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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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ABSTRACT

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_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 climate change (Adelodun and Choi, 2020; FAO, 2017). The current 4.6 billion m^3 of global water demand is projected to reach up to 6 billion m^3 for all uses by 2050, while the demand for agricultural production alone is expected to increase by 60% in the year 2025 (Boretti and Rosa, 2019). Similarly, a significant amount of energy is required at different stages of agricultural production, including pre-farm, on-farm, and post-farm processes, which are carbon-related activities, thereby leading to greenhouse gas (GHG) emissions (Berners-Lee et al., 2018; Toka et al., 2016).

Anthropogenic activities in the agriculture and food supply chain systems have generated a worrisome climate change scenario and accountable for the major cause of environmental change (Foley et al., 2011). Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are often generated from agri-food systems in large quantities, are the major greenhouse gases that drive climate change globally (Garnett, 2011; Willett et al., 2019). About 30% of the global GHG emissions are generated from food production (Vermeulen et al., 2012), while on-farm activities, including deforestation, dominate the anthropogenic GHG emissions, and responsible for 81% of agri-food system emissions (Poore and Nemecek, 2018).

Similarly, out of the 13.7 billion tonnes of CO_2eq. of global GHG emissions generated from the entire food supply chain, the retail, packaging, transport, and food processing are responsible for 18% altogether (Poore and Nemecek, 2018). Emissions from logistic operations of food materials through the food trade have received considerable attention due to their considerable end-user contributions to the GHG emissions, especially in the developed countries (Iriarte et al., 2021; Penazzi et al., 2019). There is also considerable variability in the emission impacts of food products along the supply chain, specific to each country and region, as well as resources required for their production (Adelodun and Choi, 2020; Kumar et al., 2020), leading to campaigning for dietary change to address the impending environmental impacts and climate targets in agri-food systems (Batlle-Bayer et al., 2019; Theurl et al., 2020). Food and Agriculture Organization (FAO) reported that nearly doubled GHG emissions are generated from agriculture, forestry, and fisheries over the past 50 years with a potential increment of up to 30% by 2050 if the current business-as-usual is sustained (FAO, 2014). Hence, there is a need for a multidimensional policy framework and actions to mitigate the emission impacts to achieve an ambitious target of 7.6% annual global reduction of GHG emissions between 2020 and 2030 (UNEP, 2019), most especially through decarbonization in agri-food systems, including the supply chain.

Surprisingly, food wastage, which comprises food loss from the upstream of the supply chain and food waste at the consumption stage, has become a global issue with an annual estimate of 1.3 billion tonnes reportedly wasted globally (FAO, 2015; Kumar et al., 2019). Aside from the contributions of food wastage to global food insecurity (Kuiper and Cui, 2021), it has also become a hindrance to achieving the desire sustainable food systems as substantial resources are required for the production of wasted food (Adelodun et al., 2021c; Gupta et al., 2015). More so, the management and disposal of wasted food account for a significant amount of GHG emissions. Franca et al. (2021) reported a 138.51 CO_2eq. tonne per day of emissions from food waste landfill in Rio de Janeiro, Brazil, with a potential of 90% reduction when considers food waste reduction and alternative waste management. Similarly, the annual carbon footprint of wasted food along the food supply chain reached up to 60.85 and 20.08 million tonnes of CO_2eq in China and Korea, respectively (Adelodun and Choi, 2020; Sun et al., 2018). Benis and Ferrão (2017) reported a reduction of up to 8.2% in GHG emissions when food wastage is eliminated in the supply chain. Food waste has been demonstrated as a hotspot that needs to be targeted in achieving decarbonization and emission reduction within the agri-food systems (Adelodun and Choi, 2020; Cakar et al., 2020; Malav et al., 2020).

All these accounts have created a more essential need to embrace a policy framework and actions that could promote and ensure a resilient and sustainable agri-food system. However, the prevalent economic linear system in the agri-food sector, which is a typical practice in developing and underdeveloped countries (van Bodegom et al., 2019), is currently failing in terms of social, economic, nutritional, environmental sustainability, and food security in addressing the ever-booming population, especially in these regions (Boon and Anuga, 2020). Meanwhile, the unprecedented emergence of the Coronavirus disease 2019 (COVID-19) pandemic has forced several countries to implement different measures, including lockdown, confinement, transportation 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; Ghenai 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 CO_2 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 agroecosystem. 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 agroecosystem 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;

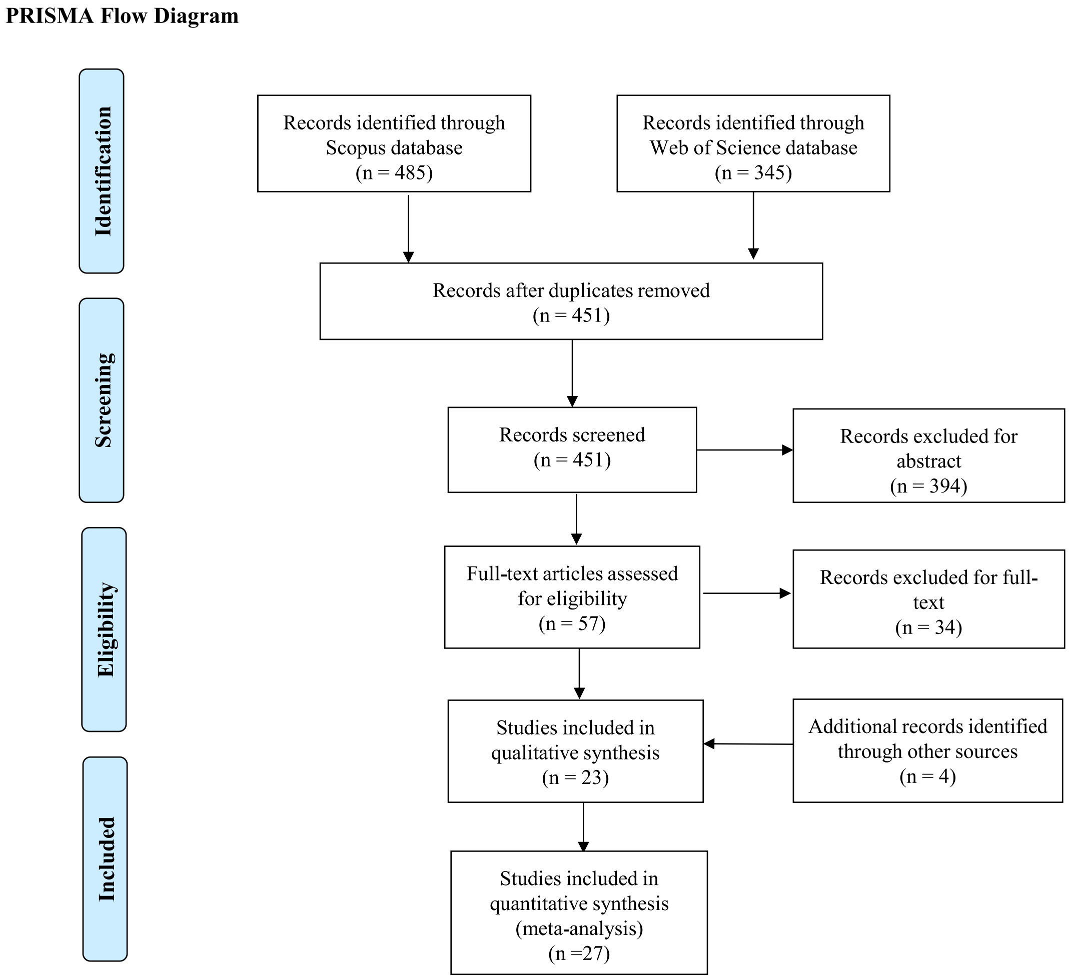

Fig. 1. PRISMA flow diagram of twenty-seven (27) reviewed papers.

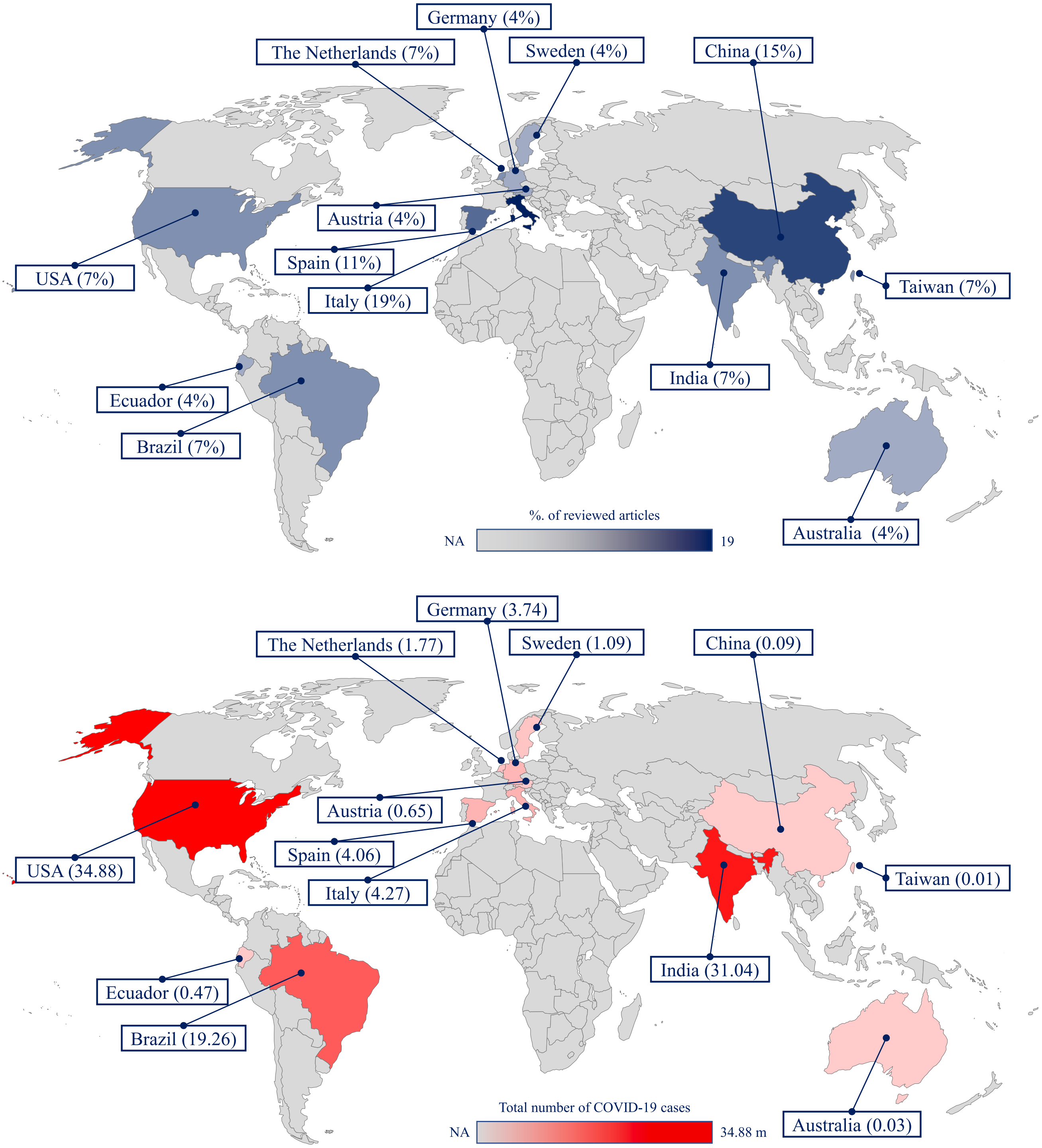

Fig. 2. Spatial distribution of reviewed articles and the spread of COVID-19 cases (NA: Not applicable for other countries except with legends).

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).

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 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, France, Spain, Brazil, Japan, and Italy, with their 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 (Haq, 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 targetted 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

Table 1
Recent studies on impact assessment of COVID-19 and implemented measures on agri-food system.

Country/region	Findings	Reference
France	F0B7 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 CO_2 emissions temporarily. F0B7 Due to economic recovery, the reduction in CO_2 emissions normalized and exceeded baseline thresholds over time, and carbon pricing was implemented. F0B7 Carbon pricing resulted in a more significant decrease in CO_2 emissions and energy use and can be translated to a non-COVID-19 period while maintaining similar climate policies.	Malliet et al. (2020)
Turkey	F0B7 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 F0B7 More food wastes collection and processing units are needed to achieve this feat. F0B7 Effective food-management behavior to include rationale use of food materials and the re-use of food left-overs.	Aday and Aday (2020); Yetkin Özbük et al. (2021)
Global	F0B7 The repositioning of logistics operations in the foodservice sector is suggested to ensure optimum service delivery by adopting e-commerce. This approach, when put in the perspective of environmental conservation, could reduce the emissions from logistic operations of food products. F0B7 Improved working conditions in the agri-food system through the integration of a robotic system are suggested. Although this suggestion is target at mitigating the spread of the virus, but can also be employed to minimize food wastage along the supply chain through process optimization.	Aday and Aday (2020)
The United States of America and Canada	F0B7 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 livelihood during crises and uncertainties.	Heck et al. (2020)
Asian Productivity Organization member countries	F0B7 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. F0B7 In Cambodia, India, and Fiji, tax breaks, policies targeted at job creation, training on new agricultural techniques, improved seeds, incentives for migrant laborers, support for rural food and nutrition security, and farm response packages were delivered by the three governments to ameliorate the effect of the pandemic and beyond. F0B7 To ensure preparedness, the Ministry of Higher Education in Malaysia is currently offering post-COVID-19 research grants to public and private institutions to overcome economic challenges, agricultural inadequacies, transportation problems, and issues.	Hossain (2020); FAO (2020a)
Canada	F0B7 Food supply chain disruptions greatly affected low-income consumers, remote indigenous communities, and food banks in northern Canada, thereby creating limited availability of fresh foods, high prices, and precarious food supply chains. F0B7 Policy formulation aimed at ensuring the availability of essential food and non-food materials to vulnerable communities during the pandemic and beyond was prioritized.	Hobbs (2020); Larue (2020)
Italy and USA	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. F0B7 Available research findings failed to evaluate the contributory impact of food loss and waste to the	Esposito et al. (2020); Omolayo et al. (2021)

(*continued on next page*)

Table 1 (*continued*)

Country/region	Findings	Reference
	occurrence of global warming, effects on water demand, and energy consumption but only majored on food safety, nutrition, public, economy, and food security.	
	F0B7 There was a negative trend in the exportation of Italian agri-food materials during the first quarter of 2020 as compared to the same period in 2019 due to the COVID-19 pandemic mitigation measures.	Coluccia et al. (2021); Aday and Aday (2020); Rodgers et al. (2021)
	F0B7 The demand for conservable food products witnessed an increasing trend while the highly perishable food items were replaced with food items with longer conservation times.	
	F0B7 Nearly 40% of the households in the USA are conscious of the perishability of food items during shopping due to the extended national lockdown.	
	F0B7 Fruits and domestic egg consumption were increased in Italy and the USA due to the restrictive measures on the importation of other meat and meat products and the need to strengthen the immune system against the contagion of COVID-19.	
United Kingdom	F0B7 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)
	F0B7 Small producers are to be integrated closer to agro-food collection centers with a high capacity to reduce mobility	
Australia	F0B7 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.	Paul and Chowdhury (2020)
Canada	F0B7 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)
	F0B7 Reduction of carbon-intensive industries, practices, and technologies.	
European Union (33 EU countries)	F0B7 Identification of the 3Ds of the energy model (Decarbonization, digitization, and decentralization) as the most important factor causing significant reductions in environmental carbon buildup during the pandemic.	Ghenai et al. (2020); Ghenai and Bettayeb (2021)
F0B7 During the pandemic, electricity generation from natural gas, nuclear, and coal was reduced by 25%, 20%, and 35%, respectively, while renewable energy usage compared favorably with the previous year's value (2019) by a 9% increment of the former.	F0B7 Statistical analysis of energy data of 33 European countries obtained from the WÄRTSILÄ energy transition laboratory showed a decline in GHG emission of about 20% and a drop in energy consumption by 10%.	
	F0B7 The first 6 months of the pandemic (January–June 2020) achieved 195.6 Mt of CO_2 reduction from 10 major economic sectors including the agri-food sector (0.3 Mt of CO_2 reduction) in 23 European countries, which represents −12% emission change as compared to 2019.	Andreoni (2021)
Global	F0B7 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 y diet in the future of post-pandemic era.	Fmcggurus (2020); Bucak and Yiğit (2021); Yetkin Özbük et al. (2021)

value chain for beef (−11%), eggs (−27%), and milk and dairy products (−5%) due to the lockdown measures (Coluccia et al., 2021). Similarly, the global cumulative impacts assessment with percentage deviation from the benchmark showed a decline in agricultural production (crops and livestock) in Malaysia, South Korea, Japan, India, Canada, USA, and Brazil by 4.2%, 3.9%, 4.7%, 3.4%, 4.3%, 3.6%, and 3.4%, respectively (Maliszewska et al., 2020).

Further, Nordhagen et al. (2021) investigated the production changes that occurred among the 367 agri-food firms in 17 low-and-middle-income countries of Asia and Africa as a result of early the impact of the pandemic in May 2020 using a survey-based approach. The authors found that 83.8% of the agri-food firms confirmed the occurrence of changes in their food production with 13% reported a total stoppage in food production, 46% reported a considerable decline, 26.9% reported a moderate decline, 9.6% reported a slight decline, while 5.5% reported an increase in their food production. Also, agri-food firms (by sector and value chain) that showed statistically significant severity of the COVID-19 impact were catering and food service (100%), processing (60.2%), retail (65.9%), crop farming (66.7%), legumes (67.4%), dairy (66.7%), and vegetable (63.3%), while distribution (46.2%), nuts and seeds (18.3%), and fish (9.7%) were reportedly stable or showed an increase in production. Meanwhile, 84.5% of the firms also reported expecting further impacts of the pandemic on their food supply chain in the next six months from May 2020 (Nordhagen et al., 2021).

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 CO_2 and non-CO_2 emissions (Malliet et al., 2020). According to findings presented by Ghenai 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 (Ghenai and Bettayeb, 2021). Similarly, Andreoni (2021) estimated the CO_2 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 CO_2 reduction was achieved with Poland, France, and Italy recorded the largest reduction of 386, 175, and 113 thousand tons of CO_2 emission, respectively. However, countries like Spain, Denmark, and the Netherlands had increased values of 245, 91, and 81 CO_2 emissions, respectively (Andreoni, 2021). These figures are in concordance with the GDP values and CO_2 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

Table 2

Decarbonization/GHG emissions reduction in agroecosystem and supply chain of the agri-food system.

Country/region	Scope and method	Target hotspots	Findings	Reference
USA	LCA of United States' food system from production to waste disposal and resources recovery using aggregated data	Food waste at post-distribution of the supply chain and food waste disposal management.	Adequate food waste management practices and a 50% reduction of post-distribution food waste resulted in 5% and 11% emission reduction, respectively.	Mohareb et al. (2018)
Chile and UK	LCA from Chilean farm to UK consumer's home	Ocean freight	The carbon footprint of exporting an apple produced from Chile to UK consumers represents 0.54 kg CO_2eq. per kg. The ocean freight contributed a considerable 39.2% of the total carbon footprint of the exported apple.	Iriarte et al. (2021)
Spain and France	Scenario-based analysis of the effect of COVID-19 on agri-food supply chain and carbon footprint	Biofuel prices, Feedstock, maize, and oilseed prices, and GHG emission quantity	A significant reduction of direct GHG from agriculture of about 1% or 50 million tonnes of CO_2eq. in 2020 and 2021 due to the pandemic Also, a sharp decline in economic growth resulted in a decrease in international meat prices by 7%–18% in 2020; and dairy products by 4%–7% relatively.	Elleby et al. (2020); FAO (2020b)
Organization for Economic Co-operation and Development (OECD) countries	COVID-19 effects from the politics and sustainable energy transition perspective	Short, medium, and long term temporal factors of energy system change	Oil usage and oil price crash due to the pandemic calls for 'Producers Economies' with an eye for sustainability	Kuzemko et al. (2020); OECD (2020a)
The Czech Republic and Singapore	Food supply chain and energy consumption in care systems	Hospitals	A more resilient food supply chain to hospitals reduces GHG emission through proper handling of food packaging items, PPEs, medical wastes, and reduction of energy consumption in hospital buildings	Fan and Jiang (2020); Wang *et.* (2019)
Italy	LCA methodological criteria assessment of carbon footprint (CF) due to COVID-19 using the CF impact indicator CF study was conducted based on recommendations of Caro (2018)	107 administrative divisions (agricultural, industrial, housing, tertiary, and provinces) of Italy	CF during the lockdown period was ~ −20% lower than the mean CF calculated in the past, with a GHG yield between ~5.6% and ~10.6 Mt CO_2eq.	Rugani and Caro (2020); Caro (2018)
Canada and USA	Biodiversity conservation investigation during the COVID-19 pandemic	Lockdown and gradual relaxation within the USA and Canada	The Global Human Confinement experiment has the potential to enhance societal support for a reduction in CO_2 emission from food materials, exploitation of natural resources, wildlife, and pollution	Bates et al. (2020)
UK	The integration of science with a 'social mandate' to tackle changing human behaviors towards the environment and food supply chains during the pandemic	Citizens of the UK	COVID-19 response is not a suitable model for climate change action because the favorable environmental benefits (e.g. reduced carbon emission, shorter food supply chains, lesser industrial wastes, etc.) that it brought was acquired at a huge cost to the economy and human welfare	Howarth et al. (2020)

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 application of artificial intelligence to achieve a more resilient, intelligent, and efficient agri-food supply chain (Zhai et al., 2020).

The USDA and FAO are currently making concerted efforts aiming at effectively managing global food wastage to achieve the Target 12.3 of the United Nations Sustainable Development Goal on food waste reduction by half by the year 2030. Being one of the largest producers of FLW, the United States sets a goal to reduce their food waste through energy recovery from the 2010 baseline estimates of 99 kg per capita 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 beneficial restoration of biodiversity, reduction in environmental pressure, promotion 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 internet and communication technologies, application of blockchain in the food supply chain, the use of industry 4.0 in the agric-food system, and research-based alternative food production and consumption such as lab-grown meat, and plant-based nutrients replacement for meat (Galanakis et al., 2021). The re-utilization of some of the food ingredients that can be recovered as by-products during food processing stage of the supply chain can go a long way in the transition towards a circular economy in the food industry. Research activities and innovation can support current public efforts in the transition phase to the circular economy model by guiding the modalities of the transition and facilitating the implementation of the circular economy for a sustainable food system. However, with the huge benefits inherent in the practice of circularity, it is regrettably noted that only 9% of the global economy is circular at the moment (Lacy et al., 2020). Consequently, a lot of industries are beginning to realize and embrace the need to shift to a circular model of manufacturing goods and services to enhance relevance and competitiveness. Policymakers, shareholders, and public-private partnerships are being spurred to institute business strategies operating on the circular economy model to harness all the benefits that the circular economy offers. Adequate funding is provided in developed countries, especially in Europe, for research tailored to this new field to foster better understanding, motivation and facilitate monitoring frameworks to evaluate the progress, success factors and facilitates a better understanding of the concept with a view of translating academic and research knowledge to practice (Muscio and Nardone, 2012; Rowan and Galanakis, 2020).

The concept of circularity in the agri-food system finds its root in innovative ideas that must be environmentally friendly i.e., eco-innovation (Muscio and Sisto, 2020; Muscio et al., 2017; Schiederig et al., 2012) and also hinged on the efficient use and reuse of agricultural materials and service (Manríquez-Altamirano et al., 2020; Kapoor et al., 2020). However, a worrisome factor that may mitigate the successful adoption and transition is the prevalent issue of climate change (Moric et al., 2020). Eco-innovation is defined as any kind of innovation that potentially enhances circularity and sustainability in the agri-food system. From another perspective, a study of the interaction between agricultural system and food processing system indicates a mutual relation, such that the food processing companies wait for the supply of raw materials, chemicals, and equipment from agriculture and other units to process into food and food materials (Teigiserova et al., 2019; Muscio and Sisto, 2020). Innovation potentials in these two separate sectors are greatly dictated by consumers' wants and needs. Market demands initiated by consumers must be met by food companies, which in turn harness innovative scientific knowledge. These scientific inputs greatly contribute to a lot of industrial innovations in the agri-food system (Acosta et al., 2011; Muscio and Nardone, 2012). It is a common practice for food companies to collaborate with research institutions for innovation development with a view of meeting market demands (Triguero et al., 2018). Such industry-university coaction is chiefly the birthplace of astounding innovative ideas and also a major game-changer in the complex econometrics of business transactions for the agri-food industries.

A CE system greatly relies on impact-driven innovations that aim at increasing efficiency in resource use, recycling prowess, and replacement of fossil fuel-based products in the manufacturing and production setting. As stated earlier, eco-innovation and clean technology are pivotal in the implementation of a CE system that requires the use of integrated policies and incentives. Research and innovation roles cannot be undermined in the agri-food systems because they jointly help unravel links that will promote resilience, sustainability, efficacy, and a close loop system with zero negative impact on the environment. Muscio and Sisto (2020) also submitted that transition from a linear economy to that of circularity does not only depend on funding of research studies focused mainly on agri-food systems and agroecosystems, but also on the funding of external projects which form integral units and share similar regulatory architecture with the CE model. This will result in a more coordinated integration of several fields to achieve a common circularity goal. Table 3 shows a review of the literature on CE in agri-food systems used for the study. The CE is projected to offer a win-win remedy while improving sustainability throughout the entire agri-food supply value chain and enhancing operational resilience borne out of the reduction of agricultural wastes through the adoption of localized food supply chains (Galanakis, 2020; Aldaco et al., 2020; Fei et al., 2020).

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 CE 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 CE in agroecosystems focuses on a viable model against the prevalent linear economy approach of "take-make-waste" by reducing the amount of external agricultural inputs, and closing nutrient cycles. This system approach 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 reuse 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 (Kirchherr 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 m^3 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.	Teigiserova 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.	Cristóbal 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.	Muscio and Sisto (2020); Esposito et al. (2020)(Muscio 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. F0B7 As a result of the complexity of the agri-food supply chain, achieving horizontal and vertical inclusiveness, and defining a unique CE model for the whole sector may appear fictitious if further research efforts fail to concentrate on integrating other different stages of the food supply chain and also concentrating on the final stages of the supply chain.
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. 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.
13.	Xia and Ruan (2020)	F0B7 The Grey-DEMATEL approach identified "B7 – local officials showed weak environmental awareness", as the most fundamental causal factor

(continued on next page)

Table 3 (*continued*)

S/ N	Authors	Findings and recommendations
		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). F0B7 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.
14.	Klerkx and Begemann (2020); van der Wiel et al. (2020)	F0B7 Applied a Mission-oriented Agricultural Innovation System (MAIS) approach to food systems transformation and analyzed the effects of technology and inventions on missions. F0B7 Developed a six-step framework for circularity while understudying 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.
15.	Barcaccia et al. (2020); Tseng et al. (2019)	F0B7 The potential application of Agriculture 4.0 tools and precision farming systems to achieve circularity in FLW of agri-industrial systems
16.	Taghikhah et al. (2021)	F0B7 Proposed a decision-support tool that offers evidence-based policy creation in the agri-food sector. They concluded that consumer's participation in CE transition pathways in agriculture may be inhibited and time-consuming if middle actors between producers and consumers do not actively participate
17.	De Corato (2020)	F0B7 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)	F0B7 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)	F0B7 An integrated farming system involving cattle breeding with zero GHG emissions and sustainable livelihood for rural dwellers was proposed.
20.	Rowan and Galanakis (2020)	F0B7 The development of wet peatland innovation, also called paludiculture, to offset the carbon footprint and restore the carbon storage capacity in the agri-food system.

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.

7.1. Circular economy in nutrient flow and effect on the environment

CE in the agri-food waste industry is poised to reduce various accompanied environmental issues in agricultural production systems, with a greater emphasis on nutrient flow within subsystems of the industry. Considering nutrient and material flow within the closed system, subsystems that constitute an impact on the environment include animal/livestock production, crop production, feed, and food processing industry, waste of food and food materials (van der Wiel et al., 2020). Environmental contributions in terms of nutrients and materials to the CE model and interactions of subsystems are greatly considered to achieve circularity and ensure the use and reuse of materials produced by every subsystem. Fig. 3 shows an illustration of the nutrient flows between the environment and the subsystems of the agri-food waste 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 Noë et al., 2019), others addressed the complete 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. Fig. 4 shows the FAO model for recycling and valorization from the agri-food unit.

Transportation of agricultural produce plays an important role in the agri-food waste sector. The effectiveness of the circularity of food wastes

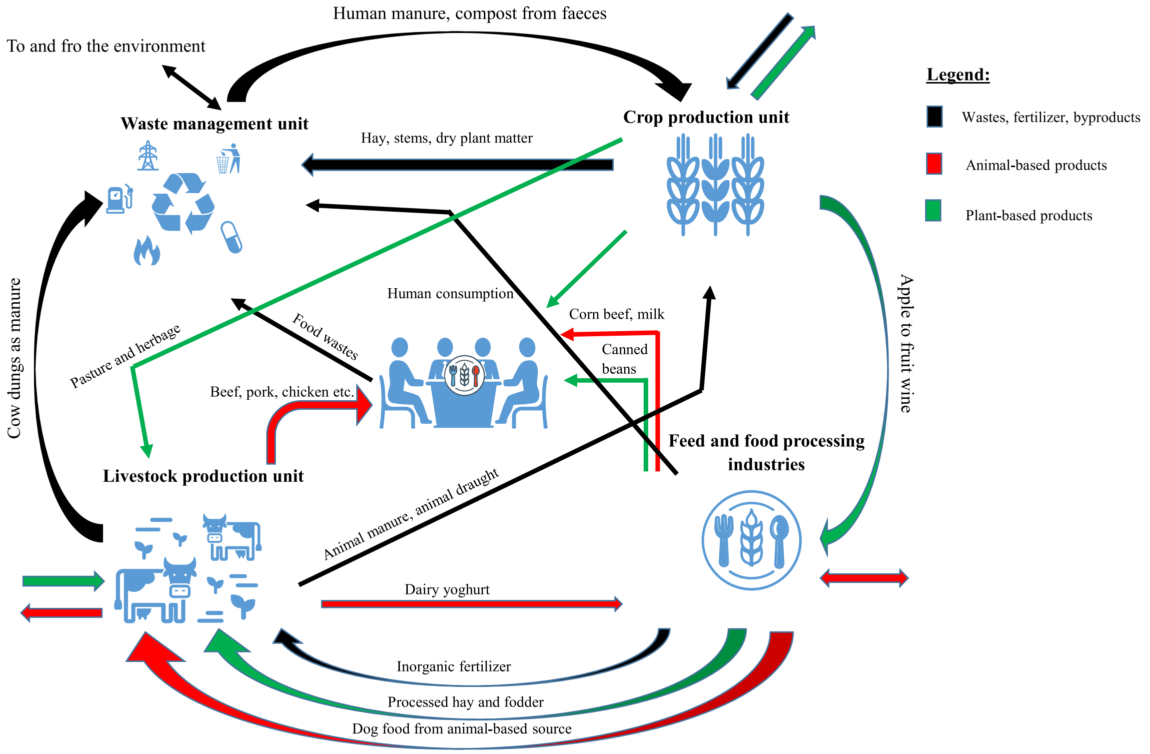

Fig. 3. Nutrient and material flow within subsystems of an agri-food system.

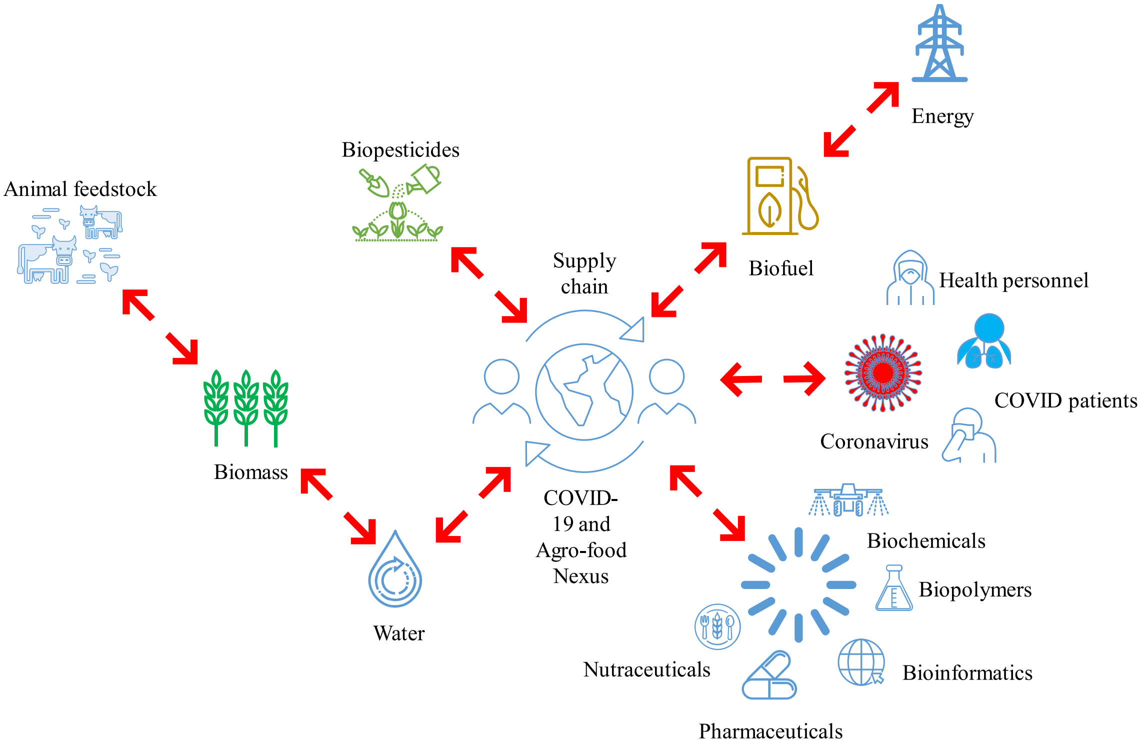

Fig. 4. Model for valorization and recycling of the agri-food sector during COVID-19 pandemic (Modified after FAO, 2020b).

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 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 game-changer for a region like Africa that heavily relies on the demand for processed and finished food products from Western Europe, South, and East Asia, and North America via a long supply chain despite the availability of abundant resources for the food production in the region (Morsy et al., 2021; Adelodun et al., 2021d). The strengthening of the intra-Africa food trade and value chain would not only unlock the full agro-economic potential of the region but also benefit the environment in terms of the reduction in logistic emissions that arise from the long supply chain (Morsy et al., 2021).

The gradual ease of lockdown protocols has required some business establishments to implement COVID-19 work ethics – one of which requires the single-use of packaging materials and online ordering of necessities to reduce transmission (Patrício Silva et al., 2021). Although, this may appear to offer a preventive effort to the transmission of the virus, however, it still poses a negative effect on the people, since recycling programs are being suspended and sustainable waste management is largely affected (Patrício Silva et al., 2020). Moreover, there have been recent reports of better quality and quantity of recyclable packaging materials in developed countries (Geueke et al., 2018), but sadly still, there is possible contaminants migration from the recycled package, especially the paper-based, to the food materials (Suciu et al., 2013).

Policy formulation should be centered on exploring other recyclable, and less toxic materials as inputs into the cycle. Public awareness programs should be incorporated into media houses' routines to urge more investment in the agri-food sector concerning increasing environmental awareness. Policymakers are urged to introduce managerial, fiscal, and regulatory guidelines on the operation of private and public firms in the food processing industry. These guidelines must be focused on enforcing stakeholders in the system to uphold the CE practice, to propagate more sustainability etiquettes through the imposition of adequate taxes, coordination of demand and supply, and dissemination of social programs promoting CE.

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 (Garcia-Garcia et al., 2020).

Proper or adequate dosages of nutrients and water can be achieved with the help of precision farming. Vertical farming, drone fertigation, 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. **Krishna Kumar Yadav:** Investigation, Visualization, Writing – review & editing. **Akanksha Yadav:** Investigation, Writing – review & editing. **A. El-Denglawey:** Investigation, Visualization, Writing – review & editing, Funding acquisition. **Marina Cabral-Pinto:** Investigation, Visualization, Writing – review & editing, Project administration. **Cao Truong Son:** 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/10.1093/fqsafe/fyaa024.

Adelodun, B., Ajibade, F.O., Tiamiyu, A.O., Nwogwu, N.A., Ibrahim, R.G., Kumar, P., Kumar, V., Odey, G., Yadav, K.K., Khan, A.H., Cabral-Pinto, M.M.S., Kareem, K.Y., 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 compartments: 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, 122562. https://doi.org/10.1016/j.jclepro.2020.122562.

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.2021.01.003.

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. 145928. https://doi.org/10.1016/j.scitotenv.2021.145928.

Adelodun, B., Mohammed, A.A., Adeniran, K.A., Akanbi, S.-U.O., Abdulkadir, 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., Laso, J., Margallo, M., Ruiz-Salmón, J., Cristobal, J., Kahhat, R., Villanueva-Rey, P., Bala, A., Batlle-Bayer, L., Fullana-i-Palmer, P., Irabien, A., Vazquez-Rowe, I., 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.

Amicarelli, 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., Edeh, H., Oboh, V., Pauw, K., Thurlow, 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/bs.af2s.2020.09.002.

Andreoni, 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 Definition and Concept of the Circular Economy in a European Perspective.

Balwinder-Singh, Shirsath, P.B., Jat, M.L., McDonald, A.J., Srivastava, A.K., Craufurd, P., Rana, D.S., Singh, A.K., Chaudhari, S.K., Sharma, P.C., Singh, R., Jat, H.S., Sidhu, 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/su12145651.

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

Bates, A.E., Primack, R.B., Moraga, P., Carlos, M., 2020. Jo ur l P 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., Ferrão, P., 2017. Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA) – a life cycle assessment approach. J. Clean. Prod. 140, 784–795. https://doi.org/10.1016/j.jclepro.2016.05.176.

Berners-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. Elem. 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, pp. 559–577.

Billen, G., Lassaletta, L., Garnier, J., Le Noë, J., Aguilera, E., Sanz-Cobeña, A., 2019. Opening to distant markets or local reconnection of agro-food systems? Environmental consequences at regional and global scales. Agroecosystem Diversity. Elsevier, pp. 391–413. https://doi.org/10.1016/B978-0-12-811050-8.00025-X.

Billen, G., Le Noë, J., Garnier, J., 2018. Two contrasted future scenarios for the French agro-food system. Sci. Total Environ. 637–638, 695–705. https://doi.org/10.1016/j.scitotenv.2018.05.043.

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/10.1007/s42824-020-00005-z.

Boretti, A., Rosa, L., 2019. Reassessing the projections of the world water development report. npj Clean Water 2, 15. https://doi.org/10.1038/s41545-019-0039-9.

Borrello, M., Caracciolo, F., Lombardi, A., Pascucci, S., Cembalo, L., 2017. Consumers' perspective on circular economy strategy for reducing food waste. Sustain. Times 9. https://doi.org/10.3390/su9010141.

Borsellino, V., Kaliji, S.A., Schimmenti, E., 2020. COVID-19 drives consumer behaviour and agro-food markets towards healthier and more sustainable patterns. Sustain. Times 12, 1–26. https://doi.org/10.3390/su12208366.

Bucak, T., Yiğit, S., 2021. The future of the chef occupation and the food and beverage sector after the COVID-19 outbreak: opinions of Turkish chefs. Int. J. Hospit. Manag. 92 https://doi.org/10.1016/j.ijhm.2020.102682.

Cabral Pinto, Marina M.S., Marinho-Reis, A. Paula, Almeida, Agostinho, Freitas, Sandra, Simões, Mário R., Diniz, M. Luísa, Pinto, Edgar, Ramos, Patrícia, Ferreira da Silva, Eduardo, Moreira, Paula I., 2019. Expo. Health 11, 181–194. https://doi.org/10.1007/s12403-018-0274-1. In this issue.

Cabral-Pinto, M.M.S., Inácio, M., Neves, O., Almeida, A.A., Pinto, E., Oliveiros, B., Ferreira da Silva, E.A., 2020. Human health risk assessment due to agricultural activities and crop consumption in the surroundings of an industrial area. Expo Health 12, 629–640. https://doi.org/10.1007/s12403-019-00323-x.

Cakar, B., Aydin, S., Varank, G., Ozcan, H.K., 2020. Assessment of environmental impact of FOOD waste in Turkey. J. Clean. Prod. 244, 118846. https://doi.org/10.1016/j.jclepro.2019.118846.

Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488. https://doi.org/10.1016/j.resconrec.2019.06.011.

Carr, A.C., Maggini, S., 2017. Vitamin C and immune function. Nutrients 9, 1–25. https://doi.org/10.3390/nu9111211.

Chakraborty, I., Maity, P., 2020. COVID-19 outbreak: migration, effects on society, global environment and prevention. Sci. Total Environ. 728, 138882. https://doi.org/10.1016/j.scitotenv.2020.138882.

Chang, C.-C., Chen, Y.-H., Lin, Y.-S., Hung, Z., Yuan, M., Chang, C., Li, Y., Shie, J., Chen, Y., Wang, Y., Ko, C., Lin, F., Ho, C., Liu, B.-L., Liu, K., Wang, S.-G., 2018. A pilot plant study on the autoclaving of food wastes for resource recovery and reutilization. Sustainability 10, 3566. https://doi.org/10.3390/su10103566.

Chen, J.Z., 2009. Material flow and circular economy. Syst. Res. Behav. Sci. 26, 269–278. https://doi.org/10.1002/sres.968.

Coluccia, B., Agnusdei, G.P., Miglietta, P.P., De Leo, F., 2021. Effects of COVID-19 on the Italian agri-food supply and value chains. Food Contr. 123, 107839. https://doi.org/10.1016/j.foodcont.2020.107839.

Cordell, D., Drangert, J.O., White, S., 2009. The story of phosphorus: global food security and food for thought. Global Environ. Change 19, 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009.

Cristóbal, J., Castellani, V., Manfredi, S., Sala, S., 2018. Prioritizing and optimizing sustainable measures for food waste prevention and management. Waste Manag. 72, 3–16. https://doi.org/10.1016/j.wasman.2017.11.007.

De Corato, U., 2020. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: a review under the perspective of a circular economy. Sci. Total Environ. 738, 139840. https://doi.org/10.1016/j.scitotenv.2020.139840.

de Paulo Farias, D., dos Santos Gomes, M.G., 2020. COVID-19 outbreak: what should be done to avoid food shortages? Trends Food Sci. Technol. 102, 291–292. https://doi.org/10.1016/j.tifs.2020.06.007.

Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, L., Van Der Bruggen, B., Verstraete, W., Rabaey, K., Meesschaert, B., 2015. Global phosphorus scarcity and full-scale P-recovery techniques: a review. Crit. Rev. Environ. Sci. Technol. 45, 336–384. https://doi.org/10.1080/10643389.2013.866531.

Elleby, C., Domínguez, I.P., Adenauer, M., Genovese, G., 2020. Impacts of the COVID - 19 pandemic on the global. Environ. Resour. Econ. 76, 1067–1079. https://doi.org/10.1007/s10640-020-00473-6.

Esposito, B., Sessa, M.R., Sica, D., Malandrino, O., 2020. Towards circular economy in the agri-food sector. A systematic literature review. Sustainability 12, 7401. https://doi.org/10.3390/su12187401.

Fan, Y. Van, Jiang, P., 2020. The energy and environmental footprints of COVID-19 fighting measures e PPE , disinfection , supply chains 211. https://doi.org/10.1016/j.energy.2020.118701.

FAO, 2020a. Fapda - food and agriculture policy decision analysis tool [WWW Document]. Food Agric. Organ. United Nations. URL. http://fapda.apps.fao.org/fapda/#main.html. 20.4.20. (Accessed 26 February 2021).

FAO, 2020b. Circular economy: waste-to-resource & COVID-19 [WWW Document]. Food Agric. Organ. United Nations. URL. http://www.fao.org/land-water/overview/covid19/circular/fr/. (Accessed 29 December 2020).

FAO, 2019. The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction. Food and Agriculture Organisation of the United Nations, Rome. https://doi.org/10.4324/9781315764788.

FAO, 2018. The Future of Food and Agriculture – Alternative Pathways to 2050. Food and Agriculture Organisation of the United Nations, Rome.

FAO, 2017. The Future of Food and Agriculture: Trends and Challenges. Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.4161/chan.4.6.12871.

FAO, 2015. The State of Food Insecurity in the World. Meeting the 2015 International Hunger Targets: Taking Stock of Uneven Progress, FAO, IFAD, WFP.

FAO, 2014. FAO - news Article: agriculture's greenhouse gas emissions on the rise [WWW Document]. Food Agric. Organ. URL. http://www.fao.org/news/story/en/item/216137/. (Accessed 24 February 2021).

Farzanegan, M.R., Feizi, M., Gholipour, H.F., 2020. Globalization and Outbreak of COVID-19: an Empirical Analysis (No. 8315). CESifo Working Paper.

Fei, S., Ni, J., Santini, G., 2020. Local food systems and COVID-19: an insight from China. Resour. Conserv. Recycl. 162, 105022. https://doi.org/10.1016/j.resconrec.2020.105022.

Fenster, T.L.D., LaCanne, C.E., Pecenka, J.R., Schmid, R.B., Bredeson, M.M., Busenitz, K.M., Michels, A.M., Welch, K.D., Lundgren, J.G., 2021. Defining and validating regenerative farm systems using a composite of ranked agricultural practices. F1000Research 10, 115. https://doi.org/10.12688/f1000research.28450.1.

Fmcggurus, 2020. Evaluating the Uncertainty and Future Outlook of COVID-19.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. https://doi.org/10.1038/nature10452.

Franca, L.S., Ornelas-Ferreira, B., Costa Corrêa, G.M. da, Ribeiro, G.M., Bassin, J.P., 2021. Carbon footprint of food waste management: a case study in Rio de Janeiro. Environmental Footprints and Eco-Design of Products and Processes. https://doi.org/10.1007/978-981-15-9577-6_2.

Galanakis, C.M., 2020. The food systems in the era of the coronavirus (COVID-19) pandemic crisis. Foods 9, 523. https://doi.org/10.3390/foods9040523.

Galanakis, C.M., Aldawoud, T.M.S., Rizou, M., Rowan, N.J., Ibrahim, S.A., 2020. Food ingredients and active compounds against the coronavirus disease (COVID-19) pandemic: a comprehensive review. Foods 9, 1701. https://doi.org/10.3390/foods9111701.

Galanakis, C.M., Rizou, M., Aldawoud, T.M.S., Ucak, I., Rowan, N.J., 2021. Trends in Food Science & Technology Innovations and technology disruptions in the food sector within the COVID-19 pandemic and post-lockdown era. Trends Food Sci. Technol. 110, 193–200. https://doi.org/10.1016/j.tifs.2021.02.002.

Garcia-Garcia, G., Azanedo, L., Rahimifard, S., 2020. Embedding sustainability analysis in new food product development. Trends Food Sci. Technol. 104743. https://doi.org/10.1016/j.tifs.2020.12.018.

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Pol. 36, S23–S32. https://doi.org/10.1016/j.foodpol.2010.10.010.

Geueke, B., Groh, K., Muncke, J., 2018. Food packaging in the circular economy: overview of chemical safety aspects for commonly used materials. J. Clean. Prod. 193, 491–505. https://doi.org/10.1016/j.jclepro.2018.05.005.

Ghenai, C., Bettayeb, M., 2021. Data analysis of the electricity generation mix for clean energy transition during COVID-19 lockdowns. Energy Sources, Part A Recover. Util. Environ. Eff. 1–21. https://doi.org/10.1080/15567036.2021.1884772, 00.

Ghenai, C., Salameh, T., Merabet, A., 2020. Technico-economic analysis of off grid solar PV/Fuel cell energy system for residential community in desert region. Int. J. Hydrogen Energy 45, 11460–11470. https://doi.org/10.1016/j.ijhydene.2018.05.110.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Ghisellini, P., Zucaro, A., Viglia, S., Ulgiati, S., 2014. Monitoring and evaluating the sustainability of Italian agricultural system . An emergy decomposition analysis. Ecol. Model. 271, 132–148. https://doi.org/10.1016/j.ecolmodel.2013.02.014.

Giudice, F., Caferra, R., Morone, P., 2020. COVID-19, the food system and the circular economy: challenges and opportunities. Sustainability 12, 7939. https://doi.org/10.3390/su12197939.

Grippo, V., Romano, S., Vastola, A., 2019. Multi-criteria evaluation of bran use to promote circularity in the cereal production chain. Nat. Resour. Res. https://doi.org/10.1007/s11053-019-09457-w.

Gupta, N., Yadav, K.K., Kumar, V., 2015. A review on current status of municipal solid waste management in India. J. Environ. Sci. 37, 206–217. https://doi.org/10.1016/j.jes.2015.01.034.

Gupta, N., Yadav, K.K., Kumar, V., Krishnan, S., Kumar, S., Nejad, Z.D., Khan, M.A.M., Alam, J., 2020. Evaluating heavy metals contamination in soil and vegetables in the region of North India: levels, transfer and potential human health risk analysis. Environ. Toxicol. Pharmacol. 103563 https://doi.org/10.1016/j.etap.2020.103563.

Gupta, N., Yadav, K.K., Kumar, V., Kumar, S., Chadd, R.P., 2019. Trace elements in soil vegetables interface: translocation, bioaccumulation, toxicity and amelioration - a review. Sci. Total Environ. 651, 2927–2942. https://doi.org/10.1016/j.scitotenv.2018.10.047.

Haq, Z., 2020. Farmers can work, says govt amid nationwide lockdown over Covid-19 pandemic [WWW Document]. Hindustan Times. URL. https://www.hindustantimes.com/india-news/govt-allows-farmers-to-carry-out-operations-amid-nationwide-lockdown-over-coronavirus-pandemic/story-GsFqQ2KOJCmu5490mo7CkN.html. (Accessed 28 May 2021).

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.J., Wiebe, K., Witzke, P., 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat. Clim. Change 8, 699–703. https://doi.org/10.1038/s41558-018-0230-x.

Heck, S., Campos, H., Barker, I., Okello, J.J., Baral, A., Boy, E., Brown, L., Birol, E., 2020. Resilient agri-food systems for nutrition amidst COVID-19: evidence and lessons from food-based approaches to overcome micronutrient deficiency and rebuild livelihoods after crises. Food Secur 12, 823–830. https://doi.org/10.1007/s12571-020-01067-2.

Herrero, M., Thornton, P.K., Power, B., Bogard, J.R., Remans, R., Fritz, S., Gerber, J.S., Nelson, G., See, L., Waha, K., Watson, R.A., West, P.C., Samberg, L.H., van de Steeg, J., Stephenson, E., van Wijk, M., Havlík, P., 2017. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet. Heal. 1, e33–e42. https://doi.org/10.1016/S2542-5196(17)30007-4.

Hobbs, J.E., 2020. Food supply chains during the COVID-19 pandemic. Can. J. Agric. Econ. 68, 171–176. https://doi.org/10.1111/cjag.12237.

Hossain, S.T., 2020. Impacts of COVID-19 on the agri-food sector: food security policies of Asian productivity organization members. J. Agric. Sci. - Sri Lanka 15, 116–132. https://doi.org/10.4038/jas.v15i2.8794.

Howarth, C., Bryant, P., Corner, A., Fankhauser, S., Gouldson, A., Whitmarsh, L., Willis, R., 2020. Building a social mandate for climate Action : lessons from COVID - 19. Environ. Resour. Econ. 76, 1107–1115. https://doi.org/10.1007/s10640-020-00446-9.

Huang, Z., Liu, Y., Qi, G., Brand, D., Zheng, S., 2018. Role of vitamin A in the immune system. J. Clin. Med. 7, 258. https://doi.org/10.3390/jcm7090258.

Huff, A.G., Beyeler, W.E., Kelley, N.S., McNitt, J.A., 2015. How resilient is the United States' food system to pandemics? J. Environ. Stud. Sci. 5, 337–347. https://doi.org/10.1007/s13412-015-0275-3.

Ibn-Mohammed, T., Mustapha, K.B., Godsell, J., Adamu, Z., Babatunde, K.A., Akintade, D.D., Acquaye, A., Fujii, H., Ndiaye, M.M., Yamoah, F.A., Koh, S.C.L., 2021. A critical review of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies. Resour. Conserv. Recycl. 164, 105169. https://doi.org/10.1016/j.resconrec.2020.105169.

IEA, 2020. Global Energy Review 2020 – Analysis [WWW Document]. Int. Energy Agency . URL. https://www.iea.org/reports/global-energy-review-2020. (Accessed 28 February 2021).

Iriarte, A., Yáñez, P., Villalobos, P., Huenchuleo, C., Rebolledo-Leiva, R., 2021. Carbon footprint of southern hemisphere fruit exported to Europe: the case of Chilean apple to the UK. J. Clean. Prod. 293 https://doi.org/10.1016/j.jclepro.2021.126118.

Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S.S., Vijay, V., Kumar, V., Kumar Vijay, V., Pant, D., 2020. Valorization of agricultural waste for biogas based circular economy in India: a research outlook. Bioresour. Technol. 304, 123036. https://doi.org/10.1016/j.biortech.2020.123036.

Khan, M., Khan, A.U., Hasan, M.A., Yadav, K.K., Pinto, M.M.C., Malik, N., Yadav, V.K., Khan, A.H., Islam, S., Sharma, G.K., 2021. Agro-nanotechnology as an emerging field: a novel sustainable approach for improving plant growth by reducing biotic stress. Appl. Sci. 11, 2282. https://doi.org/10.3390/app11052282.

Kirchherr, J., Reike, D., Hekkert, M., 2017a. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kirchherr, J., Reike, D., Hekkert, M., 2017b. Resources , Conservation & Recycling Conceptualizing the circular economy : an analysis of 114 de fi nitions 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Klerkx, L., Begemann, S., 2020. Supporting food systems transformation: the what, why, who, where and how of mission-oriented agricultural innovation systems. Agric. Syst. 184, 102901. https://doi.org/10.1016/j.agsy.2020.102901.

Kuiper, M., Cui, H.D., 2021. Using food loss reduction to reach food security and environmental objectives – a search for promising leverage points. Food Pol. 98, 101915. https://doi.org/10.1016/j.foodpol.2020.101915.

Kumar, A., Kumar, A., Cabral-Pinto, M.M.S., Chaturvedi, A.K., Shabnam, A.A., Subrahmanyam, G., Mondal, R., Gupta, D.K., Malyan, S.K., Kumar, S.S., Khan, S.A., Yadav, K.K., 2020. Lead toxicity: health hazards, influence on food chain, and sustainable remediation approaches. Int. J. Environ. Res. Publ. Health 17, 2179. https://doi.org/10.3390/ijerph17072179.

Kumar, P., Kumar, V., Singh, J., Kumar, P., 2021. Electrokinetic assisted anaerobic digestion of spent mushroom substrate supplemented with sugar mill wastewater for enhanced biogas production. Renew. Energy 179, 418–426. https://doi.org/10.1016/j.renene.2021.07.045.

Kumar, S., Prasad, S., Yadav, K.K., Shrivastava, M., Gupta, N., Nagar, S., Bach, Q., Kamyab, H., Khan, S.A., Yadav, S., Malav, L.C., 2019. Hazardous heavy metals contamination of vegetables and food chain: role of sustainable remediation approches- A review. Environ. Res. 179, 108792. https://doi.org/10.1016/j.envres.2019.108792.

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J., 2012. Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Sci. Total Environ. 438, 477–489. https://doi.org/10.1016/j.scitotenv.2012.08.092.

Kuokkanen, A., Mikkilä, M., Kuisma, M., Kahiluoto, H., Linnanen, L., 2017. The need for policy to address the food system lock-in: a case study of the Finnish context. J. Clean. Prod. 140, 933–944. https://doi.org/10.1016/j.jclepro.2016.06.171.

Kuzemko, C., Bradshaw, M., Bridge, G., Goldthau, A., Overland, I., Scholten, D., Graaf, T. Van De, Westphal, K., Jewell, J., 2020. Energy research & social science covid-19 and the politics of sustainable energy transitions. Energy Res. Soc. Sci. 68, 101685. https://doi.org/10.1016/j.erss.2020.101685.

Lacy, P., Spindler, W., Long, J., 2020. How can businesses hasten the transition to a circular economy? [WWW Document]. World Econ. Forum. URL. https://www.weforum.org/agenda/2020/01/how-can-we-accelerate-the-transition-to-a-circular-economy/. (Accessed 25 December 2020).

Larue, B., 2020. Labor issues and COVID-19. Can. J. Agric. Econ. 68, 231–237. https://doi.org/10.1111/cjag.12233.

Le Noë, J., Billen, G., Mary, B., Garnier, J., 2019. Drivers of long-term carbon dynamics in cropland: a bio-political history (France, 1852–2014). Environ. Sci. Pol. 93, 53–65. https://doi.org/10.1016/j.envsci.2018.12.027.

Leach, A.M., Galloway, J.N., Bleeker, A., Erisman, J.W., Kohn, R., Kitzes, J., 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. Environ. Dev. 1, 40–66. https://doi.org/10.1016/j.envdev.2011.12.005.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gotzsche, P.C., Ioannidis, J.P.A., Clarke, M., Devereaux, P.J., Kleijnen, J., Moher, D., 2009. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. BMJ 339. https://doi.org/10.1136/bmj.b2700 b2700–b2700.

Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042.

Liu, Z., Ciais, P., Deng, Z., Lei, R., Davis, S.J., Feng, S., Zheng, B., Cui, D., Dou, X., Zhu, B., Guo, Rui, Ke, P., Sun, T., Lu, C., He, P., Wang, Yuan, Yue, X., Wang, Yilong, Lei, Y., Zhou, H., Cai, Z., Wu, Y., Guo, Runtao, Han, T., Xue, J., Boucher, O., Boucher, E., Chevallier, F., Tanaka, K., Wei, Y., Zhong, H., Kang, C., Zhang, N., Chen, B., Xi, F., Liu, M., Bréon, F.M., Lu, Y., Zhang, Q., Guan, D., Gong, P., Kammen, D.M., He, K., Schellnhuber, H.J., 2020. Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. Nat. Commun. 11, 1–12. https://doi.org/10.1038/s41467-020-18922-7.

Mahmud, K., Panday, D., Mergoum, A., Missaoui, A., 2021. Nitrogen losses and potential mitigation strategies for a sustainable agroecosystem. Sustain. Times 13, 1–23. https://doi.org/10.3390/su13042400.

Malav, L.C., Yadav, K.K., Gupta, N., Kumar, S., Sharma, G.K., Krishnan, S., Rezania, S., Kamyab, S., Pham, Q.B., Yadav, S., Bhattacharyya, S., Yadav, V.K., Bach, Q.V., 2020. A review on municipal solid waste as a renewable source for waste-to-energy project in India: current practices, challenges, and future opportunities. J. Clean. Prod. 277, 123227. https://doi.org/10.1016/j.jclepro.2020.123227.

Maliszewska, M., Mattoo, A., van der Mensbrugghe, D., 2020. The Potential Impact of COVID-19 on GDP and Trade: A Preliminary Assessment (No. World Bank Policy Research Working. Paper No. 9211).

Malliet, P., Reynès, F., Landa, G., Hamdi-Cherif, M., Saussay, A., 2020. Assessing short-term and long-term economic and environmental effects of the COVID-19 crisis in France. Environ. Resour. Econ. 76, 867–883. https://doi.org/10.1007/s10640-020-00488-z.

Manríquez-Altamirano, A., Sierra-Pérez, J., Muñoz, P., Gabarrell, X., 2020. Analysis of urban agriculture solid waste in the frame of circular economy: case study of tomato crop in integrated rooftop greenhouse. Sci. Total Environ. 734, 139375. https://doi.org/10.1016/j.scitotenv.2020.139375.

Markard, J., Rosenbloom, D., 2020. A tale of two crises: COVID-19 and climate. Sustain. Sci. Pract. Pol. 16, 53–60. https://doi.org/10.1080/15487733.2020.1765679.

Minor, T., Hitaj, C., Kuchler, F., Skorbiansky, S., Roe, B., Thornsbury, S., 2019. Are consumers willing to pay to reduce food waste? Choice 34, 1–7. https://doi.org/10.22004/ag.econ.283544.

Mohammed, S., Gill, A.R., Alsafadi, K., Hijazi, O., Yadav, K.K., Khan, A.H., Islam, S., Cabral-Pinto, M.M.S., Harsanyi, E., 2021. An overview of greenhouse gases emissions in Hungary. J. Cleaner Prod. Preprint.

Mohareb, E.A., Heller, M.C., Guthrie, P.M., 2018. Cities' role in mitigating United States food system greenhouse gas emissions. Environ. Sci. Technol. 52, 5545–5554. https://doi.org/10.1021/acs.est.7b02600.

Moric, I., Jovanovic, J.Š., Dokovic, R., Pekovic, S., Perovic, D., 2020. The effect of phases of the adoption of the circular economy on firm performance: evidence from 28 EU countries. Sustain. Times 12, 1–12. https://doi.org/10.3390/su12062557.

Morsy, H., Salami, A., Mukasa, A.N., 2021. Opportunities amid COVID-19: advancing intra-African food integration. World Dev. 139, 105308. https://doi.org/10.1016/j.worlddev.2020.105308.

Muscio, A., Nardone, G., 2012. The determinants of university-industry collaboration in food science in Italy. Food Pol. 37, 710–718. https://doi.org/10.1016/j.foodpol.2012.07.003.

Muscio, A., Nardone, G., Stasi, A., 2017. How does the search for knowledge drive firms' eco-innovation? Evidence from the wine industry. Ind. Innovat. 24, 298–320. https://doi.org/10.1080/13662716.2016.1224707.

Muscio, A., Sisto, R., 2020. Are agri-food systems really switching to a circular economy model? Implications for European research and innovation policy. Sustainability 12, 5554. https://doi.org/10.3390/su12145554.

Neset, T.-S.S., Bader, H.-P., Scheidegger, R., Lohm, U., 2008. The flow of phosphorus in food production and consumption — linköping, Sweden, 1870–2000. Sci. Total Environ. 396, 111–120. https://doi.org/10.1016/j.scitotenv.2008.02.010.

Nogueira, J., Gerardo, B., Silva, A.R., Pinto, P., Barbosa, R., Soares, S., Cabral-Pinto, M., Freitas, S., 2021. Effects of restraining measures due to COVID-19: Pre-and post-lockdown cognitive status and mental health. Curr. Psychol. 1–10. https://doi.org/10.1007/s12144-021-01747-y.

Nordhagen, S., Igbeka, U., Rowlands, H., Shine, R.S., Heneghan, E., Tench, J., 2021. COVID-19 and small enterprises in the food supply chain: early impacts and implications for longer-term food system resilience in low- and middle-income countries. World Dev. 141, 105405. https://doi.org/10.1016/j.worlddev.2021.105405.

Omolayo, Y., Feingold, B.J., Neff, R.A., Romeiko, X.X., 2021. Life cycle assessment of food loss and waste in the food supply chain. Resour. Conserv. Recycl. 164, 105119. https://doi.org/10.1016/j.resconrec.2020.105119.

Oteros-Rozas, E., Ruiz-Almeida, A., Aguado, M., González, J.A., Rivera-Ferre, M.G., 2019. A social-ecological analysis of the global agrifood system. Proc. Natl. Acad. Sci. U. S. A 116, 26465–26473. https://doi.org/10.1073/pnas.1912710116.

Parizeau, K., von Massow, M., Martin, R., 2015. Household-level dynamics of food waste production and related beliefs, attitudes, and behaviours in Guelph, Ontario. Waste Manag. 35, 207–217. https://doi.org/10.1016/j.wasman.2014.09.019.

Patrício Silva, A.L., Prata, J.C., Walker, T.R., Campos, D., Duarte, A.C., Soares, A.M.V.M., Barcelò, D., Rocha-Santos, T., 2020. Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. Sci. Total Environ. 742, 140565. https://doi.org/10.1016/j.scitotenv.2020.140565.

Patrício Silva, A.L., Prata, J.C., Walker, T.R., Duarte, A.C., Ouyang, W., Barcelò, D., Rocha-Santos, T., 2021. Increased plastic pollution due to COVID-19 pandemic: challenges and recommendations. Chem. Eng. J. 405, 126683. https://doi.org/10.1016/j.cej.2020.126683.

Paul, S.K., Chowdhury, P., 2020. Strategies for managing the impacts of disruptions during COVID-19: an example of toilet paper. Global J. Flex. Syst. Manag. 21, 283–293. https://doi.org/10.1007/s40171-020-00248-4.

Pavitt, K., 1984. Sectoral patterns of technical change: towards a taxonomy and a theory. Res. Pol. 13, 343–373. https://doi.org/10.1016/0048-7333(84)90018-0.

Pearce, F., 2018. Can the world find solutions to the nitrogen pollution crisis? [WWW Document]. Yale Sch. Environ. URL. https://e360.yale.edu/features/can-the-world-find-solutions-to-the-nitrogen-pollution-crisis, 5.31.2021.

Penazzi, S., Accorsi, R., Manzini, R., 2019. Planning low carbon urban-rural ecosystems: an integrated transport land-use model. J. Clean. Prod. 235, 96–111. https://doi.org/10.1016/j.jclepro.2019.06.252.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216.

Prasad, S., Yadav, K.K., Kumar, S., Gupta, N., Cabral-Pinto, M.M.S., Rezania, S., Radwan, N., Alam, J., 2021. Chromium contamination and effect on environmental health and its remediation: a sustainable approaches. J. Environ. Manag. 285, 112174. https://doi.org/10.1016/j.jenvman.2021.112174.

Rasul, G., 2021. Twin challenges of COVID-19 pandemic and climate change for agriculture and food security in South Asia. Environ. Challenges 2, 100027. https://doi.org/10.1016/j.envc.2021.100027.

Razon, L.F., 2018. Reactive nitrogen: a perspective on its global impact and prospects for its sustainable production. Sustain. Prod. Consum. 15, 35–48. https://doi.org/10.1016/j.spc.2018.04.003.

Reardon, T., Mishra, A., Nuthalapati, C.S.R., Bellemare, M.F., Zilberman, D., 2020. COVID-19's disruption of India's transformed food supply chains. Econ. Polit. Wkly.

Recous, S., Lashermes, G., Bertrand, I., Duru, M., Pellerin, S., 2018. C-N-P decoupling processes linked to arable cropping management systems in relation with intensification of production. Agroecosyst. Divers. Reconciling Contemp. Agric. Environ. Qual. 35–53. https://doi.org/10.1016/B978-0-12-811050-8.00003-0.

Ribeiro, E.M., Barros, R.M., Tiago Filho, G.L., dos Santos, I.F.S., Sampaio, L.C., dos Santos, T.V., da Silva, F., das, G.B., Silva, A.P.M., de Freitas, J.V.R., 2016. Power generation potential in posture aviaries in Brazil in the context of a circular economy. Sustain. Energy Technol. Assessments 18, 153–163. https://doi.org/10.1016/j.seta.2016.10.009.

Richter, B., 2017. Knowledge and perception of food waste among German consumers. J. Clean. Prod. 166, 641–648. https://doi.org/10.1016/j.jclepro.2017.08.009.

Rizou, M., Galanakis, I.M., Aldawoud, T.M.S., Galanakis, C.M., 2020. Safety of foods, food supply chain and environment within the COVID-19 pandemic. Trends Food Sci. Technol. 102, 293–299. https://doi.org/10.1016/j.tifs.2020.06.008.

Rodgers, R.F., Lombardo, C., Cerolini, S., Franko, D.L., Omori, M., Linardon, J., Guillaume, S., Fischer, L., Tyszkiewicz, M.F., 2021. "Waste not and stay at home" evidence of decreased food waste during the COVID-19 pandemic from the U.S. and Italy. Appetite 160, 105110. https://doi.org/10.1016/j.appet.2021.105110.

Rowan, N.J., Galanakis, C.M., 2020. Unlocking challenges and opportunities presented by COVID-19 pandemic for cross-cutting disruption in agri-food and green deal innovations: quo Vadis? Sci. Total Environ. 748, 141362. https://doi.org/10.1016/j.scitotenv.2020.141362.

Roy, E.D., Hammond Wagner, C.R., Niles, M.T., 2021. Hot spots of opportunity for improved cropland nitrogen management across the United States. Environ. Res. Lett. 16 https://doi.org/10.1088/1748-9326/abd662.

Rugani, B., Caro, D., 2020. Impact of COVID-19 outbreak measures of lockdown on the Italian Carbon Footprint. Sci. Total Environ. 737, 139806. https://doi.org/10.1016/j.scitotenv.2020.139806.

Sarkodie, S.A., Owusu, P.A., 2020. Impact of meteorological factors on COVID-19 pandemic: evidence from top 20 countries with confirmed cases. Environ. Res. 191, 110101. https://doi.org/10.1016/j.envres.2020.110101.

Scherhaufer, S., Moates, G., Hartikainen, H., Waldron, K., Obersteiner, G., 2018. Environmental impacts of food waste in Europe. Waste Manag. 77, 98–113. https://doi.org/10.1016/j.wasman.2018.04.038.

Schiederig, T., Tietze, F., Herstatt, C., 2012. Green innovation in technology and innovation management - an exploratory literature review. R D Manag. 42, 180–192. https://doi.org/10.1111/j.1467-9310.2011.00672.x.

Sembiring, M., 2020. Decarbonisation on a Finite Planet: A Preliminary Assessment of Environmental and Social Impacts.

Seyhan, D., Brunner, P.H., 2018. The choice of system boundaries for effective long-term management of phosphorus. J. Mater. Cycles Waste Manag. 20, 345–352. https://doi.org/10.1007/s10163-017-0589-1.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 80, 347. https://doi.org/10.1126/science.1259855.

Storrow, B., 2020. PANDEMIC: coronavirus is reducing CO2. Why that's worrisome [WWW Document]. E&E News. URL. https://www.eenews.net/stories/1062893583. (Accessed 27 February 2021).

Stuart, T., 2009. Waste: Uncovering the Global Food Scandal. W. W. Norton & Company.

Stuchtey, M., 2020. Food and the Circular Economy [WWW Document]. URL. https://www.ellenmacarthurfoundation.org/explore/food-cities-the-circular-economy. (Accessed 29 December 2021).

Suciu, N.A., Tiberto, F., Vasileiadis, S., Lamastra, L., Trevisan, M., 2013. Recycled paper-paperboard for food contact materials: contaminants suspected and migration into foods and food simulant. Food Chem. 141, 4146–4151. https://doi.org/10.1016/j.foodchem.2013.07.014.

Sun, S.K., Lu, Y.J., Gao, H., Jiang, T.T., Du, X.Y., Shen, T.X., Wu, P.T., Wang, Y.B., 2018. Impacts of food wastage on water resources and environment in China. J. Clean. Prod. 185, 732–739. https://doi.org/10.1016/j.jclepro.2018.03.029.

Taghikhah, F., Voinov, A., Shukla, N., Filatova, T., Anufriev, M., 2021. Integrated modeling of extended agro-food supply chains: a systems approach. Eur. J. Oper. Res. 288, 852–868. https://doi.org/10.1016/j.ejor.2020.06.036.

Tamru, S., Engida, E., Minten, B., 2020. Impacts of the COVID-19 Crisis on Coffee Value Chains in Ethiopia.

Taranic, I., Behrens, A., Topi, C., 2016. Understanding the Circular Economy in Europe, from Resource Efficiency to Sharing Platforms: the CEPS Framework, Circular Economy Progress for Stakeholders Special Report.

Teigiserova, D.A., Hamelin, L., Thomsen, M., 2019. Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing. Resour. Conserv. Recycl. 149, 413–426. https://doi.org/10.1016/j.resconrec.2019.05.003.

Thanh Hai, L., Tran, Q.B., Tra, V.T., Nguyen, T.P.T., Le, T.N., Schnitzer, H., Braunegg, G., Le, S., Hoang, C.T., Nguyen, X.C., Nguyen, V.-H., Peng, W., Kim, S.Y., Lam, S.S., Le, Q. Van, 2020. Integrated farming system producing zero emissions and sustainable livelihood for small-scale cattle farms: case study in the Mekong Delta, Vietnam. Environ. Pollut. 265, 114853. https://doi.org/10.1016/j.envpol.2020.114853.

Theurl, M.C., Lauk, C., Kalt, G., Mayer, A., Kaltenegger, K., Morais, T.G., Teixira, R.F.M., Domingos, T., Winiwarter, W., Erb, K.-H., Haberl, H., 2020. Food systems in a zero-deforestation world: dietary change is more important than intensification for climate targets in 2050. Sci. Total Environ. 735, 139353. https://doi.org/10.1016/j.scitotenv.2020.139353.

Toka, A., Koh, S.C.L., Shi, V.G., 2016. Carbon footprint management for food supply chains. Supply Chain Management for Sustainable Food Networks. John Wiley & Sons, Ltd, Chichester, UK, pp. 205–231. https://doi.org/10.1002/9781118937495.ch8.

Triguero, A., Fernández, S., Sáez-Martinez, F.J., 2018. Inbound open innovative strategies and eco-innovation in the Spanish food and beverage industry. Sustain. Prod. Consum. 15, 49–64. https://doi.org/10.1016/j.spc.2018.04.002.

Tseng, M., Chiu, A.S.F., Chien, C., Tan, R.R., 2019. Pathways and barriers to circularity in food systems. Resour. Conserv. Recycl. 143, 236–237. https://doi.org/10.1016/j.resconrec.2019.01.015.

UNEP, 2019. Cut global emissions by 7.6 percent every year for next decade to meet 1.5°C Paris target - UN report [WWW Document]. United Nations Environ. Program. Rep. URL. https://www.unep.org/news-and-stories/press-release/cut-global-emissions-76-percent-every-year-next-decade-meet-15degc. (Accessed 24 February 2021).

USEPA, 2019. United States 2030 food loss and waste reduction goal: sustainable management of food [WWW document]. United States Environ. Prot. Agency. URL. https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal. (Accessed 27 December 2020).

van Bodegom, A.J., van Middelaar, J., Metz, N., 2019. Circular Agriculture in Low and Middle Income Countries.

van der Wiel, B.Z., Weijma, J., van Middelaar, C.E., Kleinke, M., Buisman, C.J.N., Wichern, F., 2020. Restoring nutrient circularity: a review of nutrient stock and flow analyses of local agro-food-waste systems. Resour. Conserv. Recycl. 160, 104901. https://doi.org/10.1016/j.resconrec.2020.104901.

van Grinsven, H.J.M., Bouwman, L., Cassman, K.G., van Es, H.M., McCrackin, M.L., Beusen, A.H.W., 2015. Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European union and the United States between 1900 and 2050. J. Environ. Qual. 44, 356–367. https://doi.org/10.2134/jeq2014.03.0102.

Van Zanten, H.H.E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P. J., Schader, C., De Boer, I.J.M., 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biol. 24, 4185–4194. https://doi.org/10.1111/gcb.14321.

Verger, Y., Petit, C., Barles, S., Billen, G., Garnier, J., Esculier, F., Maugis, P., 2018. A N, P, C, and water flows metabolism study in a peri-urban territory in France: the case-study of the Saclay plateau. Resour. Conserv. Recycl. 137, 200–213. https://doi.org/10.1016/j.resconrec.2018.06.007.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222. https://doi.org/10.1146/annurev-environ-020411-130608.

Wezel, A., Herren, B.G., Kerr, R.B., Barrios, E., Gonçalves, A.L.R., Sinclair, F., 2020. Agroecological principles and elements and their implications for transitioning to sustainable food systems. Review. Agron. Sustain. Dev. 40 https://doi.org/10.1007/s13593-020-00646-z.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Wordometer, 2021. Countries where coronavirus has spread - worldometer [WWW Document]. URL. https://www.worldometers.info/coronavirus/countries-where-coronavirus-has-spread/. (Accessed 28 February 2021).

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-p. https://doi.org/10.1108/MD-10-2018-1088.

Yetkin Özbük, R.M., Coşkun, 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., Martínez, J.F., Beltran, V., Martínez, N.L., 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.