ensuring the sustainable agri-food system should be the target of the pandemic and post-pandemic era.

Further assessment of the interrelationships that may exist between the pandemic and agri-food system can be found in the global drive to rapid urban development, overpopulation, huge global energy consumption, dense settlements, natural resource depletion, and GHG emissions. FAO (2018) reported that slightly above 60% of the global population resided in rural areas, but this figure has drastically dropped to about 46%, with a projected increase in urban population slated for 68% by 2050. Developed cities have been reported to claim 75% of global natural resources due to increasing urbanization (Stuchtey, 2020). This situation explains the probable rationale behind the connection between the pandemic, agri-food system, and decarbonization of agroecosystem, wherein China, the United States, the United Kingdom of France, Spain, where crop–livestock systems with high heavy urbanization and industrialization levels, and increased land conversion for agricultural production, recorded low GHG emissions due to the suspension of some of the carbon-intensive operations (Liu et al., 2020). The ecosystem and soil have the potential to improve due to the likely reduction in excess nitrogen pollution footprints at farm level production as a result of disruption in agricultural intensification and reduction in livestock production in many of the food-producing regions and countries (Mahmud et al., 2021; Khan et al., 2021). Food production has been responsible for two-thirds of the global nitrogen footprint (Leach et al., 2012); hence, the mitigation of nitrogen pollution in agroecosystem before the advent of COVID-19 has been part of the goals of agricultural management practices to achieve regenerative and sustainable agriculture, while reducing the downstream pollution and eutrophication of surface and groundwater resources (Roy et al., 2021; Fenster et al., 2021). The campaign to reduce the amount of nitrogen that is released into the environment in form of nitrous oxide, one of the GHGs that drives the climate change, from the agroecosystem was further strengthened by the United Nations through a co-sponsored research project in 2018 (Pearce, 2018). However, the process to achieve the nitrogen efficiency management in the farms and its pollution reduction goal had been a challenging task (van Grinsven et al., 2015; Cabral-Pinto et al., 2020). The COVID-19 scenario has indicated the possibility of achieving some levels of reduction of this intractable pollution footprint in the agroecosystem, which the environment could benefit from if the measures that translated to this positive outcome are strategically exploited during the post-COVID era.

Further, industrial and household food waste generations were greatly reduced and lifestyles have been altered due to the lockdown (Chakraborty and Maity, 2020; Amicarelli and Bux, 2020; Borsellino et al., 2020). Before the pandemic, food waste generation rate in many countries has been excessive due to consumers’ unawareness of the impacts on food security and the environment (Adelodun et al., 2021a; Parizeau et al., 2015; Richter, 2017). However, due to the prolonged stay-at-home policy in many countries, consumers have realized the need to purchase more non-perishable and highly conservable food items (Coluccia et al., 2021; Aday and Aday, 2020; Yetkin Özbük et al., 2021). The pandemic has generated a spike in new hobbies, most especially cooking, as against the initial preference for processed food (Amicarelli and Bux, 2020). This has largely altered the food supply chain and consumption patterns such that stakeholders are faced with the challenge of instituting policies and legacies that will ensure sufficient supply of such food materials in demand. Table 1 presented some of the impacts of the pandemic-associated measures on agri-food systems.

Due to the pandemic nature of the COVID-19, the degree of severity varies globally and so have been the level of strategies deployed to mitigate its spread. Consequently, the reported gains from the various implemented measures in relation to general environmental conservation and climate change mitigation from the agri-food system, in particular, differ across the countries and regions of the world. For instance, there is an exception of lockdown policy on the agri-food system in some countries (Haj, 2020; Andam et al., 2020). The level of fatality due to the COVID-19 situation in many countries in Africa is reportedly low based on the available official data as compared to Europe, the United States, and Asia, and this has led to early relaxation of some of the popular measures targeted at reducing the spread of the pandemic in African countries like Nigeria (Andam et al., 2020). The economic activities including agri-food business have been going unhindered within the locality of these countries (Andam et al., 2020). China and Switzerland were reported to achieve a positive trend of 23% and 18%, respectively, in agricultural products trading within March and May 2020 (Coluccia et al., 2021). However, many countries in Europe and other parts of the world experienced a decline in the production and trading of agricultural products due to the restrictive measures imposed by their various governments (Coluccia et al., 2021). For instance, Balwinder-Singh et al. (2020) reported the likely range of 10–23% reduction in rice and wheat production in India under different scenarios due to the COVID-19 pandemic with the potential significant air pollution that is associated with agricultural burning. Ethiopia experienced a decline in coffee trade by 32% and 26% as compared to 2019 and 2018, respectively (Tamru et al., 2020). The decline in the export of high resources consuming agricultural products between March and May 2020 as compared to the same period in 2019 was found to be statistically significant in Italian agri-food supply and
Recent studies on impact assessment of COVID-19 and implemented measures on agri-food system.

| Country/region | Findings                                                                 | Reference |
|----------------|---------------------------------------------------------------------------|-----------|
| France         | Total or selective lockdown in France recorded a negative short-term 5% GDP decline compared to its baseline trajectory but also resulted in a 6.6% decrease in CO₂ emissions temporarily. | Malliet et al. (2020) |
| Germany        | Sales of dairy products, poultry products, aquaculture industries, and the cost of crop production were greatly affected by the pandemic in Bangladesh. The Government of Bangladesh intervened with the institution of a revolving refinance scheme of BDT 5000 crores for farmers working in the aforementioned industries and also supplied 800 combine harvesters with 400 reapers to supplement the huge cost of production during the pandemic. There is hope for the sustainability of the project beyond the pandemic period to ensure improved productivity. | Hossain (2020); FAO (2020a) |
| Turkey         | Rare bioactive materials like carotenoids, phenols, and essential oils which serve as preservatives, nutritional supplements, and gelling agents can be obtained from food wastes to reuse and re-integrate back into the food chain/cycle. This approach can be implemented post-COVID to ensure the reuse of limited food wastes. | Aday and Aday (2020); Yetkin Ozbük et al. (2021) |
| Italy and USA  | Sales of dairy products, poultry products, aquaculture industries, and the cost of crop production were greatly affected by the pandemic in Bangladesh. The Government of Bangladesh intervened with the institution of a revolving refinance scheme of BDT 5000 crores for farmers working in the aforementioned industries and also supplied 800 combine harvesters with 400 reapers to supplement the huge cost of production during the pandemic. There is hope for the sustainability of the project beyond the pandemic period to ensure improved productivity. | Esposito et al. (2020); Omtlayo et al. (2021) |
| The United States of America and Canada | The Pandemic has fostered agricultural innovation and built a form of resilience against future shock through the improvisation of improved seeds to enhance connectivity between people and resources. Bio-fortified crops are a better choice for improving nutrition and food security, and precarious food supply chains. | Heck et al. (2020) |

Table 1 (continued)
| Country/region | Findings | Reference |
|---------------|----------|-----------|
| European Union (33 EU countries) | Identification of the 3Ds of the energy model (Decarbonization, rationalization, and decentralization) as the most important factor causing significant reductions in environmental carbon buildup during the pandemic. | Coluccia et al. (2021); Aday and Aday (2020); Rodgers et al. (2021) |
| Australia | Digital e-commerce and online orders of food items and agricultural inputs can be encouraged more as it ensures efficiency of service, food safety, and ease of operation. | Ghenai and Bettayeb (2021) |
| United Kingdom | Decentralization of food manufacturing such as embracing low-scale production near consumption points helps to reduce transportation costs and minimize environmental pollution from transport vehicles during the COVID-19 period. | Galanakis (2020) |
| Canada | Modification of Sustainable Transition Policy (STP) to give a new 5-principle STP proved that reduced carbon footprint experienced during the pandemic can be sustained post-COVID by improving the industrial capacity of low-carbon technologies like heat pumps, electric vehicle, wind, and photovoltaics. | Markard and Rosenbloom (2020) |
| Canada | Reduction of carbon-intensive industries, practices, and technologies. | |
| North America (72%), Europe (69%), and Asia-Pacific (74%) | Statistical analysis of energy data of 33 European countries obtained from the WAR/TSILA energy transition laboratory showed a decline in GHG emission of about 20% and a drop in energy consumption by 10%. | Andreoni (2021) |
| Global | The unavailability of regular food items during the pandemic led to the consideration of a change of eating habit by the majority of the sampled shoppers, including Africa (74%), Asian-Pacific (74%), Europe (72%), North America (69%) and South America (74%) on the need to adhere to a diet in the future of post-pandemic era. | Fmcggurus (2020); Bucak and Yigit (2021); Yetkin Ozbük et al. (2021) |
| Global | | |

Table 1 (continued)
4. GHG emissions reduction and decarbonization in agroecosystem and supply chain during the pandemic

GHG emissions from agroecosystem have contributed immensely to environmental degradation in all the countries of the world and stringent policies are being imposed on carbon-intensive industries to ensure a safe world (Hasegawa et al., 2018; Mohammed et al., 2021). The rapid growth of the global economy and population surge with the ever-increasing competition for access to limited agri-food resources have generated a substantial increase in energy demand across boards. Reduction of harmful emissions and decarbonization form the ultimate focus of any nation that aims to reduce its environmental carbon footprint. In light of this, it is pertinent that we assess the state of global emissions before, during, and possibly beyond the COVID-19 pandemic. Analysis of this procedural carbon yield will aim at achieving a comparative study of the factors that catalyzed the emission creation and also, proffer solutions that may be integrated and adapted to the post-COVID era.

Until now, the agroecosystem has been faced with the threat of climate change and predicted global warming due to carbon buildup. A counter-measure emerged with the pandemic offering restriction of movement and reduction of economic trade activities, consequently resulting in a significant reduction in both CO₂ and non-CO₂ emissions (Malliet et al., 2020). According to findings presented by Ghnai and Bettayeb (2021), evaluation of GHG emissions of about thirty-three (33) European Union countries showed a 20% decline in GHG emission and a drop in energy usage of 10%. The electricity generation from natural gas, nuclear, and coal reduced by 25%, 20%, and 35%, respectively, while renewable energy usage compared favorably with the previous year’s value (2019) by a 9% increment (Ghenni and Bettayeb, 2021). Similarly, Andreoni (2021) estimated the CO₂ emission changes during the first six months of 2020 in 10 major economic sectors including the agri-food system (i.e. agriculture, forestry, and fishing) among the 23 European countries. A total of 0.3 Mt of CO₂ reduction was achieved with Poland, France, and Italy recorded the largest reduction of 386, 175, and 113 thousand tons of CO₂ emission, respectively. However, countries like Spain, Denmark, and the Netherlands had increased values of 245, 91, and 81 CO₂ emissions, respectively (Andreoni, 2021). These figures are in concordance with the GDP values and CO₂ emission change of these countries. Besides, these countries experienced serious COVID-19 infections during the coverage period prompting the early introduction of lockdown restriction measures (Andreoni, 2021).

The prevalent global economic recession and the obvious mobility restriction have created a drop in global energy demand for agricultural processes as reported by the International Energy Agency (IEA, 2020). The agency maintained that total final energy usage reduced by 4%-6% in 2020 relative to 2019 because of poor economic recovery and stringent travel restrictions. This may appear to contribute favorably to the lowest global GHG emissions since 2010 (an 8% decrease compared to 2019). Sadly, the positive effect of the GHG reduction on the environment will be short-lived because many countries may embrace spontaneous economic recovery policies that may require that they invest more in improving the industrial capacity of high-carbon technologies which are capable of projecting GHG emission back and beyond its baseline trajectory. Some effective solutions that can be proffered to this menace are the institution of carbon pricing to regulate carbon usage and improvement of the industrial capacity of low-carbon technologies like photovoltaics, heat pumps, and electric farm machines (Markard and Rosenbloom, 2020). These practices can be sustained post-COVID and integrated into future endeavors.

Moreover, the pandemic has complemented the initial adoption of the 3Ds energy model of decarbonization, digitization, and decentralization. With mobility restrictions, carbon emission has reduced, energy usage has been digitized through digital e-commerce services, and the food supply chain has been decentralized such that food items are dispatched individually to consumers without a need for the conventional crowded traditional markets. It is now a common practice in developed Asian countries like Japan, South Korea, and China to deploy robots, humanoids, and data-driven autonomous mechanisms in food delivery, drug administration, and day-to-day activities instead of a human being (Aday and Aday, 2020). This has greatly improved efficiency of operation, reliability, and infection safety.

From the energy perspective, there has been a significant reduction in energy that may have been dissipated in every individual’s transportation to point of sales, carbon monoxide pollution from vehicle exhaust, and risk of transmitting the dreaded virus. Also, essential human needs have been confined to agri-food materials, face masks, and sanitizers during the pandemic. Similarly, extensive research has been conducted on ensuring the availability of essential human needs including food items, while reducing energy use due to transportation and distribution. A typical example of such a study was carried out by Paul and Chowdhury (2020), wherein they presented a production recovery model for high-demand items like food items and sanitizers during pandemic situations. This can be up-scaled and integrated with other statistical models to propose optimal decisions for tackling disruptions brought about not just by a future pandemic but in cases of emergency and uncertainty post-COVID while focusing on reducing carbon emission in the environment.

As the world currently battles with the pandemic, there is a need to evaluate the conventional supply chain and lay more emphasis on cooperation. Cooperation in this context creates an enabling environment for supply chain members to achieve mutual benefits such as jointly instituting policies on carbon emission amelioration, cost reduction, profit determination, and work flexibility to cope with unprecedented demand trends typical of the pandemic situation. Establishments that exhibit a very high level of cooperation within their folds will be able to synergize efforts in the fight against carbon emission. There are essential identified target hotspots that can be further explored to achieve the decarbonization agenda in the agroecosystem and food supply chain (Table 2). The authors advocate for proper enlightenment/educational programs that address carbon reduction technology and emission-reduction cooperation policies in the supply chain. This effort can be promoted and extended to the post-COVID period.

5. Food wastage – a threat to decarbonization and circular economy practice in the agri-food system

According to the United Nations Food and Agriculture Organization (FAO), Food Loss and Waste (FLW) is defined as a reduction or loss of mass of food and food materials in terms of quantity or nutritional quality (FAO, 2019), while the definition offered by the United States Department of Agriculture (USDA) is that FLW is the number of edible parts of food post-harvest, which is available for human use but not consumed for any reason (USEPA, 2019). FLW plays a vital role in the assessment of the effectiveness of agri-food chains and supply networks. Globally, it has been reported that about 1.3 metric tons of agricultural food products for human consumption end up as wastes, with vegetables and fruits taking up to 40–50% of the loss (Gupta et al., 2020). Food produce boasts over 22% of global municipal waste in our daily waste generation (USEPA, 2019). The wasted food is also connected to a consequential degradation of resources such as water, land, energy, capital, and labor used in the production of such food (Adelodun et al., 2021; Scherhaufer et al., 2018; Kummu et al., 2012). According to Kummu et al. (2012), a recorded wastage of food materials resulted in...
about a loss of a quarter of agricultural water usage and an estimated economic drain of about $940 billion globally in a year.

Generally, agricultural food losses are majorly recorded due to spoilage of a certain fraction of avoidable environmental effects of food supply chains and are caused by the perishability nature of agricultural produce, transportation problems, and underlying difficulty in achieving demand and supply equilibrium (Adelodun and Choi, 2020). Other possible FLW may be as a result of the nature of the crops in terms of the fraction of its biomass that is edible and that which is not (Caldeira et al., 2019). Non-edible parts mostly form the larger percentage of the crops and end up as low-value byproducts. Application of CE in this context will offer to reduce environmental degradation brought about by the potential decomposition and release of methane by the byproducts, through the conversion of such biomass to fertilizer, animal feed, biochemical and biofuels, as the case may be (Teigiserova et al., 2019; Foong et al., 2019). Agriculture 4.0 tools such as precision agriculture, remote sensing, vertical farming, etc., may prevent FLW through the biochemical and biofuels, as the case may be (Teigiserova et al., 2019; Iriarte et al., 2021). The efficient management of FLW is a manifestation of the paradigm shift from the conventional linear economy to a circular economy that are disposed of in landfills to 47 kg per capita, and food loss at both retail and consumer by 29 billion kg by 2030 (USEPA, 2019). These current efforts are also being favorably met by the willingness of municipal heads and consumers in implementing local policies targeted at reducing food wastage regionally while fostering better public awareness, proper sanitation, and improved nutritional inclinations among the local people (Minor et al., 2019). The efficient management of FLW is a manifestation of the paradigm shift from the conventional linear system to the circular economy system, which is currently being implemented in developed nations with a focus on ensuring a sufficient supply of materials and energy, recycling, and reusing wastes as limited resources. According to Lieder and Rashid (2016), a circular supply chain must also consider the consumption stage after considering manufacturing and distribution to achieve circularity. This was supported by Borrello et al. (2017) that the deliberate avoidance of ‘consumption’ in the definition of CE in their reviewed papers portrayed research needs to address circularity from the consumers’ perspective. Major research activity in the newly trending CE field has been reviewed by Ghisellini et al. (2016), where it was also agreed that consumer responsibility is of the essence.

6. Uncertain future of linear economy in agri-food system – transition to circular economy

The paradigm shift from a linear economy to a circular economy that...
is currently being experienced in developed countries presents a benefi-
cial restoration of biodiversity, reduction in environmental pressure, pro-
motion of environmental safety, and economic improvement across the
board. Results of this positive shift to circularity are currently manifest in most parts of Europe, the USA, and some Asian countries like
Japan, South Korea, and China, while others gradually implement the scheme (Ghisellini et al., 2016). Significant programs set aside to ensure the actualization of a circular economy in the agri-food system can only be thoroughly studied and evaluated through the research and innovation lens (Rowan and Galanakis, 2020). Galanakis et al. (2021) emphasized the need for innovation and technological approaches in the food sector especially on food safety, food security, bioactive compounds, and food system sustainability due to the direct impacts of the pandemic. Among the suggested innovations that can be deployed are
governmental support for research and development and the development of new technologies that can be used to mitigate the impacts of climate change. These technologies can help to improve food security and reduce environmental impacts.

7. Circular economy as a solution tool to sustainable agri-food systems

The restriction has started initiating a call for a major shift towards sustainable food production, supply, and consumption system based on the circular economy approach (Fei et al., 2020; Borsellino et al., 2020; Ibn-Mohammed et al., 2021). The disruption of agri-food chains as a result of the ongoing COVID-19 pandemic has generated the need to have a sustainable monitoring assessment system that will compensate for possible pandemic scenarios in the future (Rowan and Galanakis, 2020). A circular economy (CE) offers potential applications in agri-food systems focusing on the prevalent linear economy approach of “take-make-waste” by reducing the amount of external agricultural inputs, and closing nutrient cycles. This system also has the potential to mitigate unfavorable environmental impacts through the elimination of pollution from fertilizers, runoff contamination, excess nutrient load, eutrophication, and food wastage.

Indeed, the CE offers optimal use and reuse of agricultural raw materials with a great emphasis on assessing and mitigating environmental impacts that may result in unfavorable climate change (Tseng et al., 2019; Barros et al., 2020). The CE concept has been proposed for agroecosystem in an integrated farming system to address the sustainable use of resources and nutrient recycling to mitigate the carbonization of the agroecosystem while improving agricultural productivity (Thanh Hai et al., 2020; Wezel et al., 2020). In general terms, CE can be defined as a model of production and consumption that focuses on the sharing, leasing, repairing, refurbishing, reusing, and recycling of available products and materials and reduction of generated wastes (Bahn-Walkowiak et al., 2019). The CE was defined by Ghisellini et al. (2014) to be an industrial economy with a focus on achieving sustainability via restorative objects and design. When applied to the agroecosystem context, CE offers optimal use, reuse of agricultural wastes with a view of mitigating against hazardous climate change and environmental effects (Barros et al., 2020; Garcia-Garcia et al., 2020). As earlier stated, global food availability is being threatened by demographic, economic, and climate change factors and CE has been reported to provide an effective framework for achieving a closed-loop system aiming at combating the aforementioned issues (Kircher et al., 2017; Tseng et al., 2019). The CE offers potential applications in improving food security and sustainability in the agri-food system.

The circular economy concept has found applications in nutrient cycling and inputs in the agri-food industry (Verger et al., 2018; van der Wiel et al., 2020; Billen et al., 2019). According to Razon (2018), nitrogen-based fertilizers produced from available atmospheric nitrogen release toxins to the atmosphere during production, but can be
Table 3: Studies on the circularity and sustainability of agri-food systems and agroecosystems.

| S/ N | Authors | Findings and recommendations |
|------|---------|-------------------------------|
| 1.   | Pavitt (1984); Chen (2009) | F0B7 Agricultural innovations are mostly focused on the reduction of cost but fail to address the climate change effect and application of intellectualism. F0B7 Studied the concepts of material flow and circular economy concerning their contribution to economic globalization. F0B7 There is a synergy between circular economy and material as both uphold a similar pattern of ‘resources – production – material flow – consumption – recycled resources.’ |
| 2.   | FAO (2017) | F0B7 Applicability of CE models to after-consumption of agri-food products. |
| 3.   | Ribeiro et al. (2016) | F0B7 Explored feasibility of agricultural waste use for power generation using anaerobic bio-digestion of poultry manure as a circular economy practice in the rural Itanhandu-MG area of Brazil. It was concluded that optimal biogas yield and adequate power generation were recorded by 0.36 m³ of biogas/kg Total Solids, 63% of methane. This efficient use of agricultural waste in the manure management system was reported to obey circularity and ensure the provision of green renewable energy. |
| 4.   | Trigisera et al. (2019) | F0B7 Presented the potential production of high-value industrial materials from unavoidable and inedible generated food waste from food processing to achieve CE in the agri-food sector. |
| 5.   | Cristobal et al. (2018) | F0B7 Assessment of the proposed methodology for the design of food waste prevention schemes was carried out in Italy (as a case study), using mathematical programming and life cycle assessment approaches. Due to the reported correlation between ‘reducing environmental impact at a very low cost’ and ‘reducing food waste generation’. It was concluded that the management of sustainable food waste schemes should be aimed at addressing the environmental impacts of food wastes instead of targeting avoided food waste generation. |
| 6.   | Chang et al. (2018) | F0B7 Autoclaving of food wastes using different treatment levels of autoclaving time and temperature was carried out for resource recovery and utilization. Treatment level 408 K at 15 min i.e., less energy and time-consuming, yielded optimal results. The emitted gas due to autoclaving was reported to contain no carbon monoxide but some hydrocarbon. Hence, the necessary air pollution control measures were recommended. They included that autoclaving of food wastes above their boiling points offers a sustainable materials management solution to achieve CE. |
| 7.   | Bilali (2019) | F0B7 The author submitted that nutrition and food security are marginal issues in the available research findings on agri-food policy transition. The author recommended the integration of the agri-food CE transition field and food security research field and that each field must not be seen as an independent field. |
| 8.   | Grippo et al. (2019) | F0B7 Employed a multi-criteria analysis of bran use (livestock, biogas, and paper production) in Italy by considering participatory processes and analyzing bran use concerning circularity. Findings showed that bran applications that serve as inputs to other manufacturing processes helped in reducing the ecological footprint. They recommended that future research actions should be tailored towards considering circularity as the goal and not just as a criterion. |
| 9.   | Tseng et al. (2019) | F0B7 Recommended future study of multi-functional computer models which will take into account, socio-cultural considerations of human behavior to achieve proper simulation, forecasting, monitoring, and optimization of the decision-making process in the circularity of food systems. |
| 10.  | Yazdani et al. (2019) | F0B7 Proposed a supply chain multi-criteria-based approach to mitigate natural disaster impacts on the adoption of CE in crop production in Spain and developed optimal extenuating models to combat flood risk on cultivated lands. |
| 11.  | Mucio and Sisto (2020) | F0B7 The transition from a linear economy to that of circularity is greatly affected by the funding of external projects. This however forms integral units and shares similar regulatory architecture with the CE model, and not just by funding of research studies focused mainly on agri-food systems and agroecosystems. |
| 12.  | Omolayo et al. (2021); Esposito et al. (2020) | F0B7 PRISMA tool showed that less than half of the 22 reviewed research outputs on life cycle assessment (LCA) of food loss and waste circularity focused on the most important factor (i.e. prevention) in the food-recovery system. |
| 13.  | Xia and Ruan (2020) | F0B7 Available research findings failed to evaluate the contributory impact of FLW to the occurrence of global warming, effects on water demand, and energy consumption but only majored on food safety, nutrition, public, economy, and food security. |

Table 3 (continued)

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(continued on next page)
for the poor adoption of CE practice in the agriculture sector in China over the other fifteen causal factors from stakeholders (enterprises, farmers, and government).

14. Klerkx and Begemann (2020); van der Wiel et al. (2020)

FOB7 Awareness programs aimed at sensitizing the populace on the development and implementation of the agricultural CE and recycling programs like the Green Finance Policy and the Belt and Road Initiative in China were recommended.

15. Barcaccia et al. (2020); Tseng et al. (2019)

FOB7 Developed a six-step framework for circularity while understanding nutrient stock and flow in the agri-food waste system. The framework was large enough to accommodate all subsystems and small enough to reduce transportation of nutrients issues, while the framework identified several hotspots requiring the implementation of the CE model.

16. Taghikhah et al. (2021)

FOB7 The potential application of Agriculture 4.0 tools and precision farming systems to achieve circularity in FLW of agri-industrial systems.

17. De Corato (2020)

FOB7 Explored the most promising technologies in on-farm composting for the vegetable supply chain and concluded that European regulations, compost transporting, varying compost quality, GHG emissions, amongst other factors formed hard barriers to the total adoption of CE in the vegetable business within Europe.

18. Barros et al. (2020)

FOB7 Carried out a systematic review of CE for bioenergy creation, mapped bioenergy boosters via the CE approach, and reported trends and patterns in the reviewed literature.

19. Thanh Hai et al. (2020)

FOB7 An integrated farming system involving cattle breeding with zero GHG emissions and sustainable livelihood for rural dwellers was proposed.

20. Rowan and Galanakis (2020)

FOB7 The development of wet peatland innovation, called paludiculture, to offset the carbon footprint and restore the carbon storage capacity in the agri-food system.

Many reported studies have focused on analyzing the principle of circularity in nutrient stock and flow in the agri-food waste system (van der Wiel et al., 2020). While some recently published research papers have explained the contribution of the usage of inorganic fertilizers in the agricultural application on the environment, with most findings dwelling mostly on phosphorus (P), and lesser discussion on nitrogen (N), organic carbon (C), and potassium (K) (Recous et al., 2018; Steffen et al., 2015; Le Noël et al., 2019), others addressed the complex agri-food systems in terms of crop production, animal husbandry, food processing, procurement and consumption, and waste management (Van Zanten et al., 2018; Billen et al., 2018; Xiong et al., 2020), by ensuring that nutrients load on the environment is greatly reduced.

At the moment, agricultural practice is greatly dependent on raw materials and inputs of inorganic fertilizers (Kuokkanen et al., 2017). It is noteworthy to understand that the availability of some inorganic fertilizers especially phosphorus (P) cannot be guaranteed in the nearest future because phosphate rocks are a limited resource (Cordell et al., 2009). The potential shortage of P and other nutrients in the nearest future and the excessive loss of inorganic fertilizers to water bodies, atmosphere, and soil may result in an alarming record of eutrophication, biodiversity degradation, groundwater contamination, loss of riparian vegetation, the high mortality rate of aquatic life, increased human ailments, and environmental worries (Cabral Pinto et al., 2019; Desmidt et al., 2015). Also, long-term sustainability brought about by the circular economy can be achieved from the chemical recovery of P from sewage-digested food wastes for fertilizer production (Tseng et al., 2019). Although the reported case of potassium (K) fertilizers creating hazardous effects on the environment is limited, its availability concerning its K-rich rock reserves cannot be guaranteed since the availability of the rocks varies spatially. Some locations depend hugely on such K fertilizers but are constrained by their diminishing reserves and access. Therefore, there is a need to practice recycling programs for K to meet the demand required by the agri-production system.

A more essential macronutrient in the agri-food system is organic carbon, which forms an important element in the maintenance of soil fertility and water-holding capacity by soil organic matter (Verger et al., 2018). Soil organic matter has been reported to exhibit an inverse proportionality with agriculture intensification and a reduction in the former is representative of a decrease in soil fertility (Verger et al., 2018). Also, van der Wiel et al. (2020) posited that to forestall the scarcity of nutrients brought about by the disruption of all nutrient cycles as a result of anthropogenic activities, there is a need to explore research areas and policy adoption of findings focused on achieving circularity for P and N usage.

Transportation of agricultural produce plays an important role in the agri-food waste sector. The effectiveness of the circularity of food wastes is prevented through the adoption of new technologies for ammonia production, which successively constitute the major raw material for urea. Agriculture 4.0 tools, especially on precision farming systems and vertical farming, are also efficient approaches in achieving proper nutrient dosage (Zhai et al., 2020), thereby reducing environmental pressure on water and land resources, excessive nutrient wash-off, and groundwater contamination.
can be monitored through proper trade and transportation networks (Seyhan and Brunner, 2018). According to Neset et al. (2008), about 39% of food supplies consumed in Sweden are imported into the country. This implies that imported nutrients present in the generated food waste at the end of the food chain are ejected as fecal deposits and may be used for local or subsistence cropping. This generates another constraint to the implementation of CE, since food consumption patterns within a local environment may be very hard to regulate. In the presented scenario, the resulting nutrient feedback is a nutrient surplus which may create devastating effects on the environment, aquatic life, human life, and groundwater quality (Xiong et al., 2020). A possible solution is to transport such nutrients from the point of surplus to other

Fig. 3. Nutrient and material flow within subsystems of an agri-food system.

Fig. 4. Model for valorization and recycling of the agri-food sector during COVID-19 pandemic (Modified after FAO, 2020b).
points of need as organic fertilizers. However, when transportation is economically unfeasible as a result of overpriced cost implications and other reasons such as accessibility, technology, etc., practicing CE focused on reuse and recycling of sufficiently available nutrients will increase the excess supply, while the demand is defeated (Billen et al., 2019; Prasad et al., 2021). Therefore, Xiong et al. (2020) submitted that circular economy practice in the nutrient cycle cannot only be achieved by sorting technological problems alone but must also consider other aspects like moderating food consumption patterns of such an environment. This submission was largely supported by van der Wiel et al. (2020) in their review work.

7.2. CE in food production and packaging

Based on the definition of the European Union Commission, CE has been divided into three major stages – production, consumption, and waste management (Taranic et al., 2016). The positive drift towards the localization of the agri-food system may present a more sustainable remedy since it will aim at managing nutrient circularity, fostering prompt accessibility of farm produce, and decreasing waste injection into the environment (Fei et al., 2020). Shorter supply chains can be implemented to prevent wastage of agricultural produce via longer routes of supply chains, farther consumer points, and longer storage time, to create a more efficient demand-supply balance and monitoring of waste generated. In this regards, the COVID-19 situation could be a remedy since it will aim at managing nutrient circularity, fostering agronomic, microbial, and phonologic research should be carried out to extensively understand the climatic impacts on food stored or processed for future use.

7.3. CE in food waste reduction and management

The wastes reduction is tagged as the final stage of the agri-food system and the CE generally has the largest impact on this phase. According to Stuart (2009), production of food materials takes up about 24%–30% of general waste; post-harvest – 20%; and food consumption at 30%–35%. The author concluded that the reduction of agri-food wastes is crucial to attaining a sustainable system. Moreover, the non-edible parts of the food which are often regarded as food waste and sent to landfills can be reprocessed through the CE approach into biofuels and fertilizers (Kumar et al., 2021). This process would introduce back the wasted food materials into the cycle to promote continuity while reducing potential environmental pollution that could have resulted if disposed of. Individual household composting and gardening should be encouraged, as this will create a shorter and more dependable food chain and a cleaner environment. Reduction of FLW policies should be implemented by addressing domestic misconceptions about ‘shelf life’ and ‘best before’ tags on products. People should be sensitized on the concept of expiry dates of goods and enjoined to understand what a buffer zone after the ‘best before’ period elapses indicates. Further agronomic, microbial, and phonologic research should be carried out to extensively understand the climatic impacts on food stored or processed for future use.

7.4. The new agriculture 4.0 approach

A very effective tool in achieving circularity and higher efficiency of operation during the pandemic is the Agriculture 4.0 tool. This offers a multi-disciplinary approach, with a greater focus on precision agricultural practices like positioning, sensor technologies, and satellite navigation technologies. According to Tseng et al. (2019), Agriculture 4.0 technology employs the use of artificial intelligence (AI) in coordinating agricultural activities bordering from procurement of inputs down to the post-consumption stage, intending to reduce potential FLW through the operation of intelligent and agile food supply chain. Precision agriculture is an important element in this category, as it encourages excellently optimized management of agricultural inputs in farmland, based on exact crop requirements. It covers the extensive use of spatiotemporal knowledge through gathering, processing, and analyzing remotely-sensed data and ground-based data. The operations of the tool are combined with other factors to create effective management decisions in crop production, pesticide application, fertilizer use, ecosystem services, and agricultural water conservation at the right place and the right time. When precision farming is adapted to suit the circular economy approach in agricultural applications, it produces a very powerful tool that can produce optimal performance within the soil-water-plant continuum with lesser use of resources and inputs. Thereby, reducing possible pressure and pollution in the environmental footprint of such an area (García-García et al., 2020).

Proper or adequate dosages of nutrients and water can be achieved with the help of precision farming. Vertical farming, drone fertilization, drone surveillance, hydroponics, aquaponics, etc., can also promote efficient usage of limited water and land resources. These innovative ideas allow meeting the exact irrigation requirements of crops by using Arduino sensor automation, reduction of excessive nutrient load transported by runoff, and cultivation of crops in areas that seemingly would not have been possible to cultivate. This reduces the pressure on land for agriculture, encourages coherent biodiversity, and guarantees land use for other purposes. Farm wastes can be introduced back into the cycle to produce fertilizers, biofuels, and biomass materials for a cleaner environment. Discoveries in the field of biotechnology have erupted the potential applicability of nanotechnology, improved seeds, and genetically modified organisms to the improvement of biomass accumulation and yield of crops. This new field can be extensively explored especially in developing countries that have abundant land and water resources. The entire populace should be sensitized to the beneficial implications of embracing the Agriculture 4.0 technology to ensure food safety, security, and circularity across all boards.

8. Conclusion

The gains of various measures implemented to mitigate the spread of COVID-19 and their impacts on agri-food systems that could potentially
drive the decarbonization and climate agenda in the agroecosystem and food supply chain in the post-pandemic were reviewed. There was an established link between the selected implemented measures of the COVID-19 pandemic and ecosystem improvement. Although these implemented measures are temporary, they indicated that there are feasible approaches to achieve the ambitious target of 1.5 °C global warming benchmark through 7.6% global annual reduction of GHG emissions between 2020 and 2030. Meanwhile, the various adopted measures indicated that the circular economy approach is a panacea to achieve the needed sustainability in the agri-food system. The paradigm shift from a linear economy to CE in the agri-food system in the world requires global adoption and a positive attitude towards the transition process, to supplement the global efforts towards decarbonization and climate agenda.

Research activities and innovative ideas can support current public efforts in the transition phase to the CE model by guiding the modalities of the transition and facilitating the implementation of the CE for a sustainable food system. Policymakers, shareholders, and public-private partnerships are advised to institute business strategies operating on the CE model to harness all the benefits inherent in the CE, especially on the decarbonization of the agroecosystem. Funding of external projects which share regulatory architecture with the CE model should be encouraged so that a more coordinated integration of several fields is achieved. Nutrient circularity must be enforced, while food loss and waste (FLW) materials must be converted into raw materials like fertilizers, biofuel, biomass, and integrated back into the cycle. The food consumption pattern of people must be assessed to create recycling programs to reduce carbon footprint in the environment. Agriculture 4.0 technologies should be adopted to efficiently manage soil and water resources, land, and environmental pollution while ensuring the fewer generation of wastes. Finally, innovative ideas and further research should be carried out and tailored towards achieving circular economy impacts on the agri-food system.

CRediT authorship contribution statement

Bashir Adelodun: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. Kola Yusuff Kareem: Investigation, Visualization, Writing – original draft, Writing – review & editing. Pankaj Kumar: Investigation, Visualization, Writing – original draft, Writing – review & editing. Vinod Kumar: Investigation, Visualization, Writing – review & editing. Kyung Sook Choi: Investigation, Visualization, Writing – review & editing. Akanksha Yadav: Investigation, Visualization, Writing – review & editing. Krishna Kumar Yadav: Investigation, Visualization, Writing – review & editing. Santhana Krishnan: Investigation, Visualization, Writing – review & editing. Nadeem A. Khan: Investigation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Acosta, M., Coronado, D., Toribio, M.R., 2011. The use of scientific knowledge by Spanish agrifood firms. Food Pol. 36, 507–516. https://doi.org/10.1016/j.foodpol.2011.04.003.

Aday, S., Aday, M.S., 2020. Impact of COVID-19 on the food supply chain. Food Qual. Saf. 4, 167–180. https://doi.org/10.1016/j.fqsaf.2020.04.002.

Adelodun, B., Ajibade, F.O., Tianmiyu, A., Nwogwu, M.A., Ibrahim, R.G., Kumar, P., Volar, O., Odey, G., Yade, K., Khan, A.H., Cabral-Pinto, M.M.S., Kareem, K., Bakare, H.O., Ajibade, T.F., Naveed, Q.N., Islam, S., Fadare, O.O., Choi, K.S., 2021a. Monitoring the presence and persistence of SARS-CoV-2 in water-food. environmental compartmental state of the knowledge and research needs. Environ. Res. 200, 111373. https://doi.org/10.1016/j.envres.2021.111373.

Adelodun, B., Choi, K.S., 2020. Impact of food wastage on water resources and GHG emissions in Korea: a trend-based prediction modeling study. J. Clean. Prod. 271, 125662. https://doi.org/10.1016/j.jclepro.2020.125662.

Adelodun, B., Kim, S.H., Choi, K., 2021b. Assessment of food waste generation and composition among Korean households using novel sampling and statistical approaches. Waste Manag. 122, 71–80. https://doi.org/10.1016/j.wasman.2021.01.005.

Adelodun, B., Kim, S.H., Odey, G., Choi, K.-S., 2021c. Assessment of environmental and economic aspects of household food waste using a new Environmental-Economic Footprint (EN-EC) index: a case study of Daegu, South Korea Preprint. Sci. Total Environ. 149294. https://doi.org/10.1016/j.scitotenv.2021.149294.

Adelodun, B., Mohammed, A.A., Adelani, K.A., Abdullahi, T.S., Choi, K.S., 2021d. Comparative assessment of technical efficiencies of irrigated crop production farms: a case study of the large-scale Kampe-Omi irrigation scheme, Nigeria. African J. Sci. Technol. Innov. Dev. 13, 293–302. https://doi.org/10.1080/20421338.2020.1755111.

Aldaco, R., Hoehn, D., Loso, J., Margallo, M., Ruiz-Salmon, J., Cristobal, J., Kahhat, R., Villanueva-Rey, P., Bala, I., Fullana-i-Palmer, P., Irab, A., Batlle-Bayer, L., Fullana-i-Palmer, P., Ibartz, A., Vazquez-Ruiz, J., 2020. Food waste management during the COVID-19 outbreak: a holistic climate, economic and nutritional approach. Sci. Total Environ. 742, 140524. https://doi.org/10.1016/j.scitotenv.2020.140524.

Amarelli, V., Bux, C., 2020. Food waste in Italian households during the Covid-19 pandemic: a self-reporting approach. Food Secur. https://doi.org/10.1007/s12571-020-01121-z.

Andam, K., Edhe, E., Oboh, V., Puw, K., Thurtow, J., 2020. Impacts of COVID-19 on food systems and poverty in Nigeria. Advances in Food Security and Sustainability, first ed. Elsevier Inc. https://doi.org/10.1016/b978-0-12-811050-8.00025-x.

Androni, V., 2021. Estimating the European CO2 emissions change due to COVID-19 restrictions. Sci. Total Environ. 769, 145115. https://doi.org/10.1016/j.scitotenv.2021.145115.

Bahn-Walkowiak, B., Wilts, H., Reimer, W., Lee, M., 2019. Overview Report on Opening to distant markets or local reconnection of agro-food systems? Balvinder-Singh, Srisht, P.B., Jat, M.L., McDonald, A.J., Srivastava, A.K., Craufurd, P., Rana, D.S., Singh, A.K., Chaudhuri, R., Sharma, P.C., Singh, R., Jat, H.S., Siddhu, H.S., Gerard, B., Braun, H., 2020. Agricultural labor, COVID-19, and potential implications for food security and air quality in the breadbasket of India. Agric. Syst. https://doi.org/10.1016/j.agsy.2020.102954.

Barcaccia, G., D’Agostino, V., Zotti, A., Cozzi, B., 2020. Impact of the SARS-CoV-2 on the Italian agri-food sector: an analysis of the quarter of pandemic lockdown and clues for a socio-economic and territorial restart. Sustainability 12, 5651. https://doi.org/10.3390/su12215651.

Barros, M.V., Salvador, R., de Francisca, A.C., Piekarski, C.M., 2020. Mapping of research lines on circular economy practices in agriculture: from waste to energy. Renew. Energy Sci. 131, 109958. https://doi.org/10.1016/j.renene.2020.109958.

Bates, E.R., Primack, R.B., Moraga, P., Carlos, M., 2020. Jo ur 1 F re. Biol. Conserv. 108665. https://doi.org/10.1016/j.biocon.2020.108665.

Batlle-Bayer, L., Bala, A., García-Herrero, I., Lemaire, E., Song, G., Aldaco, R., Fullana-i-Palmer, P., 2019. The Spanish Dietary Guidelines: a potential tool to reduce greenhouse gas emissions of current dietary patterns. J. Clean. Prod. 213, 588–598. https://doi.org/10.1016/j.jclepro.2018.12.215.

Benis, K., Ferrao, P., 2017. Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UAP) – a life cycle assessment approach. J. Clean. Prod. 140, 784–795. https://doi.org/10.1016/j.jclepro.2016.05.176.

Berner-lee, M., kennelly, C., watson, R., Hewitt, C.N., 2018. Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. Ecol. Sci. Anthr. 6 https://doi.org/10.1525/elementa.310.

Bilali, H. El, 2019. Research on Agro-Food Sustainability Transitions: Where Are Food Security and Nutrition? Foodpol. 200, 111373. https://doi.org/10.1016/j.foodpol.2011.04.003.

Boon, E.K., Anuga, S.W., 2020. Circular economy and its relevance for improving food and nutrition security in sub-Saharan Africa: the case of Ghana. Mater. Circ. Econ. 2 https://doi.org/10.34284/2020.00005-X.

Bozetti, A., rosa, L., 2019. Reassessing the projections of the world water development report. npJ Clean Water 2, 15. https://doi.org/10.1007/s41545-019-0039-9.
B. Adelodun et al.  
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Xia, X., Ruan, J., 2020. Analyzing barriers for developing a sustainable circular economy in agriculture in China using grey-DEMATEL approach. Sustainability 12, 6358. https://doi.org/10.3390/su12166358.

Xiong, C., Guo, Z., Chen, S.S., Gao, Q., Kishe, M.A., Shen, Q., 2020. Understanding the pathway of phosphorus metabolism in urban household consumption system: a case study of Dar es Salaam, Tanzania. J. Clean. Prod. 274, 122874. https://doi.org/10.1016/j.jclepro.2020.122874.

Yazdani, M., Gonzalez, E.D.R.S., Chatterjee, P., 2019. A multi-criteria decision-making framework for agriculture supply chain risk management under a circular economy context. Manag. Decis. ahead-of-print. https://doi.org/10.1108/MD-10-2018-1086.

Yetkin Ozbük, R.M., Coğkun, A., Filimonau, V., 2021. The impact of COVID-19 on food management in households of an emerging economy. Socioecon. Plann. Sci. 101094 https://doi.org/10.1016/j.seps.2021.101094.

Zhai, Z., Martinez, J.F., Beltran, V., Martinez, N.I., 2020. Decision support systems for agriculture 4.0: survey and challenges. Comput. Electron. Agric. 170, 105256. https://doi.org/10.1016/j.compag.2020.105256.