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Current coronavirus crisis and past pandemics - What can happen in post-COVID-19 agriculture?

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ABSTRACT

Currently, there is an alarming increase in food insecurity during the COVID-19 pandemic in many countries throughout the world. This will be seen particularly in the countries of the Global South (developing countries). Many countries are trying to show efforts to keep agriculture, food industry and markets running, the supply chains and access to the markets and affordable food is still not secured. Disruptions caused by the COVID-19 pandemic are going to/or already have affected the poor and other marginalised groups, mainly those with less purchasing power. It is necessary to mitigate the pandemic's impacts across the food system, enhance the resilience of food systems and avoid any potential food shortages. Therefore, this paper provides an overview of past pandemics and tries to synthesise the main lessons learned from these while also outlining visions of post-COVID-19 agriculture and the effects on food security.

1. Introduction

As there is no slowing trend in the COVID-19 outbreak throughout the world, several authors, including Usman et al. (2021) and May and Mentz-Coetzee (2021), need to start putting more effort into reflecting the effects of the current crisis compared to past crises and pandemics. There need to be clear lessons learnt from the previous crises. These need to be assessed, reflected, and where appropriate, implemented, especially regarding what will happen in post-COVID-19 agriculture.

There is a current rise in food insecurity due to the COVID-19 pandemic in many countries throughout the world, especially in countries of the Global South. For example, in the US, food insecurity induced by COVID-19 increased by 32.3% of new households in the first quarter of 2020, per a study by Niles et al. (2020). In developing countries, lockdown stringencies varied from one country to another based on their effect on food security. In all countries of the world, governments justified the absence of stricter measures largely with poverty and food security concerns (Birner et al., 2021). Efforts in many countries to keep agriculture, food industries, supply chains and access to the markets, and affordable food haven't been adequate. Generally, agriculture-related pandemic effects can be grouped into supply, demand, labour, food security, food safety, trade and other effects (Jámbor et al., 2020).

Despite significant efforts, there is still much we do not know about the dynamics of COVID-19 and the potential negative effects on global food security. Hitherto, policy decision making depends on the new lessons from the evolving pandemic situation. James et al. (2021) applied the "5D of Redistribution" (Decolonization, Decarbonization, Diversification, Democratisation, and Decommodification) framework from the food sovereignty movement to understand policy affecting the emergence of a new food regime after the pandemic. The study partly concluded that national policies must be nested within internationally coordinated and harmonised global food policy frameworks. In Africa, like in other developing countries, May and Mentz-Coetzee (2021) still emphasise that the current food policy trend will lead to further declines in nutrition and health outcomes, increased inequality, a continued lack of inclusivity, and adverse environmental outcomes. As already reflected by the United Nations, Food and Agricultural Organisation (FAO), it is necessary to protect the most vulnerable and keep the food supply chains "alive" (FAO 2020). But this will not be enough. In addition, it is also necessary to mitigate the

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pandemic's impacts across the food system and make it more resilient and so avoid any potential food shortages.

In the next sections of this paper, the overview of past pandemics is presented, revealing their major impacts on agriculture. Furthermore, the identified effects of the current COVID-19 pandemic on agriculture are presented. From these, the visions of post-COVID-19 agriculture and the effects on food security are proposed. This is necessary to mitigate the pandemic's impacts across the food system, enhance the resilience of food systems and avoid any potential food shortages.

1.1. From history till now

Historically, epidemics and pandemics have often been accompanied by food shortages and even famine. The reasons were - apart from war events - mainly in the disrupted production and distribution of food. The disease often caused the deaths of direct food producers - farmers and their families. The chronicles say that "the fields were fallow and had no one to cultivate them" (Strnad and Stepling, 1790).

During the Justinian plague, 25% of the population died around Constantinople. This led to the extinction of agricultural settlements and food shortages (Ruddiman, 2003). The black death (bubonic plague) between the years 1347-1390 killed 25-30% of the population of Europe, i.e. according to estimates by various authors, about 15-20 million people. Even after 1420, Europe's population in densely populated areas was up to 33% below the early medieval population's peak (McEvedy and Jones, 1979). Another reason was the processing of agricultural products. The families of millers, bakers and other food producers became ill or died. In the Middle Ages and the beginning of the modern age, the cause of the shortage was mainly because of the closing cities due to the disease. There were no markets, and the influx of products from rural and unaffected areas was quite complicated (Schulz, 1901). This problem was gradually solved so that the cities and their self-government and thereafter the regions took responsibility for sufficient food at the time of the epidemic. Even so, the food does not usually reach the low-income poor classes – generally, the poorest of the poor were often strongly affected. Food distribution, where it was lacking, did not work in a better way until about the 17th century. We last encountered a great shortage and low quality of food in Europe in 1918 at the end of World War I, when the hardships of war were associated with one of the greatest pandemics in human history - the Spanish flu (Spinney, 2017). Table 1 shows the past major pandemics and their effects.

2. Main implications of the crisis for food production

2.1. Agriculture

The sustainability and security of food supply, democratic decision-making, and fair incomes for both food providers and consumers must be at the centre of the post-pandemic food system (Envisioning a Post-Pandemic Agriculture and Food System, 2021). The Food and Agriculture Organization of the United Nations (FAO 2020) states that COVID-19 affects agriculture in two significant aspects: the supply and demand for food. These two aspects are directly related to food security; hence, food security is also at risk (Siche, 2020). Since consumers are looking to protect themselves and their immune systems by adopting healthier diets, the availability of bioactive ingredients of food and functional foods may become critical, as the demand for these products may increase (Southey, 2021, Galanakis, 2020). Cooking at home will therefore increase demand for agricultural products. In response, farmers are likely to engage in a more resilient business model. The farm-to-table trend will accelerate worldwide. The producers expect to add value to their products to make production more resilient at small and large scales. Home food processing in developed countries might witness an increase after the pandemic. It is important to continue investing in critical technologies, germplasm, traits, crop protection or digital solutions. Developing countries will require adding value to farm produce and making it available to the consumers at an affordable cost. To ensure food safety, there is a need to develop traceability tools to establish optimisation opportunities, sustainability impacts, and chain of custody. Production has to be optimised, and supply chains have to be modernised. This will include the acceleration of digital agriculture. Digital tools, such as artificial intelligence that alert farmers to be pre-emptive about pest treatments which can contribute to curbing crop damage and saving money (Gullickson, 2021).

2.2. Animal industry

The primary factors responsible for the growth of the animal industry before the pandemic were the increased consumption of meat, beef, chicken, fish, and other kinds of seafood such as prawns (CISION 2021). In China, variants of COVID-19 were transmitted in food including animal products (Hu et al., 2021). To this effect, there will be an increasing need to improve food quality and hygiene across the supply chain. (Hu et al., 2021) also proposed that genetic sequencing of SARS-CoV-2 in animals destined for the food industry should be included in the routine surveillance of animal farming. As COVID-19 is also a viral disease, research has found that people consuming more animal protein had fewer antibodies, even in those consuming a small amount of animal protein (Chiorando, 2021). The consistent interplay of nutrition, virus activity, and disease, and switching to a whole-food, plant-based diet could be more observed after the COVID-19 pandemic. In response, producers are envisaging changes to the packaging of animal products. This includes the application of robotics, better labelling of products, more flexibility in packing animal products, and more contact-tracing of pigs and workers to cope with the low demand and as a means to prevent the further spread of foodborne infectious diseases.

In response to the fisheries sector, governments need to maintain long-term measures for protecting natural resources and ecosystems and the viability of fisheries. Economic, equity and environmental considerations all point to similar best practices: supporting the incomes of those most in need rather than subsidising inputs or fishing effort and ensuring that evidence-based management remains in place and are enforced (OECD 2020). The need for rapid mobilisation by all parties to support the small-scale fisheries sector was further emphasised (Bennett et al., 2020). Short-term responses must be swift and targeted to the most vulnerable. In the long run, cross-sectoral action will be needed to help rebuild the capacity and resilience of small-scale fisheries and coastal fishing communities.

2.3. Diseases

SARS-CoV, MERS, and SARS-CoV-2 may be traced to zoonotic transmission (Desmond et al., 2020). Non-zoonotic and plant diseases also significantly affect food security. In developing economies, non-zoonotic diseases' symptoms such as malaria and typhoid fever will require attention in the future. Children and the malnourished are at most significant risk from the consequences of plant diseases (He and Krainer, 2020). Three elements of a response framework for these diseases are prevention, response and recovery (USAID 2021). The Prevention element includes the activities and measures that are taken to avoid or prepare for an outbreak or pandemic. These include training, contingency plans, investments in research and infrastructure. The response consists of

Table 1
Chosen largest epidemics and pandemics from 500 AD (selected epidemics and pandemics with more than 1 000 000 deaths or affecting more than one continent).

Year	Epidemic/pandemic	Dissemination	Other disasters this year
Around the year 540 AD	"Plague of Justinian" – bubonic plague	Europe and West Asia	climatic change (large volcanic eruptions) crop failure famine
590 AD	"Roman plague" bubonic plague	Italy, France, Spain Byzantine Empire	long rains and the great flood crop failure famine
700 AD	plague (unspecified infection)*	British Isles, West Asia, Middle East	famine cannibalism ("*So that men ate each other..*" in the chronicle)
Around the year 736 AD	smallpox	East Asia	-
993-996 AD	plague (unspecified infection)*	Continental Europe, British Isles	long rains, flood, cold famine "...So great was the deaths that many houses were left desolate without inhabitants."
1031-1033 AD	plague (unspecified infection)* typhus	Europe, Middle East	climatic change - rainy winters, dry summers, sudden changes (Hekla eruption in the year 1029) crop failure, famine cannibalism – "*Individuals were forced to eat grass, and animals that had fallen [dead animals]. The people were killing each other to consume others."*
1193-1196 AD	plague fever (unspecified infection - pulmonary plague?)	Europe	long rains, flood crop failure famine *"There was so great a mortality, that there not being living healthy persons enough to bury the dead"*.
1221-1224 AD	plague (unspecified infection)	Europe	climatic change – long rains, flood (in Poland), sudden changes (eruption in Iceland – Hekla, Reykjanes) crop failure famine
1311-1318 AD	plague (unspecified infection)* "acute fever" (in the British Isles, unspecified infection)	Central Europe, West Europe	long rains, cold winters crop failure, famine *"The corpse of criminals were pulled down from the gallows and eaten*."
1346-1390 AD	"Black Death" pandemic bubonic plague, pulmonary plague (1367 in Germany) several waves	Europe, Asia	sudden climatic changes, locust raids crop failure famine *"The fields were desolate and deserted, it was impossible to cultivate or sow them, and therefore there was a general famine."*
1485-1551 AD	Sweating sickness (unspecified infection, possibly hantavirus)	The British Isles and continental Europe	-
1520-1576 AD	smallpox „cocoliztli" (possibly salmonella?)	Mexico and Central America	introduction of infection by European conquerors
1596 AD	plague - bubonic plague	East Europe, India, Asia	drought famine
1629-1631 AD	plague - bubonic plague	East Europe	famine
1770-1773 AD	plague - bubonic plague	Russia, Middle East	long rains, flood famine
1816-1824 AD	cholera	Europe, Asia	climatic change (large volcanic eruption Tambora), cold, long rains crop failure famine
1846 AD	cholera	Russia, Europe	-
1857-1859 AD	influenza	Europe, America	-
1889-1890 AD	influenza	Europe, America, Asia	-
1916-1920 AD	"Spanish flu" - influenza	Worldwide	First World War famine
1918-1922 AD	Typhus	East Europe	-
1957-1958 AD	"Asian flu" – influenza	Worldwide	-
1968-1970 AD	"Hong Kong flu" - influenza	Worldwide	-

the actions that take place during the outbreak or pandemic and include options such as rapid response teams, quarantines, and animal culling. The Recovery element demonstrates alternatives and choices to be considered after a catastrophic loss to the agricultural sector.

2.4. Chemical supplies

Chemical supplies like fertilisers and pesticides have been secure during the COVID-19 pandemic. There is a need to ensure resilience and reliability in the chemical supply chain in the future. The diversification of the supply chain will make chemicals more available and affordable to the farmers. There is also a need for a global increase in environmental standards for chemical manufacturing mandated to ensure food safety. Alternative technologies leading to the reduction of farm chemicals could provide more opportunities for more automation of farm activities.

Fertiliser prices are likely to remain stable beyond the COVID-19 era. There are not a lot of new phosphate plants being developed. So, as demand continues to grow, prices will increase

(Gullickson, 2021). Future fertiliser prices hinge on supply and demand. The crash in global energy prices keyed by COVID-19 also led to the decline in nitrogen (N) prices. A reduction in energy prices will likely rebound N prices.

2.5. Value of land

Farmland seems to be a stable investment in what has become an unstable investment world (Sents, 2021). The opportunity to amass more land continues to increase due to uncertainty caused by COVID-19. The seemingly low land prices are exacerbated by the uncertainty of the pandemic on crop and livestock production. For effective management of agricultural land use at various administrative and territorial levels, it is necessary to create a reliable and effective system of forecasting and planning indicators, from various aspects, characterising the state of land resources and the effectiveness of their management (Rasskazova and Sinits, 2019). With our planet's population expected to reach 10 billion by 2050, there's no escaping the fact that food production worldwide needs to increase. While opening up more land was once seen as an obvious solution to this problem, a stronger focus on urban farming and concerns over the consequences of encroaching into nature could spark a rethink of how we use land (DW, 2021). In Sub-Saharan Africa, there is a need to remove gender biases from land ownership.

2.6. Markets and supply chains

Agricultural inputs, farms, food processing, and distribution should be considered essential during the crisis, so that food can flow in adequate amounts from farm to fork (Laborde et al., 2020). Countries lockdown and borders' closure are strongly impacting farmers' access to input like seeds, fertilisers and agrochemicals (WFO May, 2020). There has been an increasing need to assist farmers across the globe to sustain the food supply. Assistance to the agricultural production of smallholders by boosting e-commerce is one of the strategies proposed by FAO to maintain a steady flow of farm produce to the market during the COVID-19 pandemic (Galanakis, 2020). The new pathway is also seen in utilising Information and communication technology (ICT) in agriculture, mostly for communication and marketing (Darnhofer, 2020). Social media platforms tend to close the gap between food producers and their clients.

It is necessary to realise that transboundary coordination is necessary to mitigate efficiency losses in the global food system (Von Braun, 2009). When the function of markets is diminished, particularly in the developing countries, it is necessary to employ food provision rather than providing cash to crisis-struck countries (Von Braun, 2009). The threat of a large-scale food crisis following the pandemic is identified by many authors (Clapp and Moseley, 2020). Three main factors that may contribute to an upcoming potential food crisis are trending food prices, loss of consumers' income, and disruptions of global food chains (Dahir, 2020). In the future, the functioning of markets must be improved through better governance. This is related to higher investments of governments into public goods. Lockdowns and limits on the mobility of people are also affecting the provision of key food safety, quality and certification checks, including those required to facilitate trade, such as physical inspections of goods to certify compliance with sanitary phytosanitary requirements (SPS) (OECD April, 2020). In the post-COVID-19 era, governments should foster policies that will keep trade channels open, consistent with the multilateral rules and regulations as agreed through the World Trade Organization.

According to FAO (2017), future profitable agribusiness requires returning to a global marketing strategy. Thus, entering into the food business with proper technology and know-how indicates a vast range of opportunities (Ranasinghe, 2020). Farmers need to reconfigure their supply chains away from bulk wholesale to restaurants, hotels, and schools towards grocery stores and home delivery (WEF 2021). However, this takes time as commercial, and consumer food products are prepared and packaged differently. According to the Organisation for Economic Co-operation and Development (OECD), diversified sources of supply had allowed firms along the food chain to adapt rapidly when specific input sources were compromised by transport or logistic disruptions (OECD 2020 (June)). Meeting the needs of vulnerable groups will require attention to food access, such as by ensuring targeted, flexible safety nets.

3. Jobs in agriculture

Many will probably attempt to mitigate the risks stemming from dependence on foreign seasonal workers by automating more of their operations (Sihlobo, 2021). To be sure, automation requires a considerable up-front investment, and some jobs (such as harvesting fruits and vegetables) are more difficult to automate than others. But technologies such as drones, autonomous tractors, seeding robots and robotic harvesters imply a dramatic reduction in reliance on migrant labour. In developing economies, agriculture is likely to rise in stature both as a field of study and occupation.

3.1. Shift to robotics in agriculture

Reducing agriculture labour due to the innovation of technologies and machinery equipment is a trend worldwide, resulting in a continual reduction of the number of people working in this sector (Cassidy and Snyder, 2021). Despite significant progress in this field, some activities such as harvest of special crops (like fruits and vegetables) still required much human labour when for example, the UK is recently reliant on seasonal migrant labour to harvest domestically grown produce with 70,000-80,000 seasonal agricultural workers entering the UK every year (Garnett et al., 2020). The United States, Canada and Australia all rely heavily on seasonal farmworkers who are unable to travel because of virus restrictions, including the suspension of routine visa services by some embassies or concerns that foreign workers could import cases of infections (Torrero, 2020). Agricultural robots are generally helping farmers fill labour shortages with the highest potential for routine operations such as harvesting or weeding (Gossett, 2021). Pandemic like COVID-19 seems to promote especially the segment of robotic agriculture, which is focused on the harvest of special crops routine operations like milking, which are usually realised via foreign workers. This change-over will be neither quick nor cheap, but a positive aspect could be the fact that agriculture shares the progress in machine vision or technology with other sectors.

4. Long-term effects for food security, including producers at risk and structural changes in agriculture

Since any significant change erodes "business as usual" (Gossett, 2021), also the reactions to COVID-19, if using the wording of transition theory (Kabele, 1998, Geels, 2004), have the potency to open the window for altering the regimes in the agriculture and food industry. The impacts of the pandemic might recompose the farm and food businesses and support their transition towards sustainability and resilience. The protective measures resulting in closing the national borders impacted the global nature of the agriculture and food industry, with which both sectors evolved within the last decades (Sutherland et al., 2014). An example of the low resilience of these sectors in developed countries was demonstrated in their dependence on migrant/foreign

labour. Although pandemic caused shutdown (at least temporarily) of many businesses, farming and food industry were not the case. Nature, which is the fundament of agriculture, cannot be stopped as the automotive industry, for example. That makes agriculture unique, as echoed in Bonanno et al. (1994) concept of the substantive economy (agriculture is not about rational choice among scarce resources /formal economy/ but it is about our survival since we need food as the substantive source of energy). If processes in nature cannot be stopped, agriculture and the food industry require people to work with nature. When these sectors resulted in competition for cheap labour, blocking the borders for easy moving of such labour altered the situation. Farms and food industries were not able to supply missing cheap labour because domestic labour (even unemployed due to businesses being shot down) considered the conditions under which foreign labour worked as inadequate (low level of remuneration, not being skilled for agriculture, hard work but also farm reluctance to accept off-farm labour) and as such domestic labours did not consider the work in agriculture attractive although they lost their previous jobs due to pandemic. That is why the farms depending on foreign labour are at high risk and are not resilient. The authors (Polanyi et al., 1992, Darnhofer, May 2020, Dickinson, May 2020) see COVID-19 as the possibility to reconfigure agriculture toward food sovereignty resting on local farms with local labour instead of large global businesses necessitating international labour. The experience of the Czech University of Life Sciences, Prague (CZU) documents that 175 of its students (114 international) volunteered to substitute missing foreign workers who were during the time of the pandemic out of Czechia. There was minimal interest in such labour from the large-scale Czech farms (only 30 % of these students signed the contracts. Meanwhile, the farms complained of having no foreign labour). It is another example of the low resilience of the contemporary farming sector based on large-scale farms and the food industry operating in a global context. COVID-19 also opens the window for the reconsideration of various aspects of food security and food self-sufficiency. For instance, the prices of broccoli or cauliflower doubled or tripled in March 2020 in the Czech supermarkets (owed by international capital). It started the discussion on how secure and self-sufficient in terms of food is such a global agri-food business. A sort of nationalisation (not localisation) of both sectors started. People incline to trust local (understood as national related to the country of origin). It is a reaction to closed borders.

5. Opportunities arising due to COVID-19 in the agri-food supply chain

The COVID-19 pandemic is a major global problem, but to an extent, it also represents an opportunity for many stakeholders in the agri-food supply chain. One drawback associated with online shopping is that consumers usually spend less than they would normally do in stores (Hendrickson, May 2020). The pandemic may accelerate the shift from offline to online (selling groceries online). This may also be true about inputs to production in the agri-food supply chain, specifically horticulture (E.g., selling seeds) (Lowe, 2021, Timmins, 2021).

The entire supply chain experienced a major change during the lockdowns and quarantines. All online grocery stores in the US experienced higher use by customers (Pierre-Louis, 2021).

Fast-food powerhouses such as Panda Express or Burger-king made critical decisions adoring the onset of the COVID-19 pandemic that led to more rather lucrative gains. An example may be an increased interest in the drive-through business. One of the largest fast-food chains in the United States experienced a spike of between 15 to 20% since March 2020 (Statista 2021).

While online food grocery businesses experienced an increase of 22% in 2019, the pandemic has magnified this trend. For example, the online grocery market share was up by 3.6% across China, France, Spain, and the United Kingdom by the end of April 2020 (CFO Journal 2021). A large majority of online shoppers will continue using an e-commerce channel for their grocery purchases (CFO Journal 2021). Globally, online grocery purchases have been up by almost one third since the beginning of the crisis. Some online grocery retailers even reported sales much higher, such as Kroger Co., with an increase of 92% year on year and Walmart 74% year on year (CFO Journal 2021, Melton, 2021 bib50). At the same time, the increase in sales is accompanied by considerably higher costs of production (labour, delivery vehicles and fuel).

A successful example of an online grocery business can also be found in the Czech Republic. Rohlik.cz expanded their operation during the coronavirus pandemic by more than 100% and was able to introduce innovations that speed up the delivery process or extended reach to customers. Generally, online grocery sales grew in the Czech Republic by 215% (Repko, 2021).

Increased interest in online grocery shopping was fuelled by stockpiling during the first weeks of the crisis. The most popular groceries were flour and other food with long expiration dates (E15 2020).

The same fear was driving countries to increase strategic food reserves (wheat, rice and other main commodities). This implied that food commodities prices were initially going up. For example, rice prices increased by almost 30% from February 2020 to April 2020 (idnes 2021).

A major threat identified during the pandemic was the lack of labour on some levels of the agri-food chain. For example, in the United States, outbreaks of novel coronavirus that already threatened the animal production sector also negatively impact fruit and vegetable producers (index 2020). As a result, the opinion of the authors of this article is that agricultural producers are more likely to shift to less labour-intensive technologies in the future. These include process automation systems in all elements of the existing agri-food chain. This starts with precision agriculture on farms (Rosenberg et al., 2020), through warehouse automation (Repko, 2021) to final customer deliveries using self-driving vehicles (Foote, 2021).

6. Is it time to reorient food systems?

Trends and nutritional needs in the world are contradictory. In developing countries, it is necessary to address the saturation of the growing population and the issue of malnutrition by increasing protein-energy intake and by dietary diversification (Müller and Krawinkel, 2020). On the other hand, there is a global obesity epidemic, which is not limited only to developed countries and requires a reduction in energy supply, increased physical activity and a lifestyle change (Popkin and Doak, 2020, James et al., 2020). An example of a commodity proving this contradiction is pork. While consumption and production are stagnating in Europe and the USA, they are rising sharply in China or South Korea (Moeller and Crespo, 2009, Schnitkey, 2013).

Agriculture is becoming increasingly industrialised and globalised, which could cause enormous damage to the environment. Such as the consequences of soybean cultivation for livestock fodder (Oliveira and Hecht, 2016). Another example is palm oil production, which is, in addition to energy use as fuel, an important raw material in the production of industrial food (Vijay et al., 2016). These environmental and social impacts are leading around the world, especially in rich well-developed countries, to a renewed interest in growing their food among part of the population, with an emphasis on organic farming and sustainability. Since the 1970s, a permaculture movement has developed, which is still

gaining strength. The main principles used by permaculture are multi-purpose areas (edible gardens), composting (including human faeces), mulching, low level of interventions in ecosystems (minimal ploughing, elimination of agrochemistry), water-saving, support of biodiversity. A specific effort in the field of nutrition is the effort to use local and seasonal foods (Mollison and Slay, 1991, Whitefield, 1993, Holzer and Liebchen, 2002, Svoboda, 2009, Svoboda and ekozahrady, 2018).

The generally shared opportunity to solve global food security is to move humanity towards vegetarianism. The theoretical assumption is that more plant food than animal food can be produced per unit area. However, in terms of environmental impacts, especially in terms of greenhouse gas production, vegetarianism is not a universal solution (Lomborg, 2019). In nearly all countries, diets that only included animal products for one meal per day were less greenhouse gas-intensive than Lacto-Ovo vegetarian diets in part due to the greenhouse gas intensity of dairy foods. Very favourable is exclusive plant-based (vegan) diets, which has together with diets comprised of plant foods with modest amounts of low-food chain animals (i.e. forage fish, bivalve molluscs, insects) comparably small greenhouse gas and water footprints. In any case, the country-specific approach is needed (Kim et al., 2020).

The problem is that industrially grown vegetables, when converted to calories, usually have a greater environmental footprint than animal production. When switching the current food mix to recommended food patterns containing fewer animal products without reducing caloric intake increases energy use by 43 %, blue water footprint by 16 %, and greenhouse gas emissions by 11 % (Tom et al., 2016). Of course, the solution in the rich northern countries fighting obesity is to reduce calorie intake, which will positively affect human health and the environment. In addition, the environmental footprint of vegetarians and vegans from rich countries is exacerbated by the fact that their diets are often not regional, let alone seasonal.

Over the next 40 years, population growth will require a doubling of food production in developing countries, and climate change will make achieving this goal more uncertain. There are several possible solutions to overcoming growing malnutrition in South Asia, Africa, and the Pacific and ensuring a healthier diet for the people of the north. Multi-purpose legumes as mung bean (*Vigna radiata*) and soybean (*Glycine max*) can be produced/cultivated by smallholders or large enterprises and can be consumed as highly nutritious vegetables or grains (Keatinge et al., 2011). Moreover, there are various alternative sources of food. It has long been said that insects will be a significant source of protein in the future (Bodenheimer, 1951). About six decades ago, the mass production of certain protein-rich micro-algae was considered as a possibility to close the predicted so-called “protein gap”. However, due to high production costs as well as technical difficulties to incorporate the algal material into palatable food preparations, the propagation of algal protein is still in its infancy (Becker, 2007).

Biotechnological advances are much needed to complement future food production. The implementation of innovations in biotechnology is essential in tackling modern and future issues from food security to environmental change. Some modern methods include transgenic techniques revolving around the insertion of foreign DNA strands into the host genome to obtain enhanced crop yield. In vitro production of meat has been proposed as a humane, safe and environmentally beneficial alternative to slaughtered animal flesh as a source of nutritional muscle tissue (Datar and Betti, 2010). In any case, the feeding of humanity will not be possible without significant scientific and technological progress, including in particular breeding using genetically modified organisms (GMO) methods (Qaim and Kouser, 2013, Gruissem, 2015), although this is criticised by part of the scientific public (Dona, 2009, Jacobsen et al., 2013, Urfusova et al., 2020). However, the ethical foundations of biotechnology are founded on justice, non-maleficence, and beneficence (balancing risks and benefits in production and consumption).

As seen in Fig. 1, where the overview of past pandemics to post-COVID-19 agriculture is presented, the effects of the past 23 large pandemics and epidemics are visible and linked with current COVID-19 implications and what can be expected in post-COVID-19 agriculture.

7. Ways to reduce and minimise risks of the COVID-19 on food security

There are many risks of the COVID-19 pandemic on food security affecting farmers, food producers, and food distribution directly, marketing up to the ability of many consumers to buy an adequate amount of food because of a decrease of their purchasing power. In the case of farmers, there are many direct and even indirect risks connected with COVID-19 – an insufficient number of seasonal workers because of lockdown, insufficient supply by agrochemicals and general shortage of all needs required for agricultural production changes in demand for milk and other agricultural products. For example, there has been a risk in the shortfall of about one million seasonal agricultural workers across Europe (IOM May, 2020). The COVID-19 pandemic though not an issue of migration, triggered mobility restrictions, disrupting traditional labour supplies in critical sectors, including food and agriculture. In the Czech Republic, vegetable growers were able to secure locally 1,500 - 2,000 seasonal workers (Mikulasova, 2021). These seasonal workers included actors, technicians from the music industry, retirees, workers of the automotive industry and some students. Online sourcing of seasonal farmworkers with the use of the Agroprace.cz website proved to be effective. In France, on the other hand, several local governments reached out to temporary refugee accommodation centres with the goal of enlisting recognised refugees as agricultural workers to fill temporary labour shortages in the sector, while in Canada, the government considered waiving recruitment requirements for hiring foreign workers in key occupations related to the agriculture and agri-food sectors (IOM May, 2020). A sector such as milk production can hardly be reduced from one day to the next if there is a very dramatic decrease in milk consumption, as was recorded in the USA during the start of the pandemic. In the USA, it was estimated that about 5% of the country's milk output in April 2020 was dumped, and the percentage was estimated to be higher in May and June 2020 (Qingbin et al., 2020). The only way to reduce costs connected with milk production is the slaughter of milking cows. In the USA, in April 2020, 2.3% more milking cows were sent to slaughter, and the total number of milking cows could drop by up to 90 000 in 2020 (Skerritt and Hirtzer, 2020). Such a decrease in the number of milking cows is very dangerous as milk production cannot be restored during a short time. So short term decrease in milk consumption during the start of the pandemic can have long-term negative consequences for milk production. On the other hand, Ridley and Stephen (2021) studied the effects of COVID-19 on fruit and vegetable production. Two studied scenarios based on commodity (fruit and vegetable) and labour linkages showed that commodities with the largest values of production (lettuce, grape, apple, and orange production) stand to incur most of the losses. In contrast, commodities with smaller values of production (artichokes, chilli peppers, and plums) tend to incur smaller losses. These vegetable losses, coupled with the short-term decrease in demand for vegetables and disruption of the marketing brought about partly by COVID-19 on farms, can contribute to their bankruptcy. A farmer in Washington County, Iowa testified that “*I gotta have maximum revenue coming in so I can pay the next interest payment. And that's not good*”, evidently due to disrupted farmers'

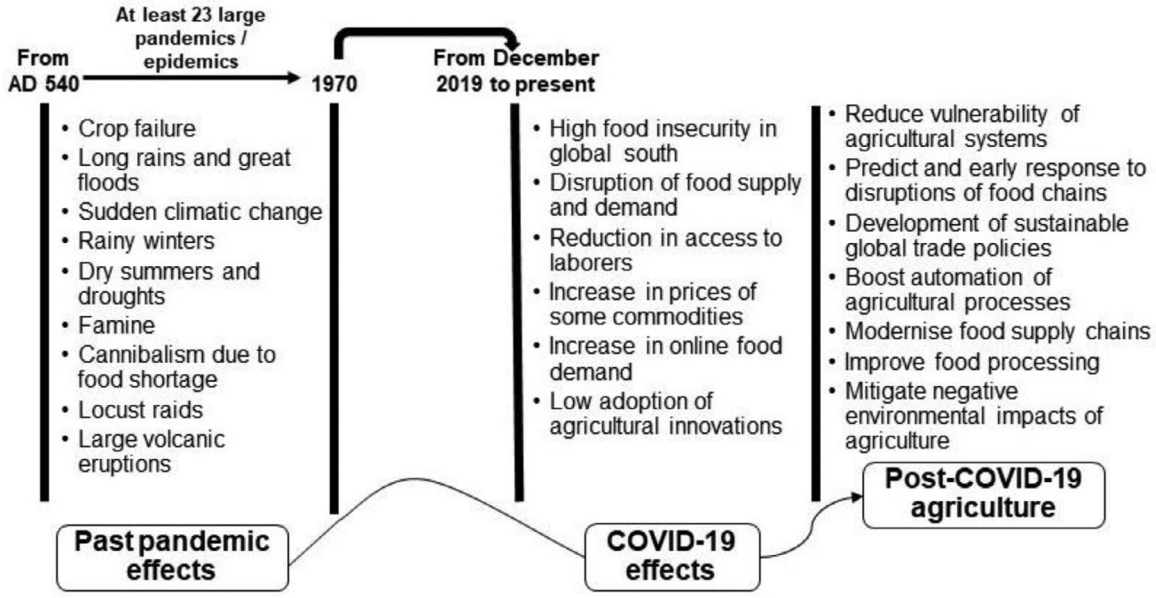

Fig. 1. Overview of past pandemics to post-COVID-19 agriculture.

supply chains caused by COVID-19, he revealed (Uhler, 2020). So short term disruption can have long-term effects on farmers. In addition, the profitability of farming, especially of small family farms, is frequently on the border of existence even in the case of normal years. This is the difference in comparison to many other economic sectors with much higher profitability and, therefore, financial reserves.

Therefore, a very important question is how to minimise the risks of COVID-19 on food security? Briefly, measures must be performed within the entire i) food production, ii) processing, iii) marketing up to iv) consumers sectors and v) globally coordinated response.

i) Food production sector – prevention of farms bankruptcy, prevention of the spread of COVID-19 into farmers and farm workers population, priority for the supply of farms by all necessary needs for agricultural production, support of stable marketing of agricultural products, measures enabling farmers to have a sufficient number of seasonal workers even during the lockdown.
ii) Food processing sector – prevention of the spread of COVID-19 into food processing companies, the most vulnerable are slaughterhouses and dairy companies as they directly affect farmers and their everyday life.
iii) Marketing – prevention of panic connected with disruption of marketing of different agricultural products, price stability.
iv) Consumers – the stable purchasing power of consumers.
v) Globally coordinated response – there is a need for a lead role in coordinating the global food security issues to minimise the risks of COVID-19. This should be done in close collaboration with agencies such as the WHO, FAO, WFP and national governments.

8. Lessons learnt and conclusion

The COVID-19 pandemic intensified the debate about food security and food self-sufficiency around the world and opened the debate on the current agricultural approaches and systematic issues in the agri-food sector, which is currently not very flexible and hard to recover. On the other hand, the COVID-19 pandemic also brought advantages and opened new opportunity windows, especially regarding the demand for locally produced food (especially in developed countries). However, the expected population growth in the upcoming decades needs to be kept in mind as this will require a doubling of food production in developing countries, and climate change will make achieving this goal even more challenging.

The COVID-19 pandemic has taught us that the modern population is vulnerable to food chain disruptions. In a globalised world, everything relates to everything, so globalisation increases the vulnerability to pandemics similar to COVID-19. Another factor increasing the future vulnerability to pandemics is the gradual increase of the human population and, therefore, the higher need for food supply and the increase in the proportion of urban population and meat consumption. Modern lifestyle relates to low level or completely missing self-supply by agricultural products and low food reserves in households. All the facts mentioned above increase the importance of the resilience and resistance of food chains to disruptions caused by pandemics.

Future research is necessary to focus on several levels, such as potential bottlenecks in the medium to long term – especially by researching short-term sector analyses and looking into how various market disruptions of food supply affect small and larger-scale producers. Furthermore, it is necessary to provide research into the long-term consequences - using economic models to calculate the possible consequences for the agricultural sector of a recession triggered by the COVID-19 implications. Finally, the negative effects on food security need to be investigated further to define necessary changes in food systems to increase their resilience.

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All the data and material within this paper are freely available.

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The authors declared that they have no conflict of interest.

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Hynek Roubík: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Michal Lošťák:** Writing – original draft. **Chama Theodore Ketuama:** Writing – original draft, Visualization. **Petr Procházka:** Writing – original draft. **Jana Soukupová:** Writing – original draft. **Josef Hakl:** Writing – original draft. **Petr Karlík:** Writing – original draft. **Michal Hejcman:** Conceptualization, Writing – review & editing.

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