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Discussion

Pandemic COVID-19 ends but soil pollution increases: Impacts and a new approach for risk assessment

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ABSTRACT

For three years, a large amount of manufactured pollutants such as plastics, antibiotics and disinfectants has been released into the environment due to COVID-19. The accumulation of these pollutants in the environment has exacerbated the damage to the soil system. However, since the epidemic outbreak, the focus of researchers and public attention has consistently been on human health. It is noteworthy that studies conducted in conjunction with soil pollution and COVID-19 represent only 4 % of all COVID-19 studies. In order to enhance researchers' and the public awareness of the seriousness on the COVID-19 derived soil pollution, we propose the viewpoint that "*pandemic COVID-19 ends but soil pollution increases*" and recommend a whole-cell biosensor based new method to assess the environmental risk of COVID-19 derived pollutants. This approach is expected to provide a new way for environmental risk assessment of soils affected by contaminants produced from the pandemic.

1. Introduction

In the past three years, the whole world has been strongly affected by the outbreak of COVID-19 with severe economic and humanitarian cost (Ciotti et al., 2019, 2020; Goudoudaki et al., 2023; Sadiqa, 2023). The pandemic-induced damages include not only the decline of the global economy, but also a global death toll of 6,790,506 human reached by 18 February 2023 (Worldometer, 2023). The global economic damages and death numbers are tremendous, but a serious attention should have also been paid to the environmental pollution as a result of COVID-19 control measures (Khan and Imran, 2023; Nguyen et al., 2023). Globally, massive amounts of discarded masks, medical protection products, pharmaceuticals, disinfectants, and hand sanitizers have entered into the environment, which aroused an unprecedented pressure on the environment (Lal et al., 2020; Ekanayake et al., 2023; Idowu et al., 2023; Nanehkaran et al., 2023; Ren et al., 2022). In addition, more people are ordering food online due to the lifting of restrictions and the temporary closure of restaurants, which has also led to a significant increase in the use of plastic packaging materials (Fronde, 2021). Soil is a major sink for pollutants, and thus soil pollution by the pandemic-induced (in)organic wastes is expected to be increased in the years after the pandemic has subsided and it is likely that a large portion of these pollutants may persist for long periods of time in the environment (Farnese, 2022).

Scientific research on the effects of COVID-19 on human health and environmental pollution increased in the past three years (Fig. S1). As shown in Fig. S1A, when searching "COVID-19" as a keyword in the web of science database, the results were mainly research works focusing on human health. Among environmental pollutants, air pollution and plastic pollution were the main focus and results when search was set to "COVID-19" and "pollution" keywords (Fig. S1B). It is noteworthy that the number of

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articles retrieved by using the keywords of "COVID-19" and "soil pollution" accounted for 4 % only of those articles retrieved by searching with the keyword of "COVID-19", which further proves the neglection of the impact of COVID-19 control measures on soil pollution. In addition, the decrease of published articles on COVID-19 (Fig. S1C) in 2022 compared to 2021, and the consequent impact soil pollution indicates a shift in the public attention (Fig. S1E). However, the pandemic-induced pollutants that entered into the soil system will not disappear with the end of the pandemic, particularly with the decrease in the public attention, as these pollutants may persist and endanger soil ecosystem and human health. In view of this situation, there is an urgent need for relevant articles to summarize the soil pollution problems caused by COVID-19, so as to guide researchers to conduct relevant studies. Therefore, we aim to increase the awareness concerning the side impacts of COVID-19 on soil pollution by discussing the types and sources of pandemic-induced pollutants, which may have entered into soils and assessing the potential associated risks using new approaches mainly based on the potential use of whole-cell biosensors.

2. Sources, types, and impacts of COVID-19 derived pollutants in soils

Soil pollution derived from COVID-19 control measures mainly originates from the discard of various protective products and/or chemicals release during the pandemic. These include masks (made of materials such as polypropylene, polyester, vinyl strips with acrylic adhesive; Patrício Silva et al., 2021), medical gloves (rubber, chloroethene polymers, neoprene, and vinyl; Benson et al., 2021), disposable plastic gowns, disinfectants (quaternary ammonium compounds, hydrogen peroxide, bleach and alcohols; Dewey et al., 2022), hand sanitizers (povidone-iodine, benzalkonium chloride, triclocarban and ethanol; Marumure et al., 2022) and pharmaceuticals (arbidol, chloroquine phosphate, hydroxychloroquine sulfate, and acyclovir; Mohamed et al., 2022). These pollutants can be classified into solid particulate pollutants (microplastics, rubber particles) and novel entities (disinfectants, hand sanitizers and pharmaceuticals), which belongs to one of nine planetary boundaries and has not been quantified (Steffen et al., 2015). As described by a paper published in *Science*, the environment is under unprecedented pressure from artificial chemicals (Wang et al., 2021b).

Globally, the estimated amount of face masks discarded from each continent and plastic waste generated per day was 1.6 million tons (Fig. 1; Benson et al., 2021). The main solid contaminants arising from protective products are plastic particles, which enter the soil environment through improper disposal (Al-Tohamy et al., 2023). For example, the decomposition of masks, medical gloves and protective clothing produces micro- and/or nano-sized plastic particles (Xu et al., 2020). The release of these plastic particles into soil system may alter soil pH, electrical conductivity, organic matter and nutrient effectiveness, affecting soil structural composition and capacity (Chia et al., 2021; de Souza Machado et al., 2019; He et al., 2023; Wang et al., 2022). These changes also pose (in)direct effects on soil microbial community (bacteria, fungi, protozoa and other organisms; Liang et al., 2019; Yang et al., 2018), further affecting the whole soil ecosystem. In addition, microplastics can absorb other contaminants such as heavy metals and organic pollutants in soil, creating a secondary contamination problem, and thus a complex contamination situation in soil (Wang et al., 2021a). The pandemic-induced soil pollution through microplastics is alarming as there is still no standard separation method of microplastics from the soil matrix and their measurement is still far from being standardized (Ekanayake et al., 2023; Idowu et al., 2023). Even the status itself of soil microplastics contamination and the level of risk microplastics pose to soil and plants are rather unclear. However, it is well established that microplastics induce health damage to organisms higher in the food chain, including humans, although the exact effects and mechanisms are yet to be fully elucidated.

Liquid COVID-19 derived pollutants, such as disinfectants, hand sanitizers, and pharmaceuticals, could enter into the soil system through direct spraying and/or application of contaminated municipal sewage. During the COVID-19, disinfectants were widely used as a control measure; for example, 2000 tons of disinfectants were estimated to have been used in Wuhan City alone, according to the data reported in April 2020 by Guo et al. (2021). According to United States Environmental Protection Agency (U.S. EPA) report, there are 545 products that have been used as disinfectants for COVID-19 control, among which quaternary ammonium compounds (QACs) accounted for 1/2 of all the products (Bureš, 2019; Dewey et al., 2022). Being cationic surfactants, QACs can be strongly adsorbed by soil (DeLeo et al., 2020) and induce damage to soil and plant growth. These damages include degradation of soil fertility, reducing seed germination and relative growth rate (Agnelo et al., 2020), damaging plant root microbial populations, thus, inhibiting plant root and shoot growth (Parveen et al., 2022), and reducing plant water uptake when soil contains

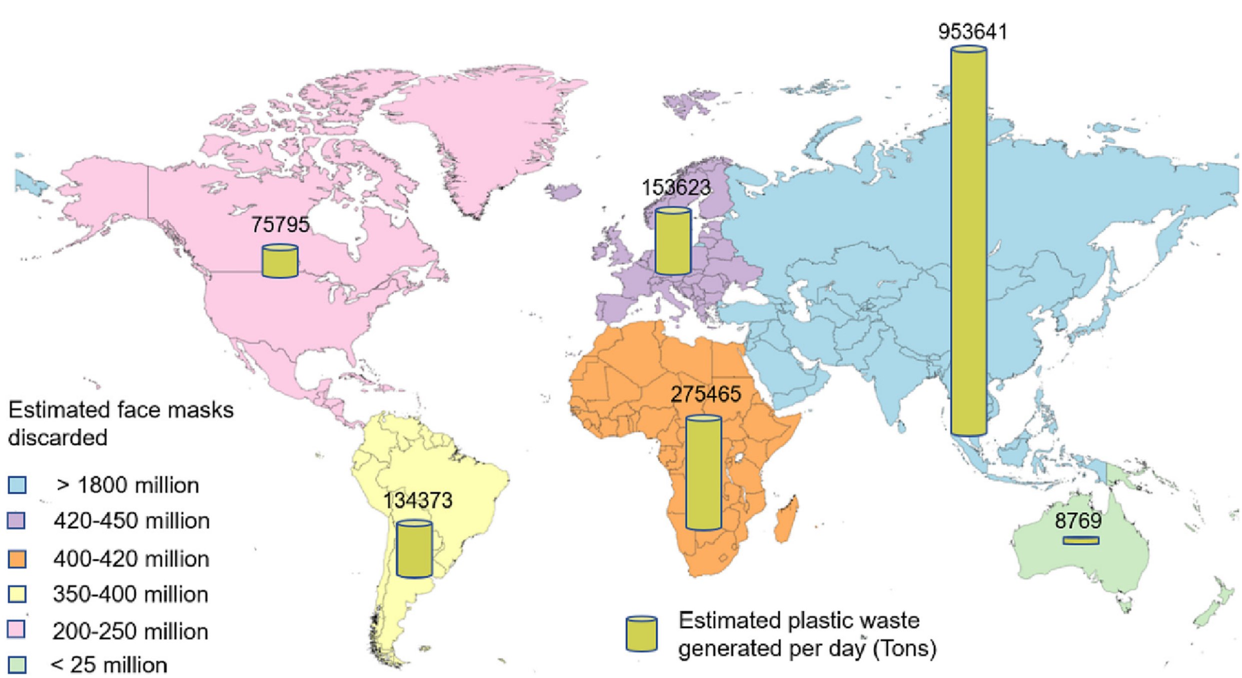

Fig. 1. Estimated global share of face masks discarded and plastic waste generated per day (tons) from each continent (adapted from Benson et al., 2021).

disinfectants at high concentrations (Parveen et al., 2022). These compounds can enter into animal and human bodies though soil and plant and provoke adverse effects on the mucosal lining of the respiratory system, resulting in inflammation, irritation, swelling, or ulcer (Dhama et al., 2021). In addition, other disinfectants like alcohols and hydrogen peroxide have also been used for their oxidative nature and capacity to target intracellular components, it is crucial to study their effects on soil quality when excessively used.

Hand sanitizers have been recommended by The World Health Organization since the early stages of the COVID-19 outbreak, and this inevitably led to their excessive use during the past three years. For example, in comparison to the usual need of 1200 tons of hand sanitizers, an increase in hand sanitizer demand of up to 3000 tons has been reported in Pakistan (Butt et al., 2022). Likewise, in Italy, hand sanitizer sales at supermarkets increased by 561 % in the first three weeks of the pandemic (Berardi et al., 2020). This significant increase has also occurred in other countries around the world. Alcohol-based hand sanitizers like ethanol and isopropyl alcohol may harm living microorganisms (Dhama et al., 2021). Studies showed that as a hand sanitizer, chloroxylenol may cause changes in the structural composition of soil microbial communities (Capkin et al., 2017; Sreevidya et al., 2018). Therefore, it is critical to study the impact of hand sanitizers on the health of the soil environment.

A large number and amount of pharmaceuticals have been applied to target viral infections and related diseases over the past three years. It has been reported that the pharmaceutical sales in the United States reached over 530 billion in 2020, with an overall increase of 8 % over the same amount in 2019 (Statista, 2022). In the treatment of COVID-19 and consequences, a large number of antibiotics were used, which further pose enormous pressure on the environment. Antibiotics as soil pollutants require great attention as they can cause growth inhibition and biomass reduction of crops, including inhibition of stem, root and shoot growth (Gomes et al., 2017; Zainab et al., 2020), depression of plant hypocotyls, cotyledons, leaf number and length (Eggen et al., 2011). Antibiotics can also affect microorganisms activity in soil and disrupt their functions and structure. For instance, tetracycline can affect negatively the activity of urease, acid phosphatase and dehydrogenase in soil (Wei et al., 2009). Also, chlortetracycline, tylosin, sulfamethoxazole and sulfamethoxazole could inhibit the activity of soil phosphatase (Cycoń et al., 2019). Moreover, these antibiotics may persist for a long period of time and induce antibiotic resistance genes in soils (Girardi et al., 2011), which may enter into the human body through food thereby increasing the resistance of human body to specific drugs (Zainab et al., 2020). However, so far, there are no control measures for the above-mentioned emerging pollutants. The detection and risk assessment standards for these pollutants are also not uniform, which poses a challenge for managing soil pollution problems caused by emerging pollutants. Therefore, more research on the management of soil contamination by emerging pollutants should be conducted in the future.

3. A new approach for assessing the risk of soil pollution by pollutants derived from COVID-19

The bioavailability and bio-toxicity of pollutants in soils are the main parameters that determine their environmental risk, which can be influenced by various soil factors, like soil pH, redox potential, dissolved organic carbon, microbial community and activities (Chien et al., 2018; Wang et al., 2020). Moreover, plant root secretions can also impact the pollutants mobility and transformation in soil and also uptake by, and translocation into, plants (Lu et al., 2017). However, research on the risk of COVID-19 related pollutants entering soils is still lacking; therefore, it is urgent to assess the environmental risk and enact reasonable management for different COVID-19 derived pollutants. For instance, for the environmental risk assessment of plastics in soil, most research works have focused on the toxicological effect of plastics on different target organisms in laboratory trials, especially of microplastics with concentrations far exceeding environmental background. Therefore, these studies do not accurately predict the environmental risk of microplastics in soil. In contrast, toxicological studies on emerging pollutants, such as plastic additives and antibiotics, are relatively well established, but toxicological experiments are usually time-consuming and complex, which requires certain level of technology and professionalism.

In recent years, there has been a growing interest in the use of whole-cell biosensors to assess the bioavailability and toxicity of contaminants in the environment (Zhang et al., 2020; Zhang et al., 2022; Zhu et al., 2022), which promises a streamlined approach for environmental risk assessment. Whole-cell biosensors are genetically modified prokaryotic or eukaryotic cells that function as sensor for hazardous substances and environmental pollutants (Li et al., 2022; Zhang et al., 2017). Whole-cell biosensors can be divided into three categories depending on the constitutive principle (Fig. 2). Biosensors that give a dose-dependent signal based on the bioavailability of a specific pollutant are called Class I biosensors, those that output a signal based on the stress caused by pollutants are called Class II biosensors, and those that exhibit a non-specific reduction in signal output due to the toxicity of a pollutant are called Class III biosensors (Fig. 2, Zhang et al., 2021; Zhu et al., 2022).

Previous studies have shown that these three types of biosensors have been successfully used to detect different organic pollutants such as antibiotics (Aga et al., 2016) and hydrogen peroxide (Rogers, 2006) in the environment. In addition, whole-cell biosensors have been recommended as approaches for evaluating toxicity of microplastic and their breakdown products (Lv et al., 2022). Compared to traditional toxicology experiments, whole-cell biosensor technology is simple, cheap and fast; therefore, it may provide new ideas for future soil pollution risk assessment, such as that from the COVID-19 derived soil pollutants. For example, tetracycline, a drug component commonly used in the clinical management of COVID-19, can be accurately and rapidly detected in soil by whole-cell biosensor with detection limits of 5.21–35.3 μg/kg (Ma et al., 2020b). In contrast, typical high-performance liquid chromatography (HPLC) method requires 7 times longer analysis time and higher cost (Ma et al., 2020a). In addition, the whole-cell biosensor for the detection of acrylic acid, a plastic monomer, in water has been developed (Meyer et al., 2019), while further studies have shown that the whole-cell biosensor can screen for acrylic acid monomers from polyacrylic acid in water body (Puhakka and Santala, 2022).

However, contaminated soil is one of the most difficult matrices for quantifying hazardous chemicals (van der Meer and Belkin, 2010). There are currently no uniform standards in most countries, which can be a limitation to the commercialization of whole-cell biosensors. Since contaminants in soil systems are often complex, the construction of whole-cell biosensors for simultaneous detection of multiple contaminants maybe a research direction in the future.

4. Conclusions

The threat posed by COVID-19 to human health is gradually diminishing, and so is the public concern about it. However, the effect of the contaminants produced and deposited into soil during the pandemic, due to the unpreceded use of protective substances (all of which may be identified as contaminants of emerging concern for soil), is not an issue that will disappear any time soon, and the subsequent soil pollution caused will likely be of primary scientific concern over a long period of many decades. Currently, there is a lack of relevant studies and reports on the effects of COVID-19 derived pollutants on soil. Pollutants in soil will continue to put a threat to ecosystem services and ultimately to human health. We anticipate that governments and environmental protection agencies will realize, through this paper, the seriousness of COVID-19 derived soil contamination. In turn, effective environmental risk assessment and soil contamination remediation studies should be carried out as COVID-19 subsides, due to the fact that soil pollution problems induced by it will sadly not disappear.

CRediT author contributions statement

Xiaokai Zhang: Conceptualization, Data extractions, Writing–original draft, Writing–review & editing; **Mengyuan Jiang**: Methodology,

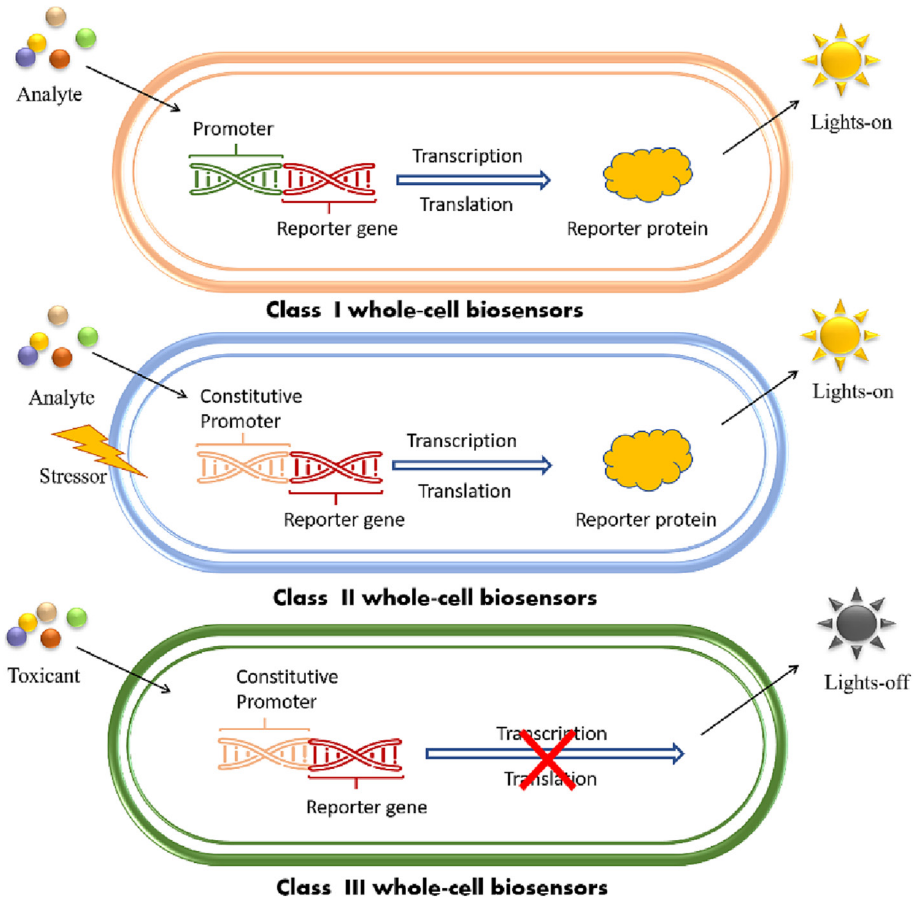

Fig. 2. Response mechanisms of different types of whole-cell biosensors to pollutants/stressors, and toxicants.

Visualization, Data extractions, Writing- reviewing and editing; **Lizhi He**: Writing-review, editing; **Nabeel Khan Niazi**: Writing-review & editing; **Meththika Vithanage**: Writing-review & editing; **Boling Li**: Writing-review & editing; **Jie Wang**: Writing-review & editing; **Hamada Abdelrahman**: Writing-review & editing; **Vasileios Antoniadis**: Writing-review & editing; **Jörg Rinklebe**: Writing-review & editing; **Zhenyu Wang**: Supervision, Project acquisition, Writing-review & editing; **Sabry M. Shaheen**: Supervision, Writing-review & editing.

Data availability

Data will be made available on request.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164070.

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