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Perspective

SARS-CoV-2 in Soil: A Microbial Perspective

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Abstract: SARS-CoV-2 has been found in soil and aquatic environments in addition to aerosols. SARS-CoV-2 enters the soil from various sources, including organic amendments and waste irrigation water. The virus counts and virulence in soil depend on spillover routes and soil properties. Organic matter (OM) and clay minerals protect and enable SARS-CoV-2 to survive for longer periods in soil. Therefore, life forms residing in soil may be at risk, but there is a paucity of scientific interest in such interactions. With this perspective, we aim to provide a new viewpoint on the effects of SARS-CoV-2 on soil microbes. In particular, we present a conceptual model showing how successive mutations within soil animals having the SARS-CoV-2 receptor angiotensin-converting enzyme 2 (ACE2) may change its characteristics and, thus, enable it to infect micro- and macroorganisms and be transferred by them. SARS-CoV-2 particles could be adsorbed on mineral or OM surfaces, and these surfaces could serve as encounter sites for infectious attacks. SARS-CoV-2 accumulation in soil over time can perturb bacteria and other microbes, leading to imbalances in microbial diversity and activities. Thus, SARS-CoV-2 and its interactions with biotic and abiotic soil components should be a future research priority.

Keywords: microbes; soil organic matter; microbial activities; SARS-CoV-2; virus infection

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Citation: Iqbal, S.; Xu, J.; Khan, S.; Nadir, S.; Kuzyakov, Y. SARS-CoV-2 in Soil: A Microbial Perspective. *Challenges* **2022**, *13*, 52. https://doi.org/10.3390/challe13020052

Academic Editor: Susan Prescott

Received: 2 July 2022
Accepted: 18 October 2022
Published: 21 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Since March 2020, human civilization has grappled with the COVID-19 pandemic. At the time of writing (13 September 2022), 6.5 million deaths and 610 million cases of infection have been reported worldwide (WHO)—these are almost certainly underestimations, given uneven testing and reporting procedures across countries. The COVID-19 pandemic was caused by the virus SARS-CoV-2, which is generally transmitted via droplets and aerosols. SARS-CoV-2 has recently been found in other environmental compartments, such as soils and waters [1,2]. Most virus particles enter urban and peri-urban soils (parks, playgrounds, etc.), threatening to re-infect human populations.

SARS-CoV-2 in soils could span quite a range in terms of number of RNA copies, depending upon spillover routes. For instance, SARS-CoV-2 content in soils near hospitals and wastewater ranged between 205–550 RNA copies g^{-1}, which is largely a result of patient respiratory droplets and aerosols from wastewater, respectively [2,3]. Additionally, SARS-CoV-2 can survive for prolonged periods (>10 weeks) in soil (with 10% moisture content) compared to other environments (40 days in wastewater) due to the absence of sanitization and presence of organic matter (OM) that protects and shields viruses [2–5].

In contrast, other viruses, e.g., avian influenza (H5N1) could not maintain a viral load in sandy soils [6]. Thus, the spread of SARS-CoV-2 to 226 countries, alongside the continuous emergence of new variants such as Omicron, Alpha, Beta, Delta, etc., mount serious challenges for both soil ecology and public health. Above all, the higher environmental stability of these variants, especially Omicron, compared to original strain of SARS-CoV-2 could present new challenges [7].

Soil amendments tainted by sewage sludge (receiving stool with 8×10^9–7.5×10^{10} virus copies g^{-1}), irrigation with wastewater (1.03×10^2–1.31×10^4 virus copies mL^{-1}), and incorrect disposal of urban, rural, and hospital wastes (can supply 5.6×10^7–1.13×10^{10} virus genomes infected person^{-1} d^{-1}) are all major routes by which SARS-CoV-2 could enter soils [8]. This type of nonpoint source viral loading gives rise to a new set of issues because: (1) there is a continuum and frequent interplay between soil and contaminated matrices, which may result in the omnipresence of SARS-CoV-2 in soils and, eventually, competition for microbial niches, which would possibly be deleterious to beneficial bacteria; (2) given a high load of SARS-CoV-2 from contaminated inputs, equilibrium of soil microbiota may be susceptible to change in a short period, affecting deliverance of key services; and (3) SARS-CoV-2 can survive by using its hydrophobic envelope to engage in adsorption onto clay minerals, iron (hydr)oxides, and organic matter, subsequently posing ecological risks to microbes and animals. These phenomena may seriously jeopardize soil ecosystems worldwide, yet the scientific community has been slow to acknowledge potential interactions between SARS-CoV-2 and soils. Although some recent studies draw attention to the microbial effects of SARS-CoV-2, relevant empirical evidence is still very scarce [9,10]. Separation between environmental compartments, unidentified loading sources, accumulation in soils compared to air or water, and non-standardized monitoring and detection methods for soil (unlike water [11,12]) explain this lag. Nonetheless, the paucity of our discipline's interest in SARS-CoV-2 and soil interactions is surprising, given that the occurrence of viruses in soil itself is not a new phenomenon [11].

2. SARS-CoV-2: A New Challenge for Soil Ecosystems

Plant–virus interactions have long since been an established research topic in plant pathology, physiology, and other related fields. Recent reports have highlighted that viruses can also be problematic for soil-dwelling microbes, particularly bacteria [13]. This raises the question: is the loading of SARS-CoV-2 and its mutants a hidden threat for bacteria or fungi? Through mutation and recombination, coronaviruses acclimatize quickly to new environments, allowing them to efficiently alter host range and tissue tropism [14,15]. Recently, SARS-CoV-2 has been reported in farmed mink, and mutation resulted in the virus being identified later in both mink and humans, demonstrating its ability to switch hosts with ease for survival. In addition, SARS-CoV-2 has been identified in several other animals, such as cats, dogs, lions, tigers, etc. However, no records exist that SARS-CoV-2 has jumped the mammalian class barrier. Cross-kingdom viral infection is plausible, as some plant viruses are well reported in humans and other vertebrate. For instance, tobacco mosaic virus and pepper mild mottle virus have been detected in animal/human feces, lungs, and serum, leading to some clinical signs of fever and abnormal pain [16–20]. Plant viruses are able to replicate in insect bodies, which act as a transmission vector [21]. Likewise, SARS-CoV-2 is also able to reach other organisms, mutate, and change its characteristics within a few days of survival, and it could threaten unicellular organisms [10].

3. SARS-CoV-2 Localizations and Effects on Soil Microbial Life

Considering reported mutations in various hosts and widespread contamination from a broad range of sources, we propose a conceptual model explaining how SARS-CoV-2 could affect soil life (Figure 1). Like marine mammals, soil mammals with a similar receptor (ACE-2) are also threatened by SARS-CoV-2 spillovers, capable of becoming new hosts for viral mutations (possibly in spike proteins and genomic parts) [22,23] and further infecting soil animals or microbes. Plausibly, higher homology of ACE-2 between human and terrestrial species of Primates and Rodentia exist [23]. This can also result in the back transmission of the SARS-CoV-2 infection, along with its impacts on soil organisms, including microbes. Additionally, genetic exchanges between viruses take place in wastewater [24], which may give rise to new variants capable of infecting various life forms in soil. A positive shift in bacterial abundance has been observed, owing to viral depletion in aquatic ecosystems [25]. In soil, the reduction in bacterial abundance has been speculated in bacteriophage hotspots [26]. Thus, SARS-CoV-2 could also affect soil microbial life through other pathways—for instance, being smaller in size (60–220 nm), SARS-CoV-2 could occupy space inside the soil pores smaller than 10 µm, and eventually cause a shift in bacterial colonies there (Figure 2).

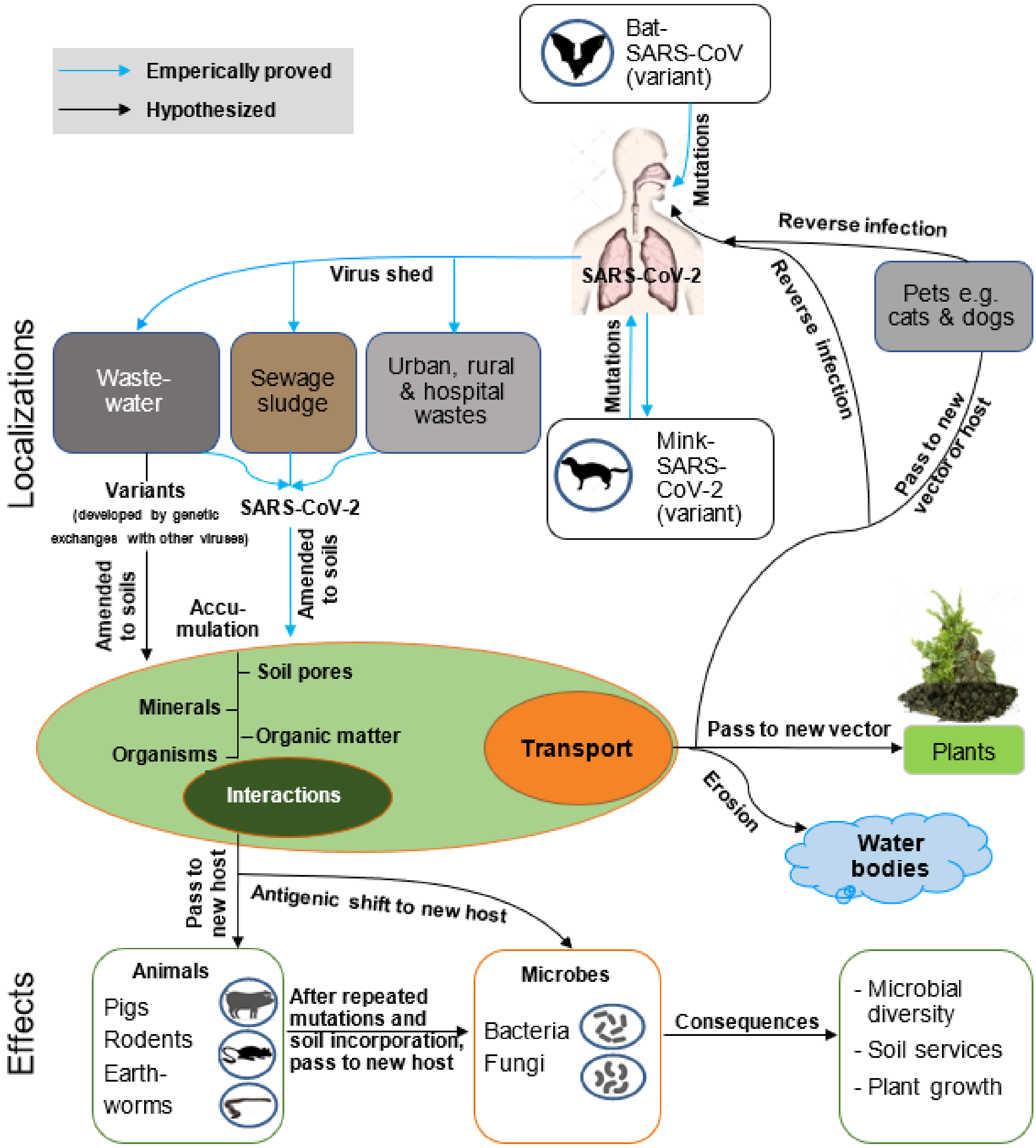

Figure 1. Conceptual model of SARS-CoV-2 entrance into soil, localization, and effects on soil life.

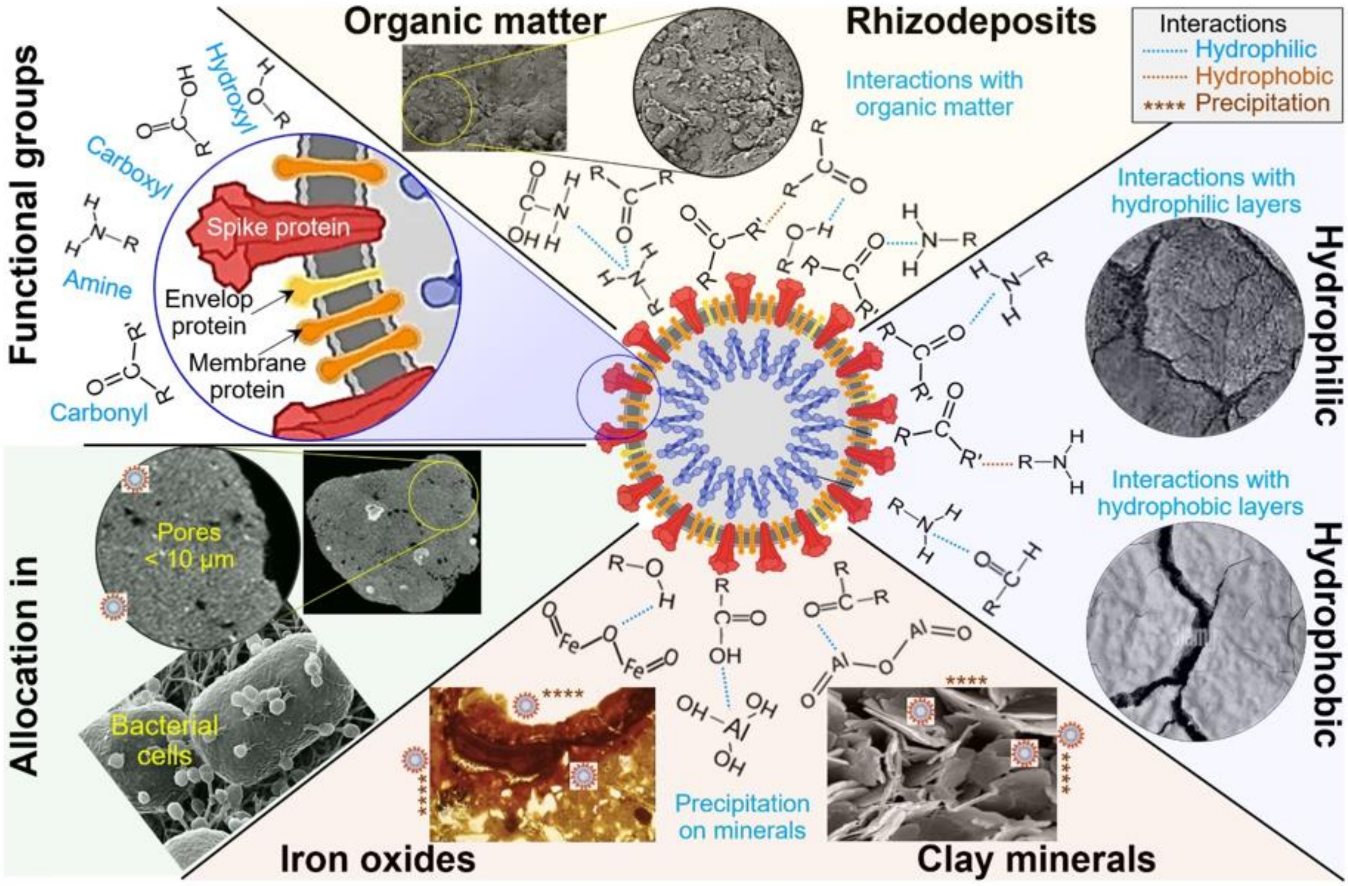

Figure 2. Adsorption of SARS-CoV-2 on soil interfaces (hydrophilic and hydrophobic), organic (organic matter and rhizodeposits) and mineral (clay minerals and iron oxides) constituents, and allocation in pores.

Phage virions are passively distributed in soils due to their smaller size and hydrophobicity, and are present across all soil compartments [13]. Phage virions adsorb on soil at a rate of 1.68×10^6–9×10^8 g^{-1} soil [27]. SARS-CoV-2 could potentially be distributed in soil compartments by passive transport with waste or manure applications, irrigation, or tillage, or adsorb on mineral or OM surfaces due to the positive charge on the SARS-CoV-2 surface (as a consequence of increased cation exchange capacity) [28]. Thus, OM and mineral surfaces can serve as sites (Figure 2) where free-living bacteria may encounter infectious viruses—a similar phenomenon (2–37% bacteria killed by virus lysis) was observed during organic particle flux in water [29]. This might be a more serious problem in the rhizosphere, where root-released rhizodeposits provide OM for virus attachment and protection. Under drought, microbial abundance commonly decreases, and viruses occupy the thin soil layer due to hydrophobic interactions. Thus, the coupling of drought and frequent SARS-CoV-2 loading could lead to exacerbated habitat degradation.

Virus particles affect microbial assembly [30], and SARS-CoV-2 accumulation over a period (resulting from frequent spilling) may perturb bacteria and other microorganisms in soils. This could imbalance microbial diversity and activities, processes and nutrient cycles. The viral load of SARS-CoV-2 could be highly maintained in alkaline soils, given that the acidic pH (<7) leads to inactivation of enveloped viruses [6]. Thus, microbial life in alkaline soils (common in (semi)arid climates) is prone to increased threat. Potentially, SARS-CoV-2 can pass to new vectors (including plants and pets) through transport with water or direct contact with soil, and, subsequently, may cause reverse infections to humans (Figure 1).

4. Conclusions

SARS-CoV-2 and its variants have appeared as new threats in various ecosystem parts, including soil. In the foreseeable future, these viruses will enter soil and likely remain there for a few days to months. SARS-CoV-2 T_{90} (time needed for 1 $\log_{10}$ unit reduction) in water bodies varies between 6–600 days [5,31–33]. SARS-CoV-2 interactions with soil life should be a research priority, with exploration into developing methods for quantifying the virus and threats to soil microorganisms, as well as measuring its persistence. Ambitious actions in such directions are required to avoid possible damage to soil micro- and macroorganisms. The degree of the challenge varies across land uses and management, as SARS-CoV-2 loads may be affected by a variety of factors, such as temperature, moisture, pH, OM, clay, and nutrient contents. Thus, the targeted research framework crucially needs to develop for soil monitoring, considering site-specific practices.

Author Contributions: Conceptualization, S.I. and Y.K.; methodology, S.I. and Y.K.; software, S.K.; resources, J.X.; data curation, S.K. and S.N.; writing—original draft preparation, S.I. and Y.K.; writing—review and editing, Y.K. and J.X.; visualization, Y.K., S.I., S.K. and S.N.; supervision, Y.K. and J.X.; funding acquisition, S.I. All authors have read and agreed to the published version of the manuscript.

Funding: Shahid Iqbal is thankful to the CAS President's International Fellowship Initiative program (Grant No. 2021PB00094) and Postdoctoral Directional Training Foundation of Yunnan for financial support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Authors are grateful to the RUDN University Strategic Academic Leadership Program and Strategic Academic Leadership Program "Priority 2030" of the Kazan Federal University.

Conflicts of Interest: The authors declare no conflict of interest.

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