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Soils, Biofortification, and Human Health Under COVID-19: Challenges and Opportunities

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Soil is an important source of resources required for human health and well-being. Soil is also a major environmental reservoir of pathogenic organisms. This may include viruses like the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), which through 2020 and 2021 created dramatic catastrophes worldwide as the causative agent of the coronavirus disease of 2019 (COVID-19). So, soil has both positive and negative impacts on human health. One of the major positive impacts is the transfer of nutrients from soil to plants, and from there to humans through their diet. Biofortification is able to enhance the levels of nutrients essential to human health in the crops we consume and represents a sustainable solution to address malnutrition, which in turn may strengthen the human immune system against COVID-19. This nutrient transfer works better when we have healthy soils. Therefore, soils and biofortification have important roles to play in combatting the COVID-19 pandemic. However, several questions still remain, such as what are the expected environmental impacts of COVID-19 on soil? Can SARS-CoV-2 be transmitted through soil, and under what conditions? Which soil processes and properties influence SARS-CoV-2 survival rates and times, as well as transmission? What are the specific links between soil health and COVID-19? What are the projected soil management scenarios in response to COVID-19? Questions such as these deserve more attention as the world seeks to recover from its most recent pandemic.

Keywords: environmental pollution, corona virus, SARS-CoV-2, soil health, soil quality

INTRODUCTION

As a major source of food, feed, fiber, fuel, and biodiversity, soil is considered an important resource not only for agriculture, but also for human health and the environment [(1, 2); **Figure 1**]. Soils contain the nutrients, or elements, that are essential for human and plant life functions. Thus, soil has a very strong link to human health [e.g., (3, 4)], agriculture-based economies (5, 6), food security (7, 8), and air and water quality (9). Furthermore, the health of soil is a pivotal global

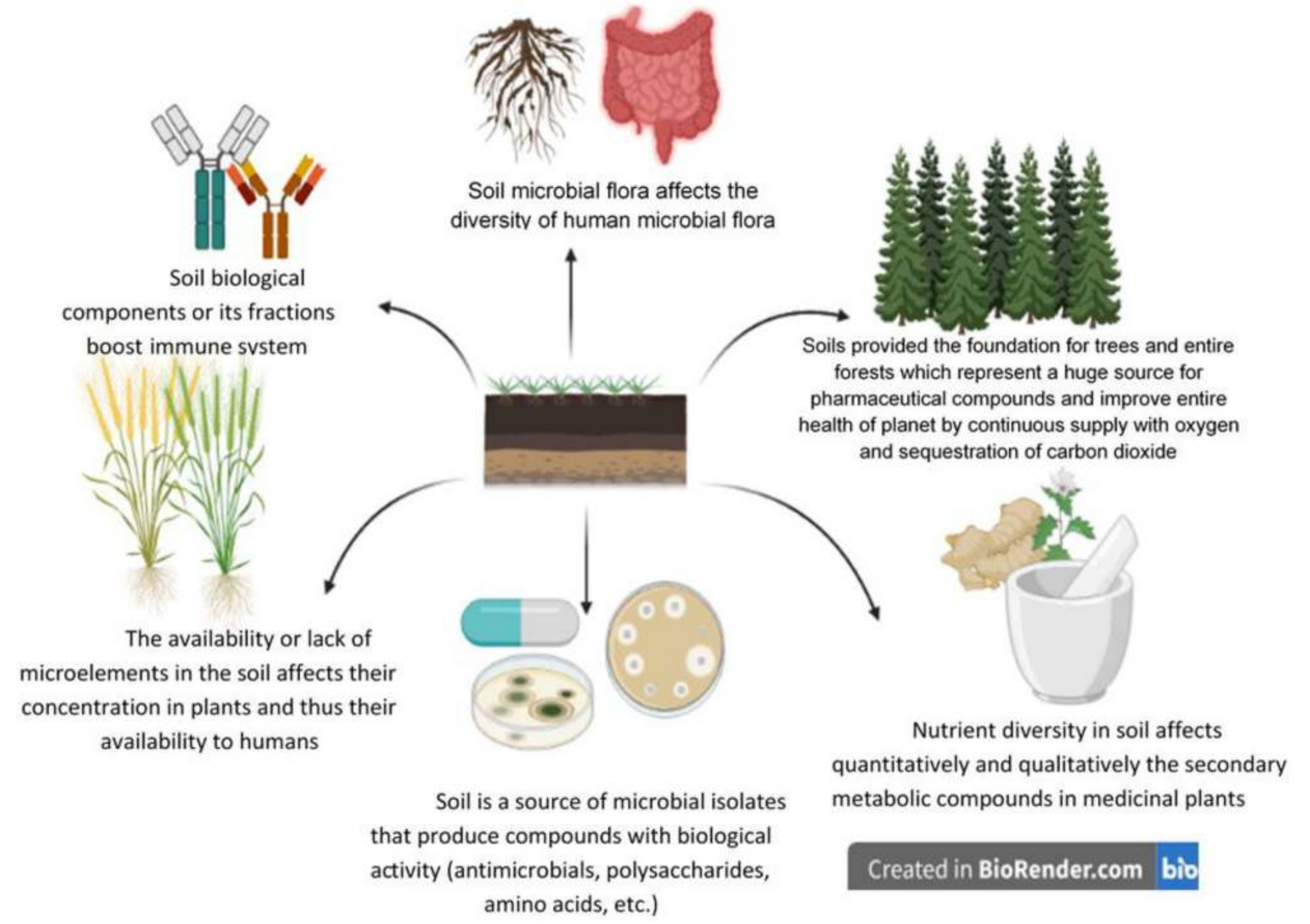

FIGURE 1 | There are direct and indirect as well as positive and negative relationships between soil and human health. For example, soil is the main source of several antibiotics derived from soil organisms, while at the same time soil hosts many pathogens.

issue for producing healthy plants, which are crucial for human health (10). However, the health of soil is under great threat across the globe. These threats may include salinization (11, 12), climate change (12), erosion (13), compaction (14), nutrient depletion (15), contamination with toxic levels of pollutants such as heavy metals or pesticides (16), human assisted migration of soil-borne pests (4), and overgrazing (17).

The relationship between soils, human health, and the coronavirus disease of 2019 (COVID-19) pandemic is very complicated and interesting (18, 19). Soil is a major host and transmission pathway for several pathogenic microbes (18, 20) because it is one of the most diverse and dense microbial habitats on our planet (21, 22). Spread of the COVID-19 pandemic may be controlled by several factors like atmospheric temperature and average daylight hours (23), wind speed (24), atmospheric stability (25), flooding (26), relative and absolute humidity (27), contaminated wastes (28), and different environmental media (29). Soils are currently considered a black box by many in microbiology. Soil microorganisms can be divided into categories such as those beneficial to plants or humans and pathogenic to plants or humans (19, 30). Thus, healthy ecosystems and healthy humans depend on healthy soils, as confirmed by the one health concept (19, 31).

Soil nutrient bioavailability problems for cultivated plants may result in malnutrition for people who rely on those plants as a source of food. Supplying necessary nutrients for cultivated plants through fertilization or other approaches is called biofortification, and is a vital process for human health (32). Biofortification has been used with many important food crops like wheat (33), rice (34), maize (35), cassava (36), sweet potato (37), pear (38), strawberry (39), and pulse crops (40). Nutrients that have been used for biofortification include boron (41), copper (42), iron (36), iodine (43), calcium (38), selenium (44, 45), and zinc (46). In addition to nutrients, edible crops can be biofortified with vitamins such as vitamin B1 (thiamine), B2 (riboflavin), B3 (e.g., niacin), B5 (pantothenate), B6 (e.g., pyridoxine), B7 (biotin), B9 (e.g., folates and their derivatives), B12 (cobalamin), vitamin C (ascorbate), vitamin E (tocopherol), and carotenoids (32, 47–49).

Therefore, this review seeks to highlight biofortification and human health opportunities and challenges related to soil under the COVID-19 pandemic. Major issues addressed include: (a) the current status of our knowledge about severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) in the environment, particularly soil, (b) the expected environmental impacts of COVID-19 on soil health, and (c) ways that soils and biofortification may help alleviate the COVID-19 pandemic.

COVID-19 TRANSMISSION AND SOIL

One might not immediately think "soil" when thinking about the spread of viral diseases. Viruses are biologically active microscopic parasites that require a host to replicate. Although aerosols and droplets are the most common methods for viruses to spread, it is widely recognized that transmission can also occur via the fecal-oral route, which may include soils. As a result, to prevent the spread of infection, all environmental compartments (i.e., soil, water, and air) the virus can affect must be monitored (50). Recent studies have established that the transmission of SARS-CoV-2, the virus that causes COVID-19, may occur through air, water, soil, cold-chain, biota, and surface contact (51). As compared to other environmental compartments, the interactions between soil and viruses have not received much attention (52). However, many research papers that addressed links between the COVID-19 outbreak and the environment were published over the last year. This included links between the outbreak and soil that addressed several issues, such as:

1. How to handle soil samples to measure or quantify SARS-CoV-2. Some studies have also investigated the detection and quantification of SARS-CoV-2 in wastewater and sewage sludge (53) as well as soils (54).
2. Why do we need to study SARS-CoV-2 in relation to soils? These studies emphasize how soils are an important component of the environment that receive this and other viruses when wastewater is used to irrigate cultivated plants, infected manure is applied as a nutrient source, or when soils are used for on-site sewage disposal, which may transfer the virus through the food chain (53–56).
3. There is currently no established procedure for detecting and quantifying SARS-CoV-2 in soil or soil-related liquid samples, although there have been attempts to develop procedures to detect this and other pathogenic viruses in liquid-soil samples (53, 54, 54).
4. What role can soil play in mitigating the effects of COVID-19 over the short- and long-term? The existence, survival, and behavior of SARS-CoV-2 in the soil is still not well-known (21). It is known that the survival of viruses (like SARS-CoV-2) mainly depended on soil properties (e.g., soil temperature, pH, moisture content, exchangeable Al) and virus characteristics (e.g., presence or absence of a viral envelop, adsorption rate of the virus on soil), and some projections for SARS-CoV-2 survival in soil have been made based on similar viruses (18, 21).
5. The positively charged form of coronavirus can attach such viruses to the negative-charge sites on soil clays, which may at least slow down their spread in soil (57). Are soil minerals able to react with and adsorb this virus, slowing or neutralizing its spread?
6. Adsorption by soil can have a significant impact on the ability of viruses to infect host organisms. Negative and positive charges on clay particles are able to absorb more than 90% of the viruses in clay-rich soils. Based on the survival rate of similar viruses, it has been concluded that the survival of corona virus in soil may be just a few days. However, no studies to date have focused specifically on the survival of SARS-CoV-2 in soil media (18, 29, 56).
7. The actual rates of transmissivity and survival of SARS-CoV-2 in soil and their relationships with soil properties and other environmental conditions are still open questions that need to be evaluated (18, 21). As vaccines are increasingly administered a critical point has been reached in the COVID-19 outbreak. How can we build a broader awareness about the importance of soil to human health and how we can manage soil to enhance the health of people, animals, and plants in the post-COVID-19 world (58)?

BIOFORTIFICATION FOR HUMAN HEALTH

Dietary malnutrition is thought to be a key cause of health deterioration in developing countries. This includes deterioration of the immune system. Around 75% of the world's population is deficient in micronutrients, namely Zn, Cu, I, and Fe, resulting in several health issues. As a result, providing these micronutrients in a balanced human diet has gained a lot of attention across the world. These micronutrients are often supplied to humans through dietary fortification. While this provides a fast way to avoid illnesses caused by nutritional shortage, it is an artificial method that requires special attention and is not socially acceptable to broad parts of the community. Instead, enrichment or biofortification of food crops throughout the crop growth and development stages has the potential to naturally supply essential nutrients to everyone, particularly people without access to expensive commercially available fortified meals or supplements (59).

Biofortification is a sustainable process that can increase the vitamin or mineral nutrient contents in cultivated plants or animals *via* agronomic practices, plant breeding or transgenic techniques (60). The production of biofortified staple crops mainly depends on the content of available soil nutrients for plant and then human health and nutrition. Soil properties including chemical (pH, salinity, CEC, SOM, Eh, nutrient interactions in soil, etc.), physical (soil texture, structure, moisture content, aeration, etc.) and biological (soil microbial populations and activities, macro-organism populations and activities, enzyme activities, etc.) are the primary factors that control the bioavailability of nutrients for cultivated plants. Promising results have been obtained using biofortification of different nutrients or vitamins for many crops under different climatic conditions in several countries (**Table 1**). Therefore, the right biofortification process should start with an analysis of the soil and its properties, then move to selection of the right edible plant or crop, which should fit the soil and climatic conditions. For example, soil or foliar agronomic Se-biofortification (up to $80\,g\ ha^{-1}$) of rice is a promising strategy that could be adopted in tropical soils in Brazil to produce rice grains rich in Se for human consumption (34). In Se or Zn deficient regions, the biofortification of soybean seeds by spiking the soil with deficient elements during the flowering phase may improve the human nutrition value of this crop. Experiments have achieved 25-fold Se and 190-fold Zn increases in soybean seeds (61). Under the acidic (pH 4.6) soil conditions in Brazil, agronomic Zn-biofortification (25 mg Zn kg^{-1} soil) on 29 genotypes of cowpea (*Vigna unguiculata* L.) was confirmed by increased Zn and soluble storage protein and decreased phytic acid in cowpea grains (62).

Soil and foliar fertilization of iodine (up to 7.5 kg I ha^{-1}) was investigated under field conditions (pH 5.5) in Germany to produce biofortified strawberry with higher iodine content in fruits. Higher iodine content was achieved using foliar application either as a single treatment shortly before harvest or when repeatedly sprayed during the flowering period (39). Different Zn-biofortification strategies, including application method and rates (0.3–10 and 1.28 kg ha^{-1}, for soil and foliar application res.), were studied under Mediterranean climatic and field conditions (pH 8.1 and $CaCO_3$ 410 g kg^{-1}) in Spain to produce wheat (70). They found that foliar applications at and after the early booting stage was a promising approach for producing both Zn-biofortified durum and bread wheat. Different programs also have been applied to overcome malnutrition problems by producing biofortified food crops such as pulses and legumes to enhance human nutrition (40, 71). Therefore, some of the great challenges facing the planet include understanding the properties of soil and cultivated plants (72). Agronomic biofortification success stories have been reported using Se-fertilization in Finland, Zn-fertilization in Turkey, and iodine-fertilization in China, among many others. Biofortification, in turn, can increase human resistance to diseases such as COVID-19, thus helping combat the current epidemic (73).

SOIL HEALTH, BIOFORTIFICATION, AND COVID-19

Soil health was described by Li et al. (74) as "*the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans*," which is in-line with the definition offered by USDA (75). Creating or maintaining healthy soil is a pivot approach to achieve both the sustainability of ecosystems and production of healthy food (76). Several studies have reported on the relationship between soil health and human health [e.g., (3, 52, 58, 74, 77)]. Soils are the main source of food production for humanity, and their health is essential to ensure a biodiverse and healthy environment, among other functions. The role of soils in food production during the COVID-19 pandemic was maximized because the disease threatened food availability in many places all over the world due to lack of workforce, the disruption of food chains, closed borders, and national lockdowns (78). There are several important ways that soil can strengthen local food production systems, enhance food resilience, and create a circular economy based on soil restoration. This restoration may be achieved through C-sequestration, cycling of nutrients on-farm, minimizing pollution of the environment, and minimizing contamination of foods (21). The sustainable management of soil resources is essential to recover from the COVID-19 pandemic because such management strengthens food supply chains and improves environmental quality while addressing interconnected issues such as the COVID-19 pandemic, global warming, hunger and malnutrition, water scarcity and renewability, and dwindling biodiversity (21).

Improving human health may include providing people with enough safe nutrients to avoid malnutrition and allow the immune system to fight against multiple diseases such as COVID-19 (73, 79). The COVID-19 pandemic has a strong relationship with other outbreaks such as severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS). These are also respiratory diseases with similar infection stages (i.e., cough and fever) caused by coronaviruses that resulted in significant mortality among people who did not have a strong immune system (80). The immune system is supported by adequate and safe nutrition, whereas malnutrition or contaminated foods (e.g., through heavy metals or organic chemicals) may make individuals more vulnerable to such infections (81, 82). This immunity could be strengthened through factors like physical exercises (83), consumption of functional food ingredients like probiotics, flavonoids, carotenoids, curcumin, and omega-3 fatty acids supplements (84) and food rich in vitamins such as vitamins A, C, D, and E (80). Appropriate intake of vitamins and bioactive lipids could increase human resistance to viruses like SARS-CoV-2 (85, 86). As previously discussed, these can be supplied through the soil-crop system using biofortification.

Industrial agriculture is the dominant mode of food production used to create adequate amounts of safe food products in the modern world (87). However, industrial agriculture has several potentially negative aspects. These include loss of biodiversity, soil degradation, erosion, and the intensive use of herbicides, pesticides, and synthetic chemical fertilizers that may have deleterious effects on soil health, all of which can negatively impact soil and food security and human health (87, 88). In some instances, industrial agriculture has also introduced pollutants such as heavy metals to the soil environment (88). With the COVID-19 pandemic sweeping the world, food insecurity increased for millions of people (89) in several countries (90–95) and in large urban school districts (96). Understanding how COVID-19 impacts food insecurity, and the role that soils can play in minimizing this, is critical.

It has been reported that all forms of malnutrition might increase drastically due to the COVID-19 pandemic, which could increase the possibility of a malnutrition epidemic (97). Biofortified crops can provide needed nutrients that can combat malnutrition and improve resistance to respiratory disorders (36).

TABLE 1 | A survey of some biofortification studies published in 2020–2021, including the place of study, targeted nutrient and crop, and a summary of the important findings of these studies.

Country/region	Applied nutrient/item	Target crop(s)	Important findings	References
Global study	Selenium	Se hyper-accumulating plants	Plants can use phytoremediation processes in producing biofortified plants enriched in Se	Trippe and Pilon-Smits (63)
Global study	Vitamins	Rice (*Oryza sativa* L.)	Based on post-harvest biofortification of rice with vitamins, increasing nutrients in rice could solve global hidden hunger	Tiozon et al. (32)
Turkey	Zn, Fe, and Se	Maize (*Zea mays* L.)	Quality of silage maize may depend on N-fertilization, which is an effective tool in improving Zn and Fe status but not Se	Grujcic et al. (42)
Portugal	Calcium	Pear (*Pyrus communis* L.) variety Rocha	Foliar applications of $Ca(NO_3)_2$ or $CaCl_2$ (0.6 or 1.6 kg ha^{-1}, resp.) produced biofortified pears in orchards	Pessoa et al. (38)
Nigeria	Iron and zinc	Cassava (*Manihot esculenta* L.)	Challenges in producing cassava biofortified with Fe and Zn were addressed by studying the dynamics of micronutrient deficiency across Nigeria	Okwuonu et al. (36)
India	Zinc and Iron	Chickpea (*Cicer arietinum* L.)	Tank mix applied $ZnSO_4$ (0.5%), $FeSO_4$ (0.5%), and urea (2%) at flowering and pod formation stages improved nutrient contents	Pal et al. (46)
Mexico	Se and Cu nanoparticles	Bell pepper (*Capsicum annuum* L.)	Nanoparticles of Se, Si and Cu increased bioactive compounds (flavonoids, phenols, glutathione, β-carotene, yellow carotenoids) in fruits under saline stress	González-García et al. (45)
Global study	Selenium and iodine	Several crops	Foliar fertilization with Se(VI) or iodide (I^-) is the best way to enrich plants with Se and I	Izydorczyk et al. (64)
South Africa	Zn and Fe	Sweet potato, common beans	Biofortification was applied at large-scale for β carotene-rich orange-fleshed sweet potato, while common beans were biofortified with Zn and Fe at the developing stages	Siwela et al. (37)
Global study	Se and Se nanoparticles	Some cereal and horticultural crops	Se and Se-nanoparticles may enhance the productivity of cultivated plants under stressful conditions	El-Ramady et al. (44)
Global study	Fe, I, Se, and Zn	Pulse crops (e.g., common beans and lentils)	Genetic engineering could be applied to improve biofortified pulse crops and develop a transgenic approach	Jha and Warkentin (40)
Mozambique	Zn and Se	Rice (*Oryza sativa* L.)	Genomic change in rice flag leaves is good for biofortified plants, because Zn is needed for biosynthesis of nitrogenous compounds and Se for biosynthesis of vitamins	Roda et al. (65)
Brazil	Selenium	Rice (*Oryza sativa* L.)	Agronomic strategies (soil and foliar) and Se application rates (up to 80 g ha^{-1} Se) produced Se-enhanced rice grains	de Lima Lessa et al. (34)
China	Iron	Wheat (*Triticum aestivum* L.)	Success of Fe-biofortification of wheat grain may be associated with beneficial microbial symbionts and endophytes	Shi et al. (33)
Pakistan	Boron	Chickpea (*Cicer arietinum* L.)	B-seed coating at low rates (1.5 g kg^{-1}) along with seed inoculation with *Bacillus* sp. improved growth, yield, and B in grains	Hussain et al. (41)
India	Isolated bacteria from soil	Wheat (*Triticum aestivum* L.), HD-3086 and HD 2967 cultivars	Combined application of native PGPB and AM fungi promoted yield and biofortified wheat grains compared to non-native bacteria	Yadav et al. (66)
Global study	Folate	Food crops	Lactic acid bacteria could produce folates, which act as plant probiotics or stimulators of biofortification	Viscardi et al. (47)
Australia	Zinc	Maize and sweetcorn (*Zea mays* L.)	Sweetcorn kernels can be biofortified with Zn, no need to increase kernel P, and associated anti-nutrients like phytate	Cheah et al. (35)
Hungary	Iodine	Green bean and lettuce	Lettuce biofortified with up to 0.50 mg L^{-1} of iodine stimulated (20–260%) uptake of P, Mg, Mn, Fe, Cu, Zn, and B but the same response was not found for green bean	Dobosy et al. (43)
Germany	Iodine	Strawberry (*Fragaria* × *ananassa*)	Foliar fertilization of up to 7.5 kg iodine ha^{-1} accumulated iodine in fruits compared to soil application	Budke et al. (39)

(Continued)

TABLE 1 | Continued

Country/region	Applied nutrient/item	Target crop(s)	Important findings	References
China	Selenium	Crop foods	Use of PGPRs and mycorrhizal fungi improved Se-biofortification	Ye et al. (67)
Global study	Multi- nutrients	Staple crops	Transgenic technology is an effective tool for multiple biofortification traits such as high provitamin A or folate, high Fe and Zn in most varieties of biofortified crops	Van Der Straeten et al. (68)
Iran	Se and S	Garlic (*Allium sativum* L.)	Up to 40 mg kg^{-1} S and 30 mg kg^{-1} Se improved bioactive compounds, mineral content, and antioxidative capacity	Sohrabi et al. (69)

PGPRs, plant growth-promoting rhizobacteria; AM, arbuscular mycorrhiza.

CHALLENGES TO BIOFORTIFICATION UNDER THE COVID-19 OUTBREAK

The current global pandemic has caused challenges such as indirect effects on soil quality (98), including negative effects on nutrient balances in soil (22). Food production is a major challenge with a pandemic sweeping the world, and food insecurity increased around the world. For example, it was recently estimated that COVID-19 is significantly aggravating already existing food insecurity in the U.S., with more than 54 million people being food insecure after COVID-19 (87).

Food insecurity is strongly related to soil health and nutrient budgets in the soil. The instant negative impact of the COVID-19 pandemic on food security and food supply systems, particularly in developing countries, has been widely reported [e.g., (21, 89)]. This impact included several obstacles that restricted the movement of goods and people between and within countries, which prevented access to markets, particularly in the agricultural sector (99). The future may include decreases in global food demand, a large loss in markets and employment, and growing concerns about international cooperation due to COVID-19 (100). Therefore, all countries need strategies to protect food and nutrition security, particularly for their poor, by focusing on the prioritization of diversification for production and markets (89). The mitigation strategies for COVID-19 as a global risk should also be linked with climate change, because both climate change and COVID-19 have rapidly expanded to all areas of the world (101) and they create some similar problems.

Many open questions need to be answered to provide sustainable biofortification under COVID-19. These include: (1) how can the world overcome the expected crises in global food security, trade, the economy, sustainable development, food waste management, agricultural production, and climate change? (2) How can countries fight malnutrition and food insecurity, particularly under the food production and distribution crisis during and post-COVID-19? (3) How can countries build resilient food systems amidst COVID-19? (4) To what extent we can depend on potential inhibitors (baricitinib, chloroquine, dexamethasone, favipiravir, fedratinib, remdesivir, vaccination, biofortification etc.) to manage COVID-19? (5) Can biofortification practices be effectively implemented in the global agricultural economy given the challenges presented by COVID-19?

CONCLUSIONS

There is no denying that COVID-19 is one of the most challenging pandemics to face humanity in the modern era. As common natural phenomena, a number of viruses are able to transfer between animals, plants, humans, and environmental compartments such as water or soil. It is important that we understand these dynamics, and the frequency of disease epidemics and pandemics has been increasing (19). The COVID-19 pandemic affected virtually all our life spheres, including the health, education, economic, political, and agricultural sectors. Several public health safety measures were implemented to restrict SARS-CoV-2 transmission, such as regular hand washing, social distancing, border closures, and restricted internal movements and lockdowns. However, the contributions that agriculture and soils might make to address the COVID-19 pandemic were rarely raised in the public discourse. Human immunity depends on nutritional status, which in turn is largely dependent on foods consumed, the nutrients they derived from soil, and a lack of pollutants in that soil. Biofortified crops that produce foods rich in functional food components can help improve general health, boost the immune system, and consequently might be useful in preventing COVID-19 transmission or improving outcomes for those who contract COVID-19. Due to the current disruptions in supply chains and demand on foods, the impacts of COVID-19 may provide the scientific community an opportunity to focus on agricultural innovations, including the development and delivery of biofortified crops and improving the transfer of nutrients from soil to crop. This represents one way that the agricultural and soil communities can assist with the current COVID-19 crisis and prepare food systems for future crises. However, several questions remain, such as what are the expected environmental impacts of COVID-19 on soil? Can SARS-CoV-2 be transmitted through soil, and under what conditions? Which soil processes and properties influence SARS-CoV-2 survival rates and times, as well as transmission? What are the specific links between soil health and COVID-19? What are the projected soil management scenarios in response to COVID-19? Questions such as these deserve more attention as the world seeks to recover from its most recent pandemic. These questions are critical to understanding soil and human health connections in the post-COVID-19 world.

AUTHOR CONTRIBUTIONS

HE-R: writing of original draft and supervision. All authors: conceptualization, methods, writing review, editing, and approval of submitted version.

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