TANIA
Interreg Europe

5th Interreg Call – additional activities

-oOo-

Fact finding mission

-oOo-

Fate of SARS-CoV-2 in urban soils
– *consequences for public policies* –

-oOo-

October 2022

Outline

Work was conducted by:

- **Jean Louis Morel**, coordinator, *Université de Lorraine – INRAE, Nancy, France*
- **Fabiano Pilato**, *ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale, Italia*
- **Martin Romantschuck**, *Faculty of Biological and Environmental Sciences, University of Helsinki, Finland*
- **Marie-Odile Simonnot**, *Université de Lorraine – CNRS*, Nancy, France
- **Andrea Torre**, *ASEV – Agenzia per lo Sviluppo Empolese Valdelsa, Italia*

Introduction

Urban soils perform a wide range of fundamental functions for the urban ecosystem. But they are often perceived only as the support of human activities, transport, habitat, socio-economic activities, are seen essentially through the two horizontal dimensions, and are managed as such. However, urban soil, like forest soil, agricultural soil, etc., is a three-dimensional system in which a variety of physical, chemical, and biological processes operate at the basis of many functions, such as infiltration, support for plants and other organisms, storage of elements (*e.g.,* carbon), etc., providing very important services of which biodiversity conservation and climate mitigation are among the most crucial ones (Morel *et al.*, 2014).

Urban soils have long been ignored by scientists because, not being the result of natural processes, they were not considered as soils. But over the past two decades, research has developed strongly in this area, bringing information about properties, functions, evolution, and management of urban soils. Soils in the urban ecosystem provide a large range of ecosystem services, and as such play an essential role, on the one hand, because of the increase in the urban population and, on the other hand, because of the many challenges to be met linked to global changes, such as global warming, the collapse of the biodiversity, the increase in violent climatic episodes and, more recently, pandemics.

Soils are generally the receptacle of a wide variety of solid and liquid substances, introduced voluntarily or involuntarily. A large array of persistent pollutants can accumulate in urban soils, whether organic (*e.g.,* PAHs, PCBs) or inorganic (*e.g.,* metals), whose chemical state and fate in the urban environment are significantly altered (*e.g.,* immobilization, degradation, soil-plant transfer, volatilization, transport to groundwater, etc.). Urban soils also receive numerous pathogens, such as bacteria, fungal spores and viruses, the fate of which remaining rather uncertain, *e.g.,* transport in and out of soil, inactivation. In the case of particularly dangerous viruses, such as severe acute respiratory syndrome coronavirus 2 (SARS-Cov-2), it is necessary to understand their fate in soils and whether they can reach people from the ground with which they are in contact in the city and draw the best decisions to be taken by the authorities to minimize risk.

Viruses are like electrically charged particles and, therefore, are likely to be subject to processes close to those described for pollutants. Their fate in soils has been studied for a long time, particularly in the context of knowledge of the risks associated with the use of wastewater for irrigation. On the other hand, in the case of the new virus, SARS-CoV-2, data remains scarce, one reason being the need for long-term and large-scale experiments. Understanding the fate of viruses such as SARS-CoV-2 in urban soils requires knowing the processes and mechanisms that lead to its presence in soils, those that preside over its inactivation, its transport in the soil profile, the emission of virus-carrying aerosol particles, and finally the impact of soil prescription and management measures in urban areas on the environmental characteristics, the soil and its functioning, groundwater, and surface water.

The aim of this report is not to produce a comprehensive review of the literature on the fate of SARS-CoV-2 in soils and, more generally, of analogous viruses, but to shed some light on the main processes that control the fate of the virus in urban soils to contribute to the understanding of the whole phenomena and bring information about risk assessment. It is based on the analysis of the existing literature, the most recent when available, from which the important information is extracted and reported, then used as a basis for the development of a research strategy intended to better understand the processes and mechanisms. It is aimed also to propose practical recommendations for public policies for appropriate management of urban soils in the context of a pandemic or, more generally, for reducing the risks of contamination of citizens by pathogens from urban soils.

The report is organized in three parts, I) literature review on SARS-CoV-2 behavior and fate in urban soils, II) recommendations for research actions, and III) recommendations to policy makers to minimize the risk of virus spread from urban soils.

I. Fate of SARS-CoV-2 and other analogous viruses in urban soils

The literature review was intended to shed some light on the current knowledge regarding the fate of viruses in urban soils, focusing primarily on SARS-CoV-2 and, when information was not available, on analogous viruses, such as rotaviruses and noroviruses, which have similar behaviors in the environment. The urban soil as a sink and source of viruses likely to be transmitted to populations is the central question that has been studied.

The aim was to provide enough data to develop a first survey of the future of SARS-CoV-2 in urban soils and to identify recommendations that could be proposed to public policies. Consequently, this review of the literature is not intended to be comprehensive but essentially exploratory, to make it possible to make an initial diagnosis of the introduction, transport, and inactivation/persistence of the virus in urban soils and the risks that this could generate in terms of transmission to urban populations. It also identifies knowledge gaps and research needs on this subject.

The literature review was structured in six complementary items.

1) identification of the sources and characteristics of the viruses that can be found in urban soils, considering SARS-CoV-2 and similar viruses for which the information is more complete than for the novel coronavirus.
2) synthesis of the knowledge on urban soils by emphasizing their particularities (composition, properties, functions) compared to natural soils and by showing their fundamental role in the functioning of the urban ecosystem, through the services they provide to citizens.
3) description of the processes and mechanisms of virus immobilization and inactivation in soils.
4) description of the processes of virus transport in soils and to characterize the potential fluxes of viruses within urban soil profiles towards aquatic targets.
5) characterization of the potential of urban soils as a source of viruses for the air and conditions for the transport of viral particles.
6) Identification of the impacts of urban soil management methods, healthy or polluted, on virus transmission and soil functions.

For each of these six points, a summary of three to five pages is given, and when possible, with illustrations chosen to provide a synthetic presentation of the information available. Emphasis is placed on the state of the art, scientific questions, and obstacles to be studied, actions and recommendations for public policies and socio-economic actors.

1. Sources and characteristics of viruses contaminating urban soils

Andrea Torre & Fabiano Pilato

Since the first report in December 2019, the novel coronavirus (SARS-CoV-2) has spread to practically every corner of the planet, infecting over 500 million people, and killing more than six million. Evidence suggests that the virus is largely transmitted by respiratory droplets and contact pathways, while airborne carriers such as atmospheric particles and aerosols have also been identified as major vectors of SARS-CoV-2 in the environment.

a) Sources of viruses contaminating urban soils

A wide range of human activities can transmit pathogenic viruses to the environment and so to urban soils as well. This polluted matrix can play a significant role in the spread of pathogenic viruses in the environment, posing a potential public health. However, when compared to other environmental compartments, the interactions between pathogenic viruses and the soil matrix have received less attention by the scientific community. Understanding the presence of viruses, their persistence, and fate in solid and liquid matrices such as soil and wastewater is critical for successful infection management.

The soil could be a viral sink acting as a secondary source for the spread of SARS-CoV-2 over an extended period (Zhang *et al.*, 2020), likely due to inappropriate sanitization actions that can allow soil contamination by viruses (Foladori *et al.*, 2020). In addition, the detection of a not negligible viral load of the human excrements has increased the concerns regarding the potential spread of SARS-CoV-2 through the soil and other environmental compartments within the ecosystems *(e.g.,* plant, animal, groundwater) (Patel *et al.*, 2020).

Sewage and human excreta have long been recognized as possible pathways for human disease transmission. The culprit responsible for the COVID-19 pandemic, SARS-CoV-2, has been found in human faeces and urine, where it may survive for days and infect humans. Metropolitan flooding, a regular summer danger produced by heavy rains, is commonly recorded in urban neighbourhoods, as are sewage overflows. With urban floods and the frequently accompanying sewage overflows might endanger past mitigation measures by creating new risks of viral transmission in impacted areas and towns. To reduce the hazards of disease transmission via sewage overflows during epidemics, local communities might prioritize wastewater infrastructure upgrades and investigate combined sewer separations (Figure 1; Han and He, 2021).

Figure 1. Combined sewer overflows from manholes during an urban flooding event in China (Han and He, 2021)

Another obvious potential source of SARS-CoV-2 is the municipal solid waste, where the workforce, from the collection to the unloading station, are particularly exposed if the virus remains infectious.

Additionally, inappropriate disposal of municipal and hospital waste, such as protective equipment designed to prevent the virus, such as gloves and face masks, can be a source of interaction between the earth and SARS-CoV-2 (Iyer *et al.*, 2021; Rahman *et al.*, 2020; Zand and Heir, 2020). The composition of these devices, like other waste, leads to consider another subject that has been very popular in recent years, microplastics. As we know, plastics compared to other types of materials are much more resistant when they are exposed to environmental conditions, so they can persist for a long time in the environment. The degradation of microplastics increases the surface area of the particles and so does their ability to absorb and adsorb pollutants in their pathway from human use to the environment. Thus, not only a wide range of viruses and other pathogens, but also POP persistent organic pollutants such as PAHs, PCBs, OCPs and PAHs can end up in various environmental matrices such as wastewater and then urban soils (Figure 2).

It is important to remember that wastewater may be utilized for secondary purposes such as field irrigation, and that sewage sludge from wastewater treatment facilities can be used as fertilizer in agricultural operations (Lamastra *et al.*, 2018; Martínez Puchol *et al.*, 2020). Because SARS-CoV-2 was discovered and proved to be present in these matrices, this sort of action might allow the virus to migrate from wastewater and/or sewage sludge to the ground (Balboa *et al.*, 2020; Nunez Delgado, 2020a).

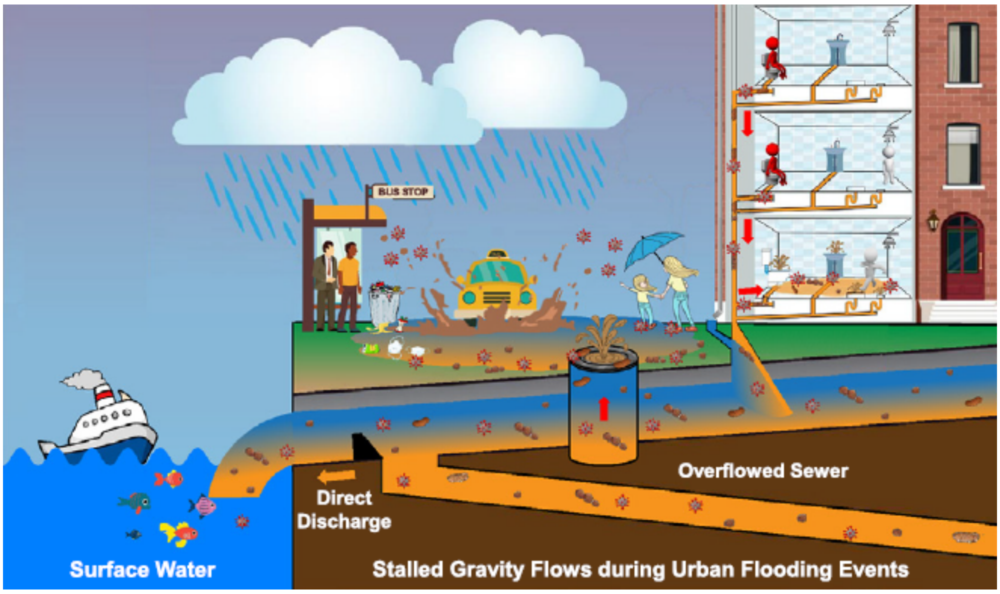


Figure 2. Potential routes for the transmission of human pathogens in the environment (Han and He, 2021)

b) Characteristics of viruses contaminating urban soils

Viruses are notably abundant in various soils and are characterized by exhibiting more limited variability compared to host bacteria in the function of environmental circumstances. When they are found in soils, they can impact economy and production likely due to an infectious cycle that helps the gene transformation process (Breitbart and Rohwer, 2005; Jain, 2003; Jones *et al.*, 2007).

Individually, a virus is not able to absorb and save energy, or even enabled out of their host target. Hence, a virus is not considered as an independent living organism in biology but as an infectious agent encompassed by a protein capsid and is distinguished by internal and relational characteristics (Regenmortel, 2000). Viruses that contaminate urban soils can be either enveloped or non-enveloped viruses. This difference is given by their DNA, structure, replication, pathogenicity, and persistence (Wigginton and Boehm, 2020). Thus, this element can be crucial in determining the interactions (*e.g.,* hydrophobic) that can allow enveloped viruses such as SARS-CoV-2 to be adsorbed onto solid particles.

According to Gutierrez and Buchy (2012), avian influenza (H5N1) could not sustain the viral load in sandy topsoil but could in soil-based compost, demonstrating that differing soil qualities significantly impact the survival of the virus. The viral load of encapsulated viruses such as SARS-CoV-2 might be sustained in the soil environment for an extended period depending on several parameters such as temperature, moisture content, pH, OM, solar exposure, and the presence of clays and nutrients (Anand *et al.*, 2021) (Figure 3).

Similarly, the survival of enteric viruses such as SARS-CoV-2 can be reduced in dried soils when compared to soils with 10% moisture content at room temperature (Bosch *et al.*, 2006). As a result, migration of coronaviruses from soil to other environmental compartments should be limited (Kumar *et al.*, 2020), but their survival in soil may be guaranteed due to moisture content and low temperatures (Mohan *et al.*, 2021) while the presence of acidic soil, for example soil with a pH lower than 7, on the other hand, can inactivate enveloped viral particles

(Gutierrez and Buchy, 2012). Sunlight radiation can also inactivate the SARS-CoV-2 virus by lowering the T90 to a value less than 10 min depending on the parameters (*i.e.,* latitude, season, and hour) (Herman *et al.*, 2020).

Persistence (T_{90}) of different enveloped (i.e. CoV and H1N1) and non-enveloped (i.e. Adenovirus, Enterovirus and Orthorevirus) virus causing respiratory diseases (e.g., pneumonia) reported for various matrices (i.e. water, tap water, biosolid and soil) in the function of the temperature (i.e. ambient, 4, 37 and 50 °C) and pH values. T_{90} is the time (d) needed for 1 log_{10} unit reduction.

Viruses	Characteristics					T_{90} [d]						References
	Envelope	Genome type	Genome size [bases]	Diameter [nm]	Isoelectric point	4 °C	Ambient	37 °C	50 °C	pH	Matrices	
CoV[a]	Enveloped	+ve sense single strand RNA	30,000	60–220	6.24	28–588	1.6–59	6–9	15 min	1[b]	Wastewater, tap water	(Ahmed et al., 2020b; Bivins et al., 2020; Cascella et al., 2020; Franklin and Bevins, 2020; Kumar et al., 2020c; Mohapatra et al., 2020)
H1N1	Enveloped	Single RNA	13,500	80–120	6.50–7.00	200	–	–	–	–	Water	(Dublineau et al., 2011; Michen and Graule, 2010)
Adenovirus	Non-enveloped	Double strand RNA	26,000–48,000	90–100	4.50	9–51	4.3–214	–	–	14–98[c]	Biosolids (i.e. manure, sludge)	(Magri et al., 2015; Michen and Graule, 2010; Wei et al., 2009)
Enterovirus	Non-enveloped	+ve sense single strand RNA	7200–8500	25–30	3.80–3.90	–	14	–	–	–	Soil	(Michen and Graule, 2010; Pourcher et al., 2007)
Orthoreovirus	Non-enveloped	Double strand RNA	23,500	70–85	4.00–5.50	807	66–151	–	–	14–98[c]	Biosolid (i.e. sludge)	(Magri et al., 2015; Michen and Graule, 2010)

a = SARS-CoV, SARS-CoV-2, MERS-CoV; b = pH of 2–3 and 11–12; c = pH of 9.

Figure 3. Persistence of different enveloped and non-enveloped virus
(Anand et al., 2021)

Similarly, high concentrations of contaminants in environmental matrices (*e.g.,* soil) because of improper discharge of polluted wastewaters (Papirio *et al.*, 2014) could have a significant impact on the T90 of SARS-CoV-2 (Foladori *et al.*, 2020).

Non-enveloped viruses and other pathogenic microorganisms like adenovirus, enterovirus, and orthoreovirus are non-enveloped viruses that can cause respiratory tract disease (Michen and Graule, 2010). These non-enveloped viruses could have a great potential to infect a large variety of environmental compartments such as the soil, being resistant to hostile conditions and water treatments (Kumar *et al.*, 2020). For example, adenovirus reaching the soil through sewage sludge application (Horswell *et al.*, 2010) are sorbed by the soil particles through electrostatic interactions due to its isoelectric point, as suggested by Wong *et al.* (2013).

c) Conclusion regarding sources and characteristics of viruses contaminating urban soils

It can be concluded that the main ways of virus spread are aerosols and droplets, but all the environmental compartments like water, air and soil on which viruses can act should be necessarily monitored to control the spread of the infection. Hence, a substantial screening should be conducted on the wastewater effluents and sewage sludge before their application in soils to prevent the COVID-19 migration to other environmental compartments.

With the SARS-CoV-2 viruses still loom in our communities, governments around the world are bracing for a possible come back wave so it is time for local municipalities to reprioritize their capital expenditure on upgrading the main sources of viruses contaminating the urban soils. First, the wastewater infrastructure, not only for the long-lasting benefits of better wastewater management but to reduce the immediate risks of pathogen transmission from the main sources mentioned, but we need to update waste collection and street cleaning systems too and everything that could involves a further spread of nowadays and future viruses.

2. Characteristics of urban soils

Jean Louis Morel & Andrea Torre

"Urban soil" designates all soils present in highly anthropized areas, beyond just urban areas (de Kimpe and Morel, 2000). Indeed, industrial, mining and transport areas, and areas impacted by military activities are also characterized by soils whose properties differ markedly from those of natural soils. It is to meet the need to consider the diversity of the locations of highly anthropized soils that the grouping under the acronym SUITMA (*Soils of urban, industrial, traffic, mining, and military areas*) was proposed[1] (Burghardt *et al.*, 2015). However, "urban soil" and "SUITMA" are used alternately, as they have the same general meaning.

Although many urban soils resemble natural soils, except for greater compaction and the presence of contaminants, several other types of soils are also present. Indeed, in highly anthropogenic areas soils have characteristics that are the result of the drastic pressures induced by human activities to which they are submitted. A complete report on SUITMAs was published earlier (Levin *et al.*, 2017).

Here is presented the state of knowledge on urban soils, their formation, their general characteristics, their functions, and their role in the urban ecosystem as a providers of ecosystem services. Finally, the needs for new knowledge are presented.

a) Soil formation in anthropized areas

Soil formation in anthropized areas is controlled mainly by the human factor, which produces specific parental materials, and soil formation and evolution conditions, including climate, relief, and biological conditions (Figure 4).

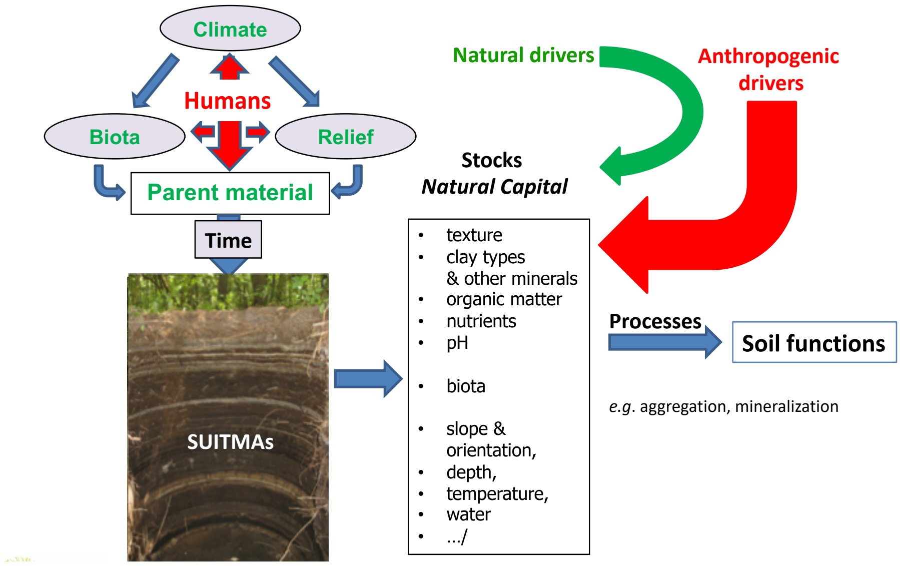


Figure 4. The formation of soils in anthropized areas
(Morel *et al.*, 2015; Huot *et al.*, 2015)

[1] SUITMA is also a Working Group of the International Union of Soil Science created in 1998 (Burghardt and Morel, 1998)

b) Common characteristics of soils in anthropized areas

Composition

Despite the great diversity of soil types, SUITMAs have common characteristics. They are mainly composed of coarse materials. They can contain several anthropogenic materials, also called "artifacts", which are derived from rubble and various wastes (*e.g.,* concrete, asphalt, bricks, glass, ceramics, oxides, plaster, plastic, coal, wood, waste, ballast) and industrial materials (*e.g.,* slag, mining cuttings, dredge sediments, bedrock cuttings). Also, natural coarse materials, such as sand and gravel, widely used in construction operations, can be present at high rate. Among the artifacts, some have properties that may interfere with the fate of contaminants, including viruses. An example is brick, which is mainly present in the coarse fraction and has a very dense internal pore system, giving high water retention capacity and the ability for organisms to enter the pores (roots, fungi, bacteria, virus) (Nehls *et al.*, 2013). Bricks are widely present in the soils of anthropized areas.

pH

In general, SUITMAs have a high pH, due to the presence of large amounts of carbonates in anthropized areas. An example is the use of lime for road construction which greatly increases soil pH (Kida and Kawahigashi, 2015). Construction materials are also highly rich in carbonates (*e.g.,* concrete). Due to this action on the pH, the physical and chemical properties of urban soils are therefore different from those of the natural soils of the same region. Consequently, the functioning of urban soils, both physically (structure) and chemically (reactivity, availability of elements, fate of charged particles), and biologically (level of microbial activity, for example), is therefore very specific. It is rather similar than that of natural carbonated soils developed on limestone materials. Urban soils often have properties of calcareous soils

Organic matter

The organic matter composition of SUITMAs is highly variable. Some have a high organic matter content (*e.g.,* disposal of combustion residues and organic waste, soils used for horticulture, black carbon, which is very stable and contributes a high percentage of soil organic carbon (Nehls and Shaw, 2015). Other soils contain low concentrations of organic matter, for example after removal of topsoil by civil engineering (*e.g.,* mining soils). Others may contain highly stable C (*e.g.,* PAHs in industrial soils) which can be found very deep in the soil profile. Their high bulk density is also variable but often very high due to compaction by heavy machinery.

Contaminants

Most SUITMAs contain contaminants, either organic (*e.g.,* hydrocarbons, PCBs) or inorganic (*e.g.,* metals), or both groups of contaminants. They come from all urban and industrial activities (*e.g.,* traffic, waste). The contaminants react with the solid organo-mineral phase of the soil. This results in a partition between the two phases, solid-liquid, which determines its future. They can be degraded (organic contaminants), immobilized (precipitation, sorption, absorption, complexation), or introduced into the soil solution where they can be transferred to different targets (*e.g.,* organisms, groundwater). Soil composition and properties (*e.g.,* clays, organic matter, pH, Eh) are key factors that determine the fate of pollutants in soils. These factors also play similar roles with respect to charged viral particles. In urban soils, due to the high pH, the risk of transfer of heavy metals to targets such as plants is low. On the other hand, soil particles (*e.g.,* clays, silts) carrying contaminants can be transported in the form of dust and contribute to the contamination of populations by toxic compounds or even pathogens which are thus transported.

Sealing

Finally, a large part of the urbanized surface is also sealed by impervious layers (*e.g.,* pavement, concrete, asphalt), giving the soils very specific characteristics and functions, *e.g.,* water infiltration and runoff, biodiversity, local climate. The functioning of these soils, including water flows and root paths under impermeable surfaces, is not well established.

c) Diversity of soils in anthropized areas

SUITMAs cover a wide range of soils. The main reason is the variety of parent materials on which they grow. These parent materials come from the operations of mixing, compacting, leveling, and sealing of the initial materials, as well as from the export of earthy materials and the contribution of exogenous materials (*e.g.,* soils, waste). Unlike natural soils, SUITMAs are young, poorly evolved soils because the parent material subjected to pedogenesis is mostly recent. It is also often disturbed, following the transformation of the anthropized environment.

But with deeply transformed soils also coexist soils very close to natural soils, except that they evolve in a very different environment (*e.g.,* temperature and water regimes, compaction). In the city, the latter are mainly found in urban forests, parks, and gardens.

There are also soils that are deliberately constructed to perform specific services. This is of course the case of sealed soils whose primary function is to support human activities (*e.g.,* mobility). But recently the construction of soils whose properties and functioning are close or even analogous to those of natural soils has made it possible to envisage the sustainable restoration of ecosystems degraded by human activities (*e.g.,* brownfields, mining sites) (Séré *et al.*, 2008). This strategy, which responds to the needs of the profound changes that cities are undergoing, the transition from an industrial activity to a leisure activity, housing with the search for well-being for the populations, allows the recycling of degraded territories. It should be noted that soil construction uses secondary materials (*e.g.,* urban, and industrial waste, treated earth), thus preserving natural soil. In a context of health risk, they can carry contaminants or even pathogens. Which is a key point to study as the soil construction strategy tends to develop more and more.

SUITMAs are present in soil classifications, especially in the WBR. They fall into three WRB soil groups: Regosols, Anthrosols and Technosols (Figure 5). Regosols are young soils with an AC type profile. Anthrosols are marked by the presence of a high rate of organic matter (*e.g.,* horticultural soils) at great depth.

Figure 5. Example of Anthrosol in an old garden soil
(Tolstoï House, Suitma conference tour, 2017, Moscow)

Technosols are soils that contain a high proportion of anthropogenic materials, or artefacts, resulting from human technologies (Rossiter, 2007) (at least 20% in the first meter of the profile). Constructed soils are Technosols because they contain a large amount of technogenic materials (Figure 6).

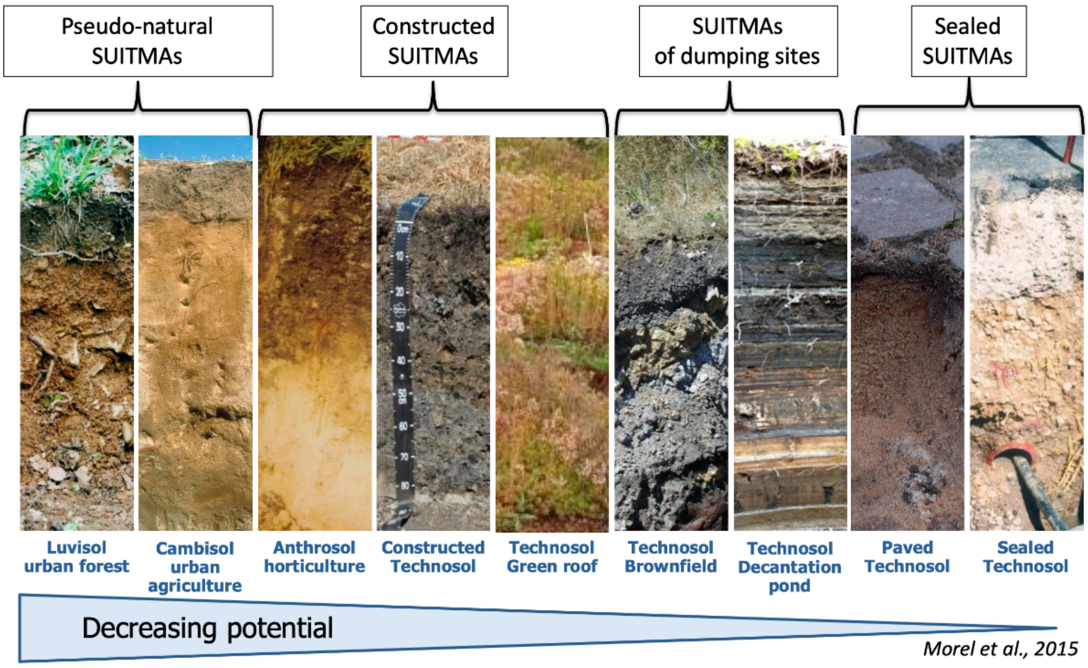


Figure 6. Groups of SUITMAs according to their potential to provide ecosystem services

SUITMAs perform a wide range of functions, like natural soils. But these functions can be severely degraded as for sealed soils or soils containing large amounts of artifacts. Their functions are the basis of a series of ecosystem services (Morel *et al.*, 2015; Vasenev *et al.*, 2018). They support biodiversity, help to mitigate the effects of climate change (*e.g.,* carbon storage - Rees *et al.*, 2018, heat island effect), intervene in the water cycle through their infiltration function and in the mitigation of pollution. Regarding viruses, in addition to the role of sink and source mentioned above, the physico-chemical and biological processes in urban soils can also contribute to their attenuation.

d) Conclusion regarding characteristics of urban soils

SUITMAs offer a wide variety of substrates and habitats, unlike agricultural land, depending on the multiplicity of human actions over time. They can provide many ecosystem services, provided they perform basic functions (*e.g.,* plant support, water infiltration). Soil construction is an appropriate strategy to develop and/or restore soil functions in response to city needs. In urban areas, the variety of soils is an asset, particularly for biodiversity, which must be preserved and enhanced. In this regard, soil management in cities must preserve this diversity and avoid a one-size-fits-all building solution. Also, the pressure on secondary materials, which can also find alternative ways of recovery, can lead to significant fluctuations in their availability and their costs, thus modifying the construction conditions of the soils. Due to the specific characteristics of urban soils, the fate of viruses cannot be deduced solely from knowledge acquired in other soils. Dedicated research should be carried out to understand the functioning of soils regarding its impact on viruses and provide relevant recommendations for managing soils to minimize the risk of transfer to other compartments and people.

3. Immobilization and inactivation

Martin Romantschuk

Viruses survive for a limited time outside the host organism, and the resilience of the virus varies substantially depending on virus type. Enveloped viruses, such as corona viruses (SARS-CoV-2) and influenza viruses are relatively short lived and sensitive to factors such as drought, UV and visible light radiation and the killing effect of various surfaces (Vaverkova *et al.,* 2021; Mosselhy *et al.,* 2022).

Municipal solid waste is an obvious potential source of SARS-Co-2 infection in case the virus stays infective. In this environment the exposed waste station workforce or waste utilizers are particularly exposed. Various surfaces have been tested for survival duration or conversely, inactivation of virus particles, with the following results (reviewed by Vaverkova *et al.,* 2021): Stainless steel up to 72h; plastic 72h; copper 4h; glass 4h; surgical glows 24h.

Antiviral surface coatings have been suggested as a novel approach to tackling the surface-mediated transmission of viral diseases. Such coatings could provide a permanent, continuously acting barrier to transmission, and some studies have already shown the efficacy of metallic compounds in reducing the infectivity of SARS-CoV-2 on surfaces (Behzadinasab *et al.,* 2020; Mlcochova *et al.,* 2020).

The fact that copper, titanium, silver, and various other components can inactivate viruses rapidly has been used to develop furniture, fabrics, filters etc. for rapid elimination of infection source. In some cases, the specific technology used in a product is confidential and covered by patents, but they are normally based on scientific studies proving the efficacy of a certain component. How well the results of a scientific study can be generalized and applied may be debated, and in the case of the effect of surfaces, the prerequisite is that the virus is deposited on the surface. Such deposition can be boosted by filtering air through a tight filter, or by electrostatic forces, or combinations of these (Salokas *et al.,* 2022 manuscript in preparation).

SiO_2 microparticles decorated with Ag nanoparticles (Ag NPs) within ethyl vinyl acetate polymeric matrix inactivated SARS-CoV-2 efficiently (Assis *et al.,* 2021). The suggested mechanism was the induced reactive oxygen species (ROS; OH* and O_2H*) by the interaction of SiO_2 with water and oxygen. Hosseini *et al.,* [2021a] showed a reduction in infectivity effect of a ZnO/SiO_2 coating by >99.98% as detected by the median tissue culture infectious dose after 1 h contact. The authors recommended administration of such coatings on handrails or doorknobs to reduce the spread and infectivity of SARS-CoV-2. The reduced SARS-CoV-2 infectivity was suggested to be linked to destructive reactive oxygen species (ROS) released in the presence of Zn^{2+} ions and the porosity of the hydrophilic coating, trapping the soaked viral droplet and allowing the facilitation of the ZnO antimicrobial role.

Mantlo *et al.* (2021) demonstrated the efficacy of copper ions (Cu^{2+}) in copper and copper–nickel surfaces, producing ROS in the inactivation of SARS-CoV-2 and Ebola Marburg viruses through a suggested genome disruption by the produced free radicals. Further, Hosseini *et al.* (2021b) demonstrated that a hydrophilic cupric oxide (CuO) coating almost entirely inactivated SARS-CoV-2 after 1 h and attributed the viral inactivation mechanism to contact inactivation.

Mosselhy *et al.* (2022) showed substantial inactivation of the SARS-CoV-2 Alpha variant and the murine norovirus after only one minute of contact to surfaces containing Cu–Ag nanocomposites. Applying such inhibitory surfaces might be used to break the SARS-CoV-2 and human norovirus transmission routes at high traffic places (Lopman *et al.* 2012). The observation that also norovirus is inactivated is notable since this type of virus can survive in the environment for weeks or even months.

Viruses in airborne aerosol particles may be inactivated by drought, when the aerosol particle originating from a sneezing patient dry, or by irradiation, which is much more prominent outdoors in sunlight.

A substantial factor in elimination of viral infection comes from dilution of the infecting agent. Successful infection requires a specific minimal dose, which varies between virus types. Nevertheless, in indoor conditions, where the air circulates in a limited space, one single or a limited number of virus emitters may raise the level of airborne or surface attached viruses above threshold for infection, while outdoors the virus level can stay low enough to be safe by even a light wind. Large and tightly packed gatherings at *e.g.,* sports events may be an exception to this.

Indeed, high use public spaces have been considered an unsolved problem (Albert *et al.,* 2021), which may be partially alleviated by spraying disinfectants. Such sprays may, however, have unwanted environmental and human health effects. Three types of chemical disinfectants are used for virus inactivation: alcohol based (>70%), quaternary ammonium, and oxidizers (chlorine, hydrogen peroxide or ozone) (Wigginton *et al.*, 2012; Hora *et al.*, 2020). Due to low cost, ease of use, and efficacy across a broad spectrum of microorganisms, including viruses (Kampf *et al.*, 2020) chlorine bleach (1000–5000 mg/L), is the most used disinfectant, despite recognized health concerns (Gorguner *et al.*, 2004; Medina-Ramón *et al.*, 2005).

Oxidizers such as ozone and hydrogen peroxide may offer a safer alternative since they rapidly convert to oxygen and water without leaving residual toxicity on disinfected surfaces. Aqueous ozone was suggested and tested as a relatively safe agent that can be disseminated, *e.g.,* from drones in public spaces (Albert *et al.*, 2021). Effective concentrations were reported to be low enough not to cause harm on non-target organisms including humans and insects.

a) Inactivation by UV

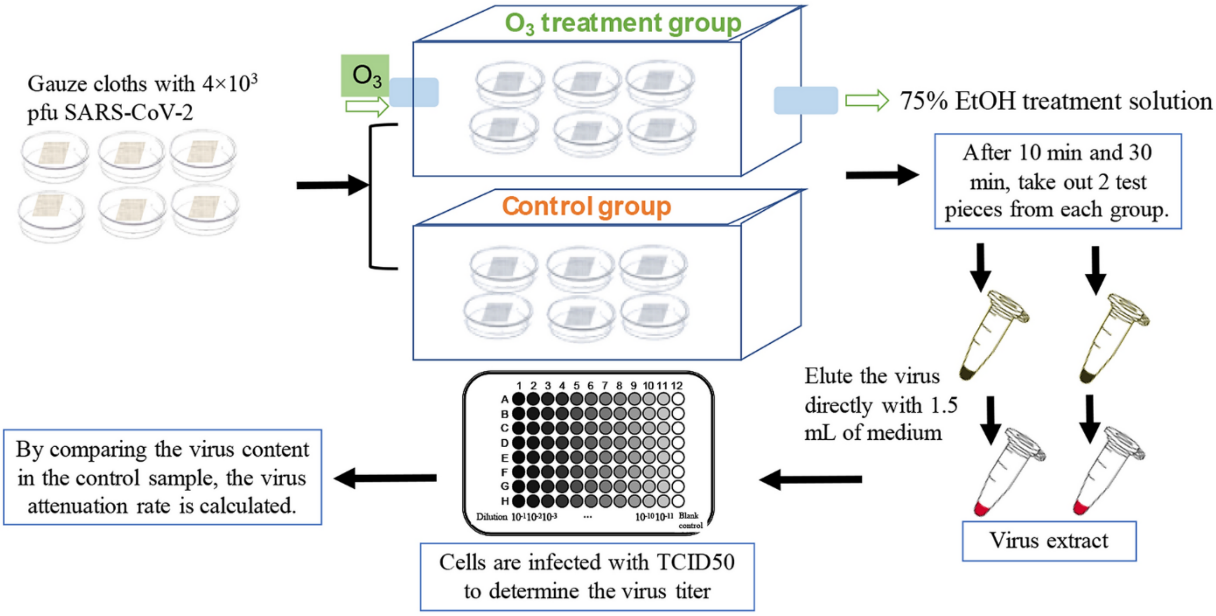
SARS-CoV-2 aerosolized from infected patients and deposited on surfaces were shown to remain infectious outdoors for considerable time during the winter in many temperate-zone cities, with continued risk for re-aerosolization and human infection. Conversely, presented data indicate that SARS-CoV-2 would be inactivated relatively fast (faster than influenza A) during summer in many populous cities of the world, indicating that sunlight has a role in the occurrence, spread rate and duration of coronavirus pandemics (Sagripanti & Lytle, 2020)

Preliminary evidence suggest that sunlight may rapidly inactivate SARS-CoV-2 on surfaces, suggesting that persistence, and subsequently exposure risk, may vary significantly between indoor and outdoor environments. Additionally, data indicate that natural sunlight may be effective as a disinfectant for contaminated nonporous materials (Ratnesar *et al.,* 2020).

b) Inactivation of airborne virus –ozone.

The issue of indoor ozone use has been extensively studied (Figure 7) and a recent review conclude efficacy and safety when used correctly (Farooq & Tizaoui, 2022). Cao *et al.* (2021)

proposed a new Safety O_3 Emission (SOE) method to increase indoor O_3 to levels (< 160 µg m^{-3}) that inhibit the transmission of the SARS-CoV-2 but are not harmful for humans. They suggest ozone as a timely and low-cost solution for suppressing COVID-19 outbreaks throughout the world.



- The reaction environment of the O_3 treatment group use a sealed small box to facilitate the calculation of the ozone concentrations.
- The control group is the indoor temperature and humidity environment.

Figure 7. Inactivation of viruses with O_3 (Farooq and Tizaoui, 2022)

c) Conclusion regarding inactivation

It can be concluded that viruses residing on surfaces can be inactivated by chemicals and by disinfecting irradiation, and obviously also by physical means such as heat. Almost all tests that have been done have used surface located viruses – either smooth or porous surfaces. How inactivation with the same means would work in the soil matrix or in solid waste fractions is not known, but speculations have been made *e.g.,* regarding the safety of virus laden waste, and this area should be studied in more detail. It can be speculated that on one hand viruses may be inactivated in soil or degraded by soil microbes, but on the other hand, soil retains moisture and provide protection against irradiation, both of which may promote virus survival.

4. Transport in the soil profile

Marie-Odile Simonnot

The SARS-COV-2 pandemic reminds us that understanding the transport of viruses in soils, from the vadose zone to the saturated zone, is fundamental to predicting the risk of groundwater contamination (Figure 8). For the time being, to our knowledge, there is no evidence of contamination of groundwater by this virus, but the question deserves to be asked. Most pathogens enter the soil through the application of sewage sludge, animal waste, and leaking sewage pipes (Zhang *et al.*, 2010; Yang *et al.*, 2004; Gholipour *et al.,* 2022). Precipitation and water flow due to human activities (irrigation, artificial groundwater recharge, etc.) can contribute to the spread of contamination and transport of contaminants to the groundwater, which considerably amplifies the risks to human health. The most frequently identified pathogens in groundwater include enteroviruses, hepatitis viruses, noroviruses, adenoviruses, and rotaviruses. In 2004, for example, they were identified in 20 to 30% of 550 wells in the USA and UK.

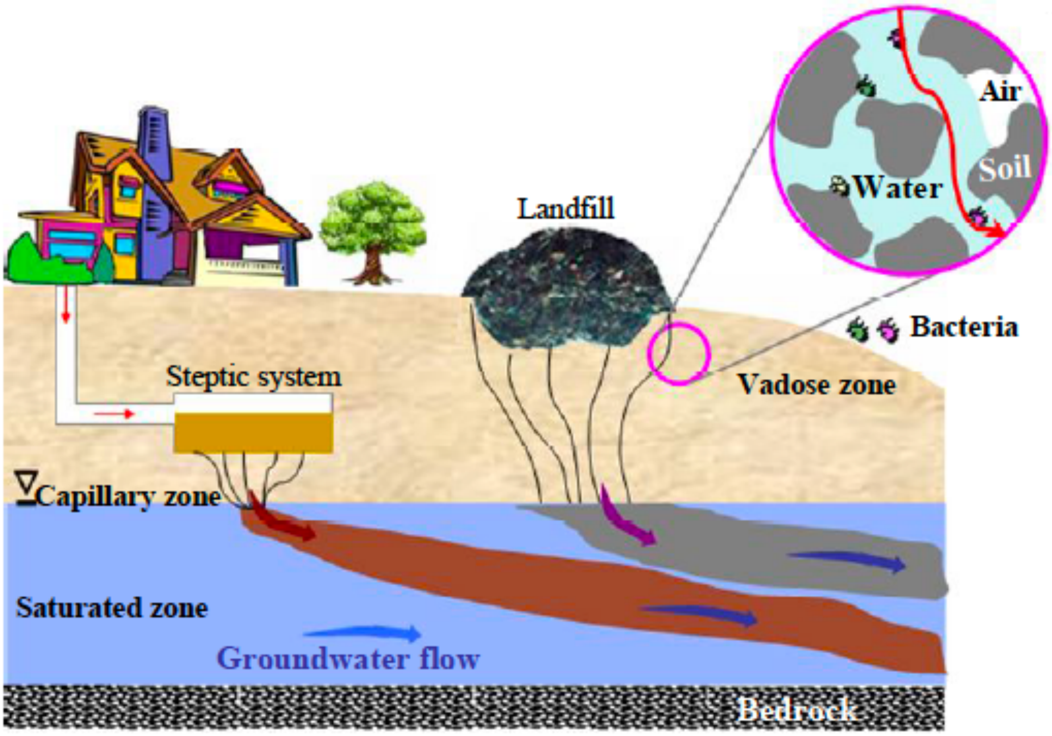


Figure 8. A representation of sources and patterns of movement of bacteria in the subsurface environment *(adapted from Chrysikopoulos and Sim (1996) - From Bai, 2017)*

Pathogens (viruses and bacteria) behave as bio-colloids, whose transport by water can be facilitated, compared to solutes (Sen *et al.*, 2006). It is therefore essential to study this transport, in porous media, saturated or not, and in fractured media. The knowledge gained can also help develop strategies or design processes to protect the water resource (Betancourt *et al.*, 2019).

The literature on the transport of colloids in porous media, whether biological or not, has developed considerably since the 1980s, both from an experimental and a modelling point of view. This transport depends on the bio-physical-chemical properties of colloids, the retention mechanisms at the interfaces (air/water in unsaturated media and water/solid), the properties of the solid phases and of the soil solution, and the hydrogeology.

This report, inspired by the recent review by Zhang *et al.,* (2022), presents the factors that play a significant role in pathogen migration in the subsurface, with a view to predicting the behavior of SARS-COV-2 and giving indications on the potential risks of groundwater contamination.

a) Pathogen characteristics

The characteristics that affect the behavior of pathogens in the environment, like colloids, are known to be shape, size, surface hydrophobicity, surface charge and membrane structure.

Size is a critical factor: the smaller the bio-colloids, the faster they migrate in saturated porous media. Thus, viruses with characteristically smaller dimensions than bacteria (20 - 90 nm versus 0.5 - 3 µm) move faster. In particular, 60 nm is considered the limiting size below which viruses propagate at longer distances (Cao *et al.*, 2010; Chrysikopoulos *et al.*, 2014; Walshe *et al.*, 2010). It has been reported, for example, that MS2 coliphage (27-29 nm) moves much faster than human adenoviruses (70-90 nm) (Wong *et al.*, 2014; Kokkinos *et al.*, 2015).

Morphology is also important. Bio-colloids can have various shapes, spherical, rod-shaped, helical, filamentous, ellipsoidal etc. Spherical colloids move faster than others. Spherical colloids move faster than others. Indeed, the higher the length/diameter ratio, the more likely bacteria are to adhere to solid surfaces (Jiang and Bai, 2018; Ma *et al.*, 2020).

This characteristic has also been noted for viruses, which can be spherical, filamentous, polymorphic, or tailed. Spherical viruses, like many common viruses (enterovirus, hepatitis virus, norovirus, adenovirus, rotavirus). SARS-COV-2 is also spherical and tailless (Kumar *et al.*, 2020), which could favor its mobility in porous media.

The surface charge, usually measured via the zeta potential, is characterized by the isoelectric point (positive surface charge when the pH of the solution is below the isoelectric point and negative above). For many mineral surfaces (sand, clays etc.) the charge is negative near neutrality, and this is also the case for pathogens such as the bacteria *Escherichia coli* O157:H7, *Yersinia enterocolitica* and *Enterococcus faecalis*, which causes electrostatic repulsion and limits sorption onto the surfaces (Jacobs *et al.*, 2007; Schinner *et al.*, 2010). However, the effects depend on the thickness of the electronic double layer surrounding the bio-colloids, which is governed by the ionic strength of the solution. If the ionic strength increases, the double layer becomes thinner, which limits repulsion and promotes adhesion. For viruses, the surface charge distribution can be split between a positively charged area (the head and tail) and a negatively charged area (the filaments), which makes interpretation more difficult.

The hydrophobic character is also to be considered, as it tends to limit migration. Indeed, hydrophobic pathogens tend to be sorbed to solid surfaces by hydrophobic interaction. Many pathogens tend to be hydrophilic, except for those that are enveloped, which are rather hydrophobic (Feng *et al.*, 2019).

The membrane has a surface composed of macromolecules, extracellular polymers, protein, liposaccharides which also affect sorption. Bacteria are classified as Gram-positive and Gram-negative, depending on the structure and composition of their membrane. The former has a higher negative charge and are likely to migrate faster. Viruses are classified into enveloped, unenveloped (Blanco *et al.*, 2019) and vesicle ones (Zhang *et al.*, 2021). The non-enveloped ones have been the most studied. Enveloped ones have a lipid bilayer membrane that resembles that of bacteria and tend to be more sorbed (Paul *et al.,* 2021).

Although the effects of size, shape, surface charge, surface hydrophobicity and membrane structure appear to be decisive, it is not easy to predict their respective importance on the migration capacity. Zhang *et al.,* (2022) propose an evaluation algorithm considering that this capacity depends on the size (40%), the isoelectric point (surface charge) (20%), the contact angle (hydrophobicity) (20%), the length/width ratio (shape) (15%) and the presence of flagella (5%) (Figure 9).

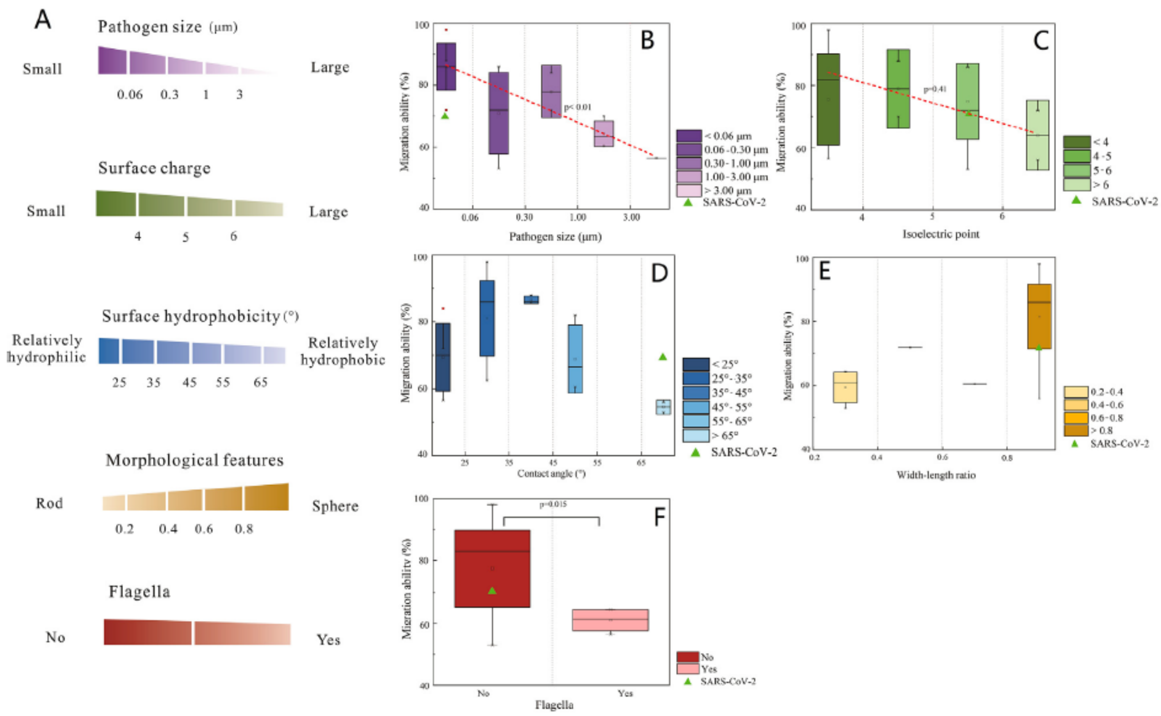


Figure 9. A) Impacts of pathogenic physiological characteristics on the estimated migration abilities of pathogens. B) The estimated migration ability vs pathogen size. C) The estimation migration ability vs surface charge (isoelectric point). D) The estimated migration ability vs surface hydrophobicity (contact angle). E) The estimated migration ability vs morphological features (width-length ratio). F) The estimated migration ability vs membrane structure (flagella). From Zhang *et al.*, 2022

SARS-COV-2 is a spherical, pleomorphic virus, 60-140 nm in size, consisting of four major structural proteins: spike protein (S), membrane protein (M), nucleocapsid protein (N) and envelope protein (E) (Sarkar and Saha, 2020). Its ability to migrate in porous media may depends on protein S (which promotes host attachment), but this is not yet clear, nor is its hydrophobicity and insulating point. According to the calculations proposed by Zhang *et al.,* (2022), its migration capacity would be 0.70.

b) Geochemical characteristics

Although the migration behavior of pathogens depends mainly on their intrinsic characteristics, geochemical and hydrological properties are also important, soil composition and texture, water composition, pH, ionic strength, saturation, and hydrodynamic conditions.

Soil texture determines pore size, which directly affects pathogen mobility. It depends on grain size, grain roughness and specific surface area, and heterogeneity of the size distribution. Transport will be easier the larger the grain size, as in sands (Bai *et al.*, 2016). High roughness linked to a large specific surface area favors retention. For example, for biochar-amended sands, E. coli adsorption has been shown to be much stronger than on sand alone (Mohanty *et al.,* 2014a, b) (but is this the only reason?). This said, interpretations can be more subtle, and a small-scale repulsion/attraction force balance (DLVO theory) is needed to finely interpret the effects, as proposed by Bai *et al.,* (2016).

The chemical composition of the groundwater also plays a fundamental role. Indeed, a wide variety of mineral and organic compounds of different sizes can co-exist. The mineral composition depends on the rocks and solid matrices in contact with the water. For example, some authors have highlighted the influence of phosphate concentration, which can promote *E. coli* migration in sandy environments. Natural dissolved organic matter, such as humic substances, also have an influence. They can promote the transport of pathogens, which can associate with them by hydrophobic interaction, or possibly slow it down by attaching themselves to sorption sites and thus causing a mechanical blockage. But overall, pathogen transport is facilitated in aquifers rich in organic matter.

Moreover, pathogens are also likely to bind to colloids, and be subject to facilitated transport. This is especially true for organic colloids, with which pathogens form stable associations, then for mineral colloids, which are more likely to cause blockages (Qin *et al.*, 2020).

The pH is an extremely important parameter since it determines the sign of the surface charge. At low pH (surface charge of bio-colloids is generally positive), adsorption is favored, thus migration is slowed or stopped, and the opposite is true at high pH (Zhang *et al.*, 2018). Near their isoelectric point, viruses can aggregate, which reduces their mobility.

The role of ionic strength is well known in the field of colloidal transport, due to its influence on the electrokinetic properties of the surfaces of the grains composing the medium and of the pathogens. A high ionic strength favors the attachment of viruses to sand, for example, while a low ionic strength favors electrostatic repulsion, decreases sorption, and thus increases mobility. In groundwater, where the mobility is in the range of 0.02-0.04 M, the migration speed of pathogens is rather high.

Regarding temperature, an increase tends to decrease the energy barrier and viscosity of water. Research shows that the sorption of viruses can increase by more than 100% when the temperature increases from 4 to 20 °C (Sasidharan *et al.*, 2017). At the same time, the temperature-dependent properties of pathogens also need to be considered. Overall, it can be considered that transport is slowed down at depth at low temperature but can be considerably increased in surface waters.

Migration is also highly dependent on the state of water saturation. In the vadose zone, it is rather inhibited, due to a more consistent attachment at low moisture levels (Flury and Aramrak, 2017; Gargiulo *et al.*, 2008; Kim *et al.*, 2008). Thus, viruses are much less mobile in this zone, but can be remobilized in case of intermittent infiltration.

Migration also depends on hydrogeological conditions, such as flow (Yan *et al.*, 2020). It will be stronger at high flow rates, due to advective transport (positive correlation) and will be reduced at low flow rates or during flow interruptions.

c) Conclusions regarding transport in the soil profile

Like other pathogens, the SARS-COV-2 virus that could arrive in soils is likely to be transported, depending on geochemical and hydrogeological conditions, and to contaminate groundwater. This risk must be weighed against the deactivation of the virus (Moresco *et al.*, 2021). Currently, very few studies have been carried out on this subject, which remains to be explored.

A detailed literature review is required on the transport and inactivation of SARS-COV-2 virus in soils. This will enable us to take stock of our knowledge and to determine what remains to be done and for what purpose, whether it be to better understand the coupling between transport and inactivation of the virus, and thus to predict the risks of long-distance transport, or to develop strategies for treating contaminated water.

It would be relevant to study transport at several scales, from model situations under controlled conditions (laboratory column, saturated conditions) to real situations with pilot-sized lysimeters, under unsaturated conditions. It will obviously be essential to work under safe conditions. These experiments should be accompanied by transport modelling, which could subsequently help to understand the mechanisms and choose strategies.

Finally, it would also be interesting to examine the environmental problems arising from the Covid 19 pandemic and affecting the soil, such as those linked to micro-plastics from masks discarded in nature by users.

5. Emission of airborne particles and transport

Martin Romantschuk

a) Introduction

Viruses, including SARS-CoV-2 may become airborne through a variety of processes, the most obvious and direct of which is in the form of emissions from an infected patient, as droplets during sneezing and coughing, but also by merely talking or singing. Larger droplets sediment and are deposited on surfaces rather fast and reach only the persons within a few meters (Figure 10).

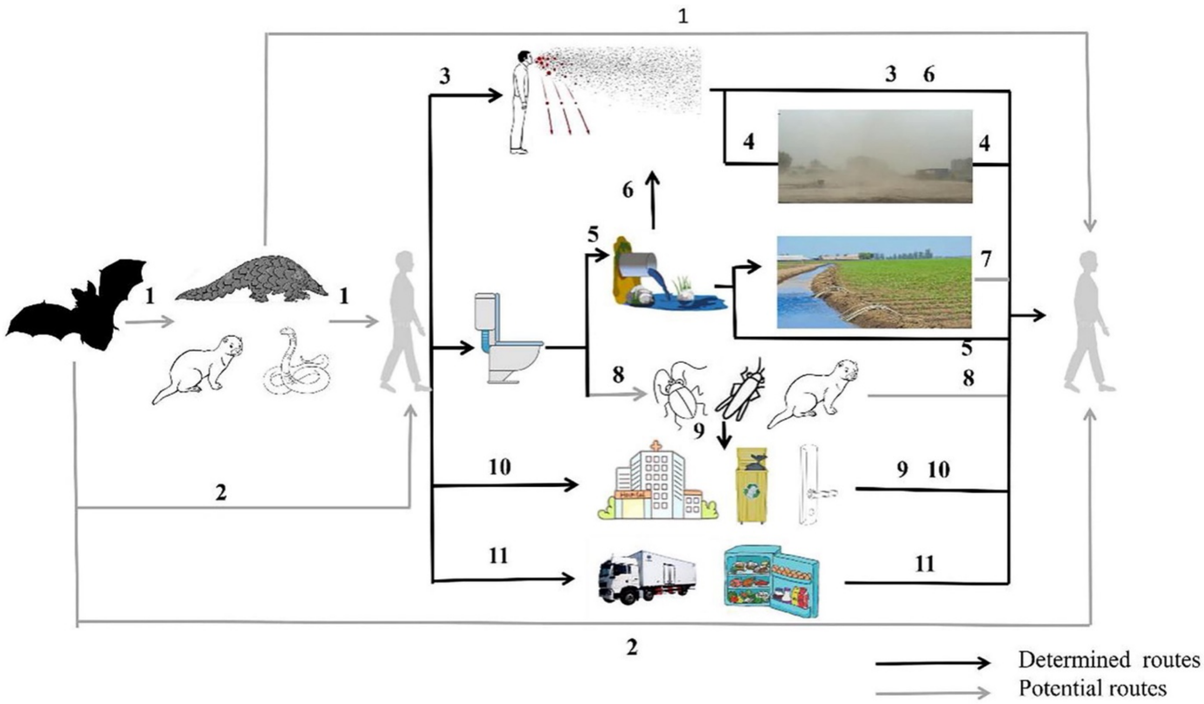


Figure 10. Fate of viruses in the biosphere (From Shao *et al.,* 2021)

It has, however, been shown that viruses can also become airborne as part of smaller aerosol particles that may stay airborne both indoors and outdoors for minutes of hours. Indoors this phenomenon is under vigorous study both using the Covid virus itself in exposed settings (Malmgren *et al.,* 2022, manuscript in preparation) and by using harmless but structurally similar bacteriophages as substitutes (Oksanen *et al.,* 2022). Outdoors any empirical study of airborne SARS-CoV-2 is challenging in that the pathogenic virus itself cannot be used in controlled releases, while an approach trying to sample freely spreading viruses causing the pandemic may be futile because of the low abundance. This might still be possible by filtering large quantities of urban air through filters that catch the virus at some dense population gathering, such as an outdoor concert or a sports event, but the outcome is uncertain and may not generate results that are statistically testable. This, however, does not mean that outdoors airborne spread of viruses is not an epidemiological issue, since large numbers of infected patients in an urban environment may generate a large enough airborne virus load to travel sufficient distances while staying principally infective (Figure 11).

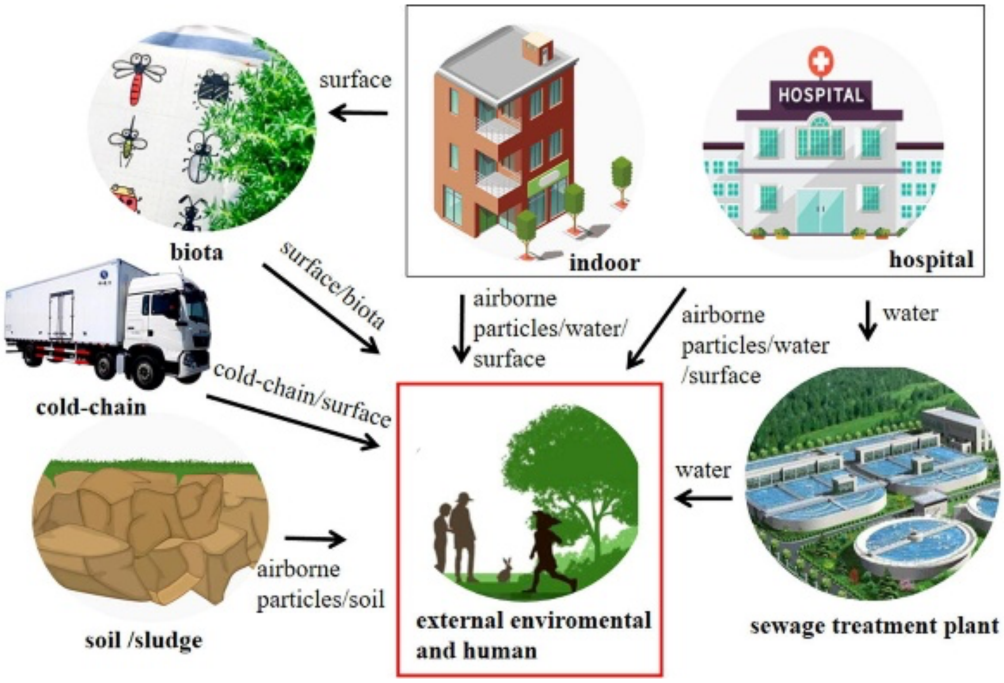


Figure 11. Transport of viruses to environmental and human targets

Indoor environmental conditions that promote virus (including SARS-CoV-2) spread and survival have been recognized, and relevant factors were found to be droplet size, air relative humidity and temperature (Oksanen *et al.* 2022 and references therein). Apparently, also dilution, mixing, and exchange of air is relevant indoors, while these factors are much more pronounced outdoors. Occupational and environmental exposure to SARS-CoV-2 has been studied at mink farms (de Rooij *et al.,* 2021), and it was shown that indoor exposure was highly frequent, while outdoor identification of airborne viruses was rare and located close to the entrance of recently infected mink farms, but not beyond the premises of the farms. Dust at infected farms, however, tested positive for SARS-CoV-2 RNA in over 80% of cases. The government decision in Denmark in the spring of 2020 to eradicate all 15 million farmed minks has been criticized, but with the information available at the time, the decision may be seen as justified as a precaution, although apparently not in all respects legal.

b) Spread of airborne viruses – empirical studies

Using surrogate viruses such as Phi6, the decrease in virus particle density was followed in a restaurant setting (Oksanen *et al.,* 2022) and found to be substantial but gradual during a half hour period after stop or release of new phages, while a similar test outdoors (Malmgren *et al.,* 2022) showed that no viruses could be caught from the air five minutes after stop of release. Considering that even in light wind conditions, the release plume has moved >100 m within a minute, this finding is no surprise. A subsequent presence in the air close to the former source is not ruled out under the assumption that viruses deposited onto surfaces or attached to particles may become airborne by *e.g.,* wind gusts or mechanical forces such as people walking or car traffic. The latter mode of aerosol generation would be efficient both in dry (dust) and wet (splash) conditions. In this context, the survival, *i.e.,* the retention of infectiveness of the viruses in outdoor conditions potentially exposed to UV and visible light, is an essential risk determining factor.

The phenomenon of outdoors survival has been studied using surrogate viruses, such as Phi6, an enveloped RNA bacterial virus infecting the host bacterium *Pseudomonas syringae*. Because of its structural similarity to the Corona viruses Phi6 (Turgeon *et al.*, 2014) has also been used in simulations of environmental survival of SARS (Fedorenko *et al.,* 2020), and ongoing studies determine the usability of Phi6 as a model for outdoors airborne spread and survival in UV exposure (Romantschuk, M., personal communication). To enable catching viruses of even very diluted air samples (up to 100 m downwind of the source) the virus preparation used in the nebulizer representing one human head had a very high virus concentrations, but the results are fully scalable. Preliminary results show that Phi6 spread as bioaerosols for >100 m and stay viable for at least several minutes even when exposed to sunlight.

c) Spread of airborne virus – field and epidemiological monitoring.

Risk associated with air pollution

Air pollution has been reported to increase the risk of Covid-19 (Curtis 2021; Keikhosravi & Fadavi, 2021; Li *et al.,* 2020). As has been shown for various microbes, *e.g.,* bacterial cells can spread as part of aerosols, and are found in clouds where certain bacteria function as ice nuclei that take part in the process of could condensation. Bacteria can also spread attached to airborne particles, such as pollen or PM2.5 particles in polluted air conditions. As for many viral diseases, such as influenza, seasonality has been observed also for SARS-CoV-2. In Spain transmission rise was observed to be linked to air quality issues (Zoran *et al.,* 2021). As discussed also by others (Curtis, 2021), it could not be established whether the main reason for the correlation between poor air quality and higher incidence of infection was caused by irritation of patient lungs and mucous membranes or by infectious virus particles spreading with the dust etc. particles in the air.

A relationship of air pollution and Covid-19 spread was reported (Keikhosravi & Fadavi, 2021), so indirect evidence for virus spread attached to air pollution particles exists although empiric evidence is so far lacking. Curtis (2021), however, suggests that the higher incidence of Covid-19 in polluted environments mainly is caused by pollutant-related stress upon lungs and other tissues rather than higher incidence of virus, but spread of the virus as part of airborne dust was not excluded. The virus has been detected in PM2.5 and PM10 fractions of air (Tung *et al.,* 2021) also outdoors in Italy (Chirizzi et. al., 2021). It was also concluded that SARS-CoV-2 may stay viable in air for more than an hour, and on surfaces for up to several days.

In many regions there is a clear seasonality in air quality (dust, smoke, low temperatures, air dryness etc.), but the cause-effect relationship for virus spread and infection rate remains somewhat obscure (Curtis, 2021). It is conceivable that viruses that survive dry conditions can become airborne in windy conditions from poorly managed medical waste from *e.g.,* landfills as part of dust particles, while viruses that thrive in water may spread from storm water ponds as aerosols by wind gusts or in car tire splashes.

Spread by wastewater and disposed solid waste – risk for becoming airborne?

A little studied issue is how well SARS-CoV-2 survive outside its host on outdoor surfaces, for example in soil, or in water ponds in high enough quantities and time spans to become again airborne by wind, air convection or for example water splashing caused by car tires. This is an issue that would merit study.

Mancuso *et al.,* (2021) reviewed the literature and found little evidence that SARS-CoV-2, that frequently can be found in urban and rural waste waters, would become airborne in dust or aerosols, and thereby reenter an infectious cycle. They do, however, conclude that SARS-CoV-2 RNA in water environments might represent a risk of irrigation water contamination, and that it is necessary to investigate the eventual persistence of SARS-CoV-2 in crops (Figure 12).

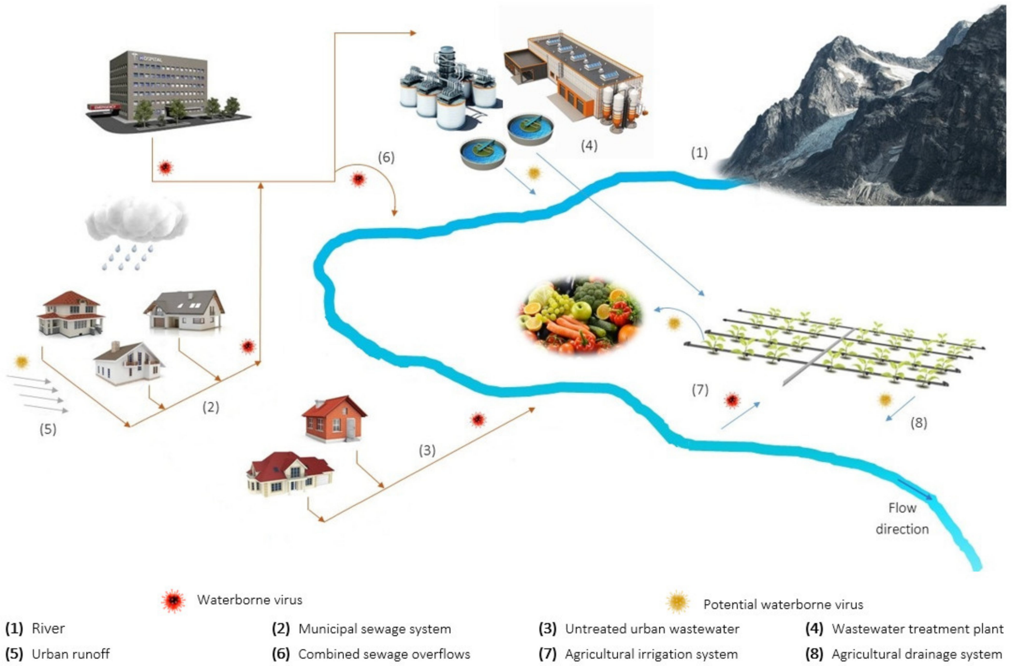


Figure 12. Putative spreading routes for SARS-CoV-2 in agricultural settings
(Mancuso *et al.*, 2021)

Also, alternative transmission pathways through human interactions with environmental samples should not be ignored since more infectious and transmissible SARS-CoV-2 variants may evolve (Figure 13; Adelodun *et al.,* 2021)

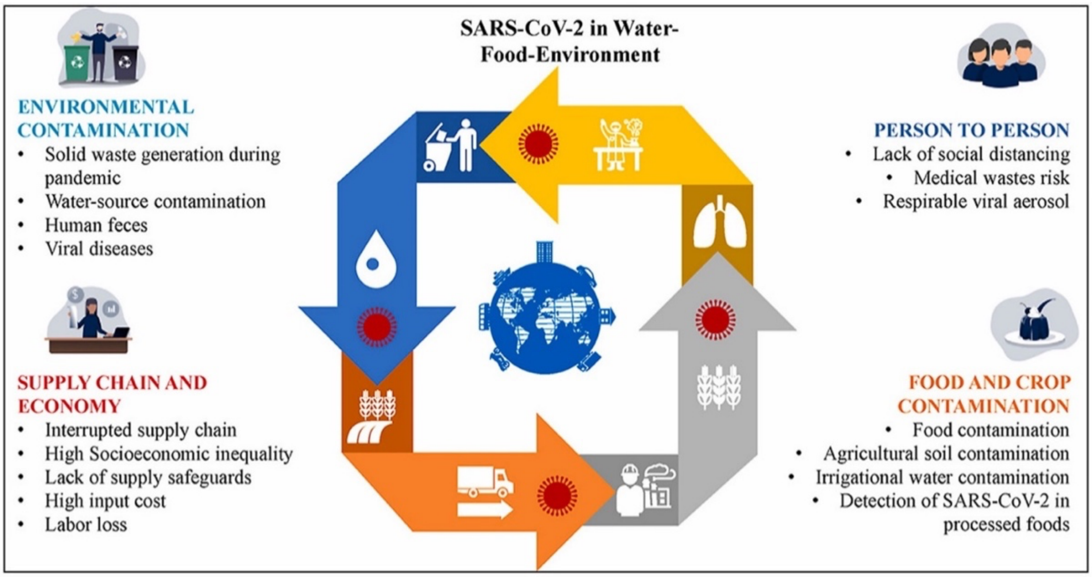


Figure 13. Possible transmission routes and sources of SARS-Co-2
(Adelodun *et al.,* 2021)

d) Conclusion regarding emission of airborne particles and transport

Airborne virus particles transport is considered the main route of spread of infection. In the case of SARS-CoV-2. In indoor conditions the infective particles released from patients may circulate and stay infective for some time, while in outdoor conditions the infective dose is rapidly diluted by the wind. These issues have been and are currently extensively studied in a variety of local conditions. Unknown and unstudied issues are whether SARS-CoV-2 and similar viruses can be aerosolized by wind gusts, by physical agitation, or by splashing water, from wet ponds or dry soil. Wet medical or household waste, where virus density may be high and conditions suitable for virus survival, may pose a threat, and should be studied. Dry conditions – street dust etc. is less likely to maintain infective virus populations but can perhaps not be excluded without testing. In industrialized countries medical waste is properly taken care of, while in developing countries this may not be the case (Figure 14). Furthermore, bodily fluids – also others than nasal mucus – from infected persons may be a source of airborne infective particles even when taking the route via soil or storm water ponds.

Figure 14. Mitigation of risks associated to medical waste disposal
(El-Ramady *et al.*, 2021)

6. Impact of soil management on virus transmission and on soil functions

Jean Louis Morel

The regular management of urban soils takes little or no account of contaminants, whatever they may be, organic and metallic pollutants and pathogens such as SARS-COV-2 (Nú˜nez-Delgado, 2020b). However, some of these actions initially intended to ensure the quality of life in the city (*e.g.,* waste management, street cleaning) can produce effects opposite to those expected, with the suspension of contaminants. In the case of polluted sites and soils, there is a set of effective technologies to reduce the importance of pollution and allow the safety of sites. But in some cases, they destroy soil functions and can also contribute to introducing new contaminants into soils. Urban agriculture is booming, in response to expectations in terms of product quality and short circuits. But uses such as, for example, the use of poor-quality irrigation water (*e.g.,* wastewater) can be the source of the introduction into the soil of contaminants, including pathogens. Finally, the pandemic due to SARS-CoV-2 has led to health-related operations for the massive disinfection of urban soils, based on the use of disinfectant compounds.

a) Regular management of urban soils: impacts on virus transmission

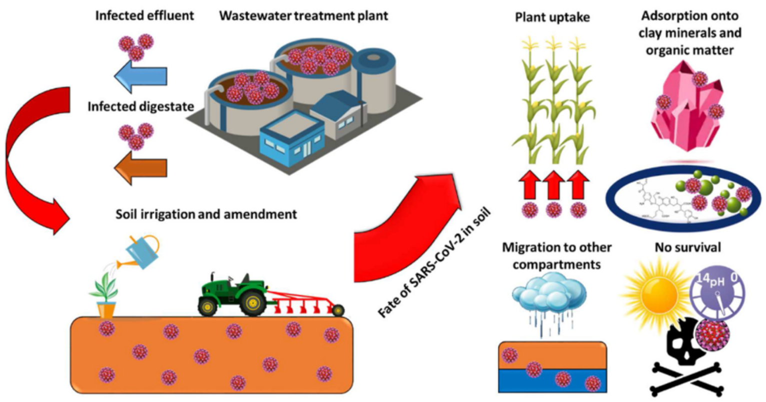
All actions that result in the production of dust are likely to increase the risk of spreading contaminants and, consequently, of deteriorating the health conditions of citizens.

The construction of buildings, road works are important dust emitters. In addition, the use for landscaping of non-native soil or amendments can also introduce contaminants into the urban environment, where they accumulate in soils. There are, in general, strict rules which must be applied by civil engineering to avoid or at least limit the emission of dust.

Surface cleaning of streets and sidewalks widely uses leaf-blowing. Blowing is convenient for cleaners, but it generates several disadvantages. In addition to machine-induced noise and odors, leaf-blowing releases organic contaminants into the air, *e.g.,* benzene, formaldehyde, heavy metals, and particles that may contain mold, fungal spores, insect eggs, bacteria, and viruses. This practice is banned in some places and questioned in others, as it has become a major source of discomfort for citizens and a threat to health (Shao *et al.*, 2021).

b) Urban agriculture and landscape management (*i.e.,* management of the soil-plant system)

Urban agriculture is growing as emphasis is placed on local food production. It was also triggered by the COVID-19 pandemic, to overcome food safety and security concerns (Lal, 2020a, b). This is also an effective way to reduce greenhouse gas emissions as it normally reduces transport. It also meets the expectations of citizens of greener cities. In general, urban agriculture is practiced directly on soils, on a large scale (horticulture *vs.* gardening). Green roofs and green walls have also attracted recent interest not only for the sole greening effect, but also to produce edible foods. In all cases, the presence of contaminants in the substrates and in the amendments, in particular pathogens, represent a main health concern, as plants can be contaminated through the soil-to-plant transfer processes or directly by the deposition of dust on edible leaves.



Irrigation and fertilization of gardens and even parks with wastewater, solid waste, organic and mineral amendments can bring virus particles to the soil-plant system, as described Figure 15 in the case of agriculture based on irrigation with wastewater

Figure 15. Possible contamination route of soil contamination by the SARS-CoV-2 (Anand *et al.*, 2021)

The soil-to-plant transfer of viruses is not well elucidated. It is not known for SARS-CoV-2. From the hypotheses of the fate of the virus in the soil-plant system (Pietramellara *et al.*, 2021), it is possible to infer those interactions between the viral particles and plants (Figure 16). However, the potential mechanisms of uptake and transport in plant are uncertain. Processes occurring within the rhizosphere could change its fate, through inactivation by soil organic matter, mobilization by root exudates, and changes in pH at the soil-root interface.

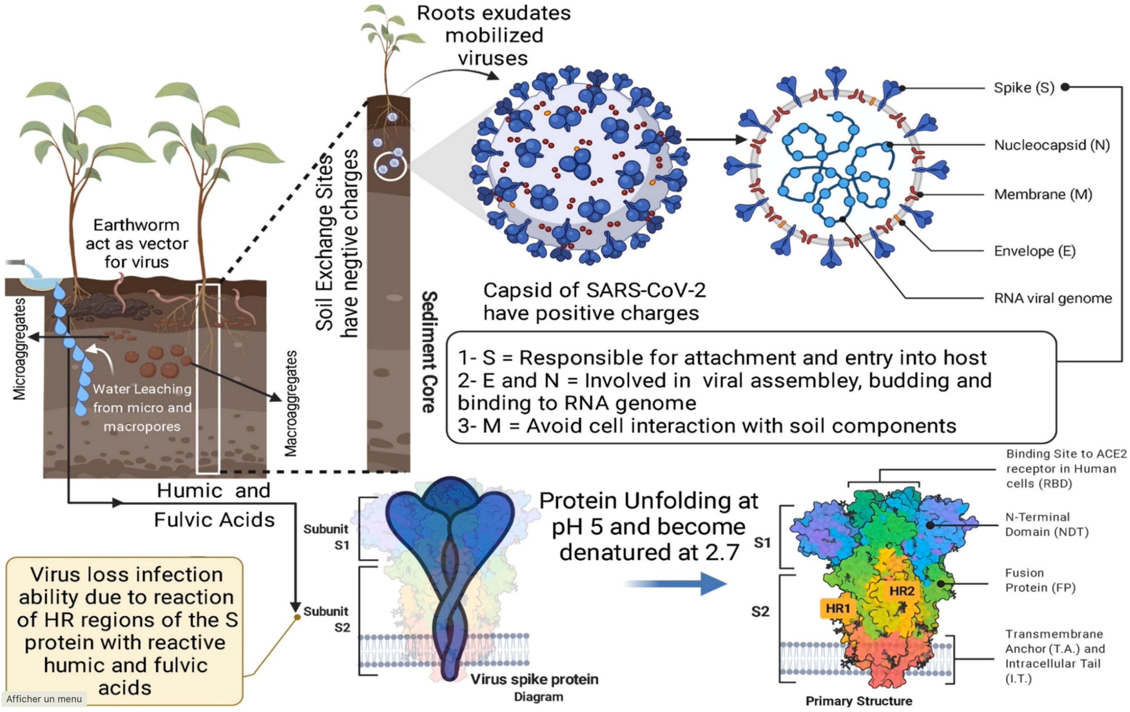


Figure 16. Hypothetical fate of SARS-CoV-2 in the soil-plant system
(after Pietramellara *et al.*, 2021)

c) Pandemic disinfection procedures

Persistence of coronaviruses in the environment

Virus particles are present in human excretions, medical equipment, everyday objects, and the air. Wastewater may contain coronaviruses (Figure 17; Wiktorczyk-Kapischke *et al.*, 2021).

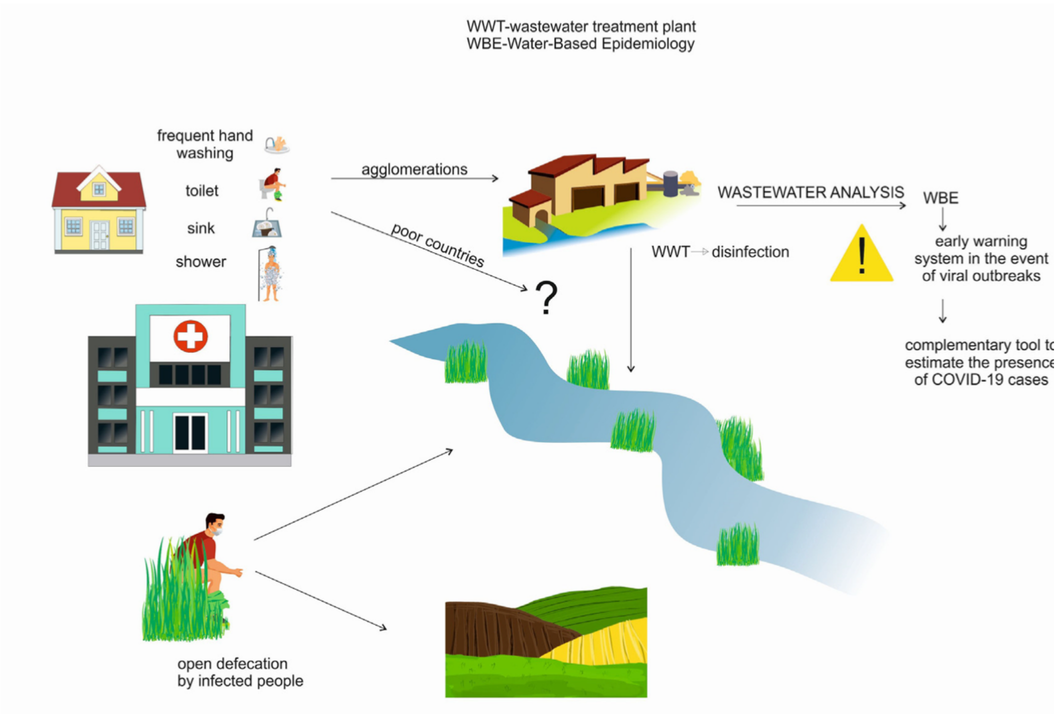


Figure 17. Transmission of SARS-CoV-2 via the fecal-oral route

Figure 18 shows that SARS-CoV-2 can persist in wastewater up to several days (Wiktorczyk-Kapischke *et al.*, 2021). It is likely that soils can act as a reservoir for the virus. Organic substances can protect viruses (Kuzyakov and Mason-Jones, 2018). But no report is available yet on the survival of SARS-CoV-2 in urban soils.

Persistence of coronaviruses in wastewater.

Virus	Sample	Temperature [°C]	Persistence	Reference
SARS-CoV-2	Tap water	20	1.5 days	Bivins et al. (2020)
SARS-CoV-2	Wastewater	20	1.7 days	Bivins et al. (2020)
SARS-CoV-2 (high-starting titer (10^5 $TCID_{50}$ mL^{-1})	Wastewater	20	Persisted for the entire 7-day sampling time course	Bivins et al. (2020)
SARS-CoV-2	Wastewater	50	15 min	Bivins et al. (2020)
SARS-CoV-2	Wastewater	70	2 min	Bivins et al. (2020)
SARS-CoV-1	Sewage	4	14 days	Wang et al. (2005)
SARS-CoV-1	Sewage	20	2 days	Wang et al. (2005)
SARS-CoV-1	PBS	4	14 days	Wang et al. (2005)
SARS-CoV-1	PBS	20	14 days	Wang et al. (2005)
HCoV-229E	PBS	37	6 days	Sizun et al. (2000)
HCoV-229E	Primary effluent filtered	23	2.35 days	Gundy et al. (2009)
HCoV-229E	Primary effluent unfiltered	23	3.54 days	Gundy et al. (2009)
HCoV-229E	Secondary effluent	23	2.77 days	Gundy et al. (2009)
HCoV-229E	Tap water unfiltered	23	12.1 days	Gundy et al. (2009)
HCoV-229E	Tap water filtered	23	10.1 days	Gundy et al. (2009)
FIPV	Primary effluent filtered	23	2.40 days	Gundy et al. (2005)
FIPV	Primary effluent unfiltered	23	2.56 days	Gundy et al. (2009)
FIPV	Secondary effluent	23	2.42 days	Gundy et al. (2009)
FIPV	Tap water unfiltered	23	12.5 days	Gundy et al. (2009)
FIPV	Tap water filtered	23	10.1 days	Gundy et al. (2009)
TGEV	Pasteurized settled wastewater	25	4 days (predicted)	Casanova et al. (2009)

HCoV-229E — Human Coronavirus 229E, SARS-CoV-1 — severe acute respiratory syndrome coronavirus 1, SARS-CoV-2 — severe acute respiratory syndrome coronavirus 2, TCID — tissue culture infectious dose, FIPV — feline infectious peritonitis virus, MHV — mouse hepatitis virus.

Figure 18. Persistence of coronaviruses in wastewater
(Wiktorczyk-Kapischke *et al.*, 2021).

The duration of SARS-CoV-2 on surfaces is variable, from less than 10 h on latex glove and copper surface (pipe), to 2-3 d on steel and gown, up to 4-5 d on paper, metal, wood, glass, and even 9 d on plastic (Wiktorczyk-Kapischke *et al.*, 2021)

Disinfection practices

There are several efficient disinfection methods to control the dissemination of SARS-CoV-2 in the environment, *e.g.,* 65-70% ethanol, 0.5% hydrogen peroxide, or 0.1% sodium hypochlorite. Quaternary alkylammonium compounds (QAACs) are also widely used and released in the environment with manure, sewage sludge and wastewater (Heyde *et al.*, 2021).

The fate of QAACs in soils is poorly understood. But they persist then accumulate in soils over time (Figure 19; Heyde *et al.*, 2021). Concentrations of 16 QAACs increased linearly and slowly during the period of irrigation (Figure 19b), but after 40 y of wastewater irrigation an exponential increase in QAAC concentrations (up to 155 µg kg^{-1}) was observed (Figure 19a). They may cause disorders in the functioning of soils and ecosystems. They are known to cause the selection of antibiotic-resistant bacteria.

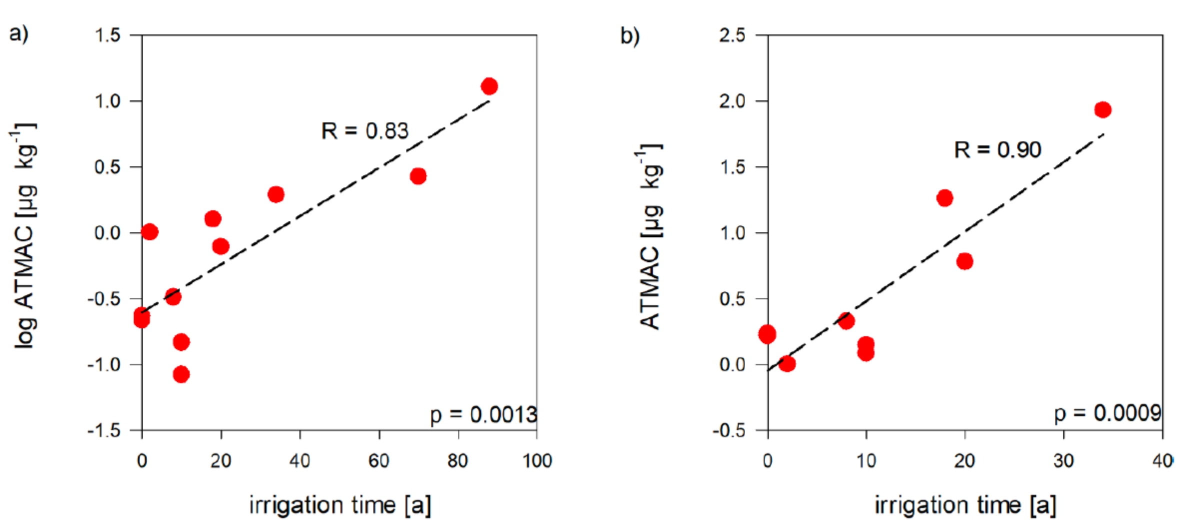


Figure 19. Accumulation of QAACs in soils irrigated with wastewater (Mexico City)

During the pandemics, drastic measures were taken to disinfect the urban environment at large scale (Figure 20 Parveen *et al.*, 2021).

Figure 20. Examples of disinfection procedures during the covid-19 pandemics

Environmental disinfection in cities uses calcium hypochlorite spread in alleys, open lands, roadside plants, lawns, gardens, and other vegetative areas (Parveen *et al.*, 2021). Hypochlorite addition to soil can increase chlorine/chloride concentration, which can be fatal to plant species if exposed. The microbial population in the rhizosphere which is important for plant health are also destroyed by the CBDs which consequently affect the root's health. Also, CBDs release free chlorine which reacts with natural organic matter to form potentially harmful organochlorine ("disinfection byproducts").

d) Impact on soil functions

soil biota and face masks

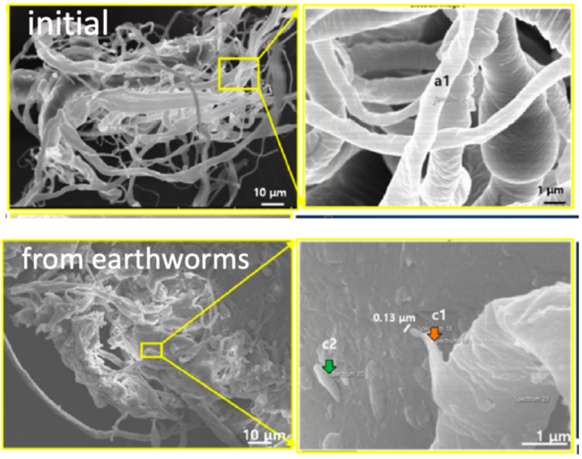


Figure 21. Generation of nanofibers

Faced masks commonly made of plastics such as polypropylene generate nanofibers from meltblown* filters (MB). Melt blowing is the fabrication of micro- and nanofibers where a polymer melt is extruded through small nozzles surrounded by high-speed blowing gas (Wikipedia). MBs produce adverse effects on soil earthworms and springtail (Kwak and An, 2021) (Figure 21 & 22). At a high concentration (1000 mg kg^{-1} dry soil) MB inhibited reproduction and stunted growth in springtails, decreased intracellular esterase activity in earthworm coelomocytes, and inhibited spermatogenesis in male earthworm reproductive tissues.

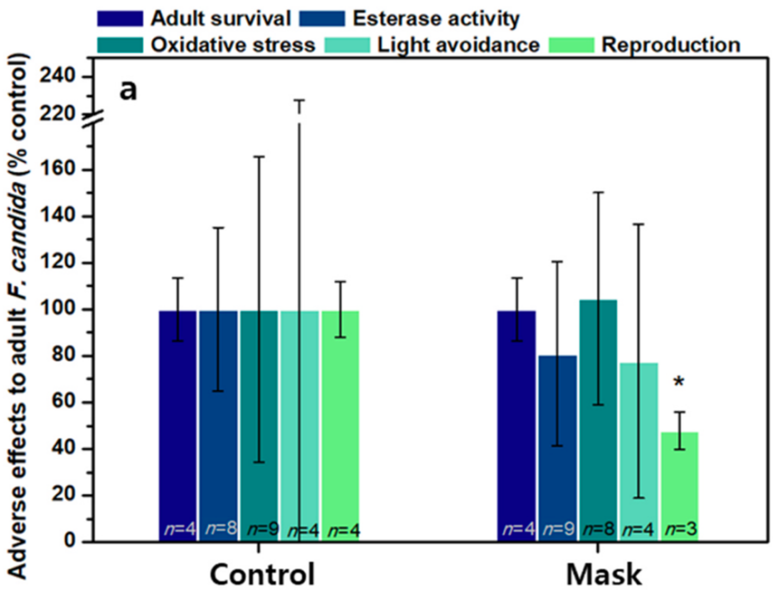


Figure 22. Effect of MB on *F. candida* (Kwak *et al.*, 2021)

Treatment of polluted soil generally induces strong changes in soil properties and functions. For example, chemical oxidation eliminates organic matter, destroys structure, eliminates all organisms and including viruses. But a fast recovery of soil functions can be achieved with the addition of amendments (*e.g.,* microbial and enzyme activity) (Laurent *et al.*, 2012; Figure 23). Regarding nanoremediation, no information is available yet on the effect on SARS-CoV-2.

Other techniques like stabilization/solidification are widely used to remediate contaminated soils (*e.g.,* chemical fixation and physical encapsulation/adsorption) (Tang *et al.*, 2021). Their application to SARS-CoV-2-contaminated soils is possible but the mechanisms of disinfection of SARS-CoV-2 is unclear, and appropriate agents with the dosages should be identified, and tested at real scale.

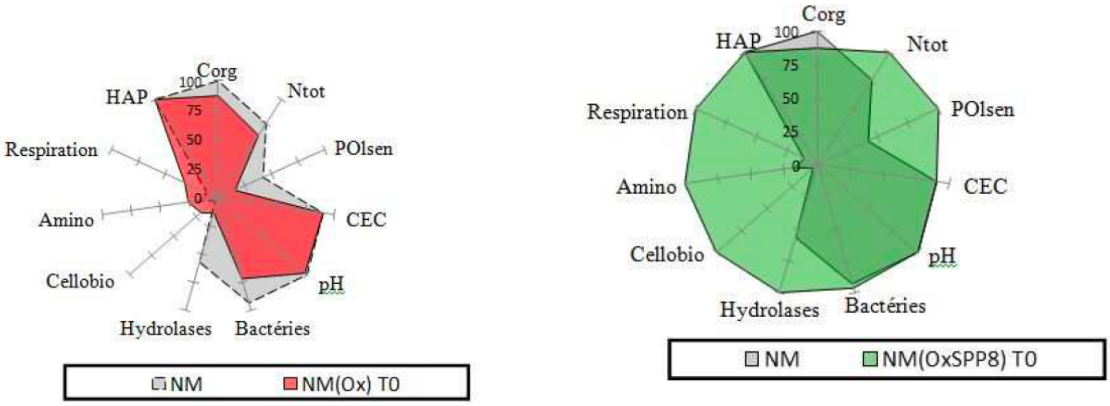


Figure 23. Effect of chemical oxidation and soil restoration of soil functions

Solidification of pathogenic-virus-contaminated soils with magnesium phosphate cement, geopolymers and other types, novel binders with high early strength, low permeability and diffusivity and high resistance to climate change can be considered (Du *et al.*, 2020; Haque and Chen, 2019; Qiao *et al.*, 2010; Xia *et al.*, 2019; Zhang *et al.*, 2020, in Tang *et al.*, 2021).

e) Impact of ecological soil restoration on the fate of viruses

Ecological restoration is based on the restoration of soil functions (Sere *et al.*, 2008; Figure 24). For this, one way is the construction of Technosols from the use of secondary materials (Vidal Beaudet *et al.*, 2016). As there is growing interest in this strategy to remediate and reuse degraded sites, *e.g.,* brownfields, urban areas, using secondary materials, *e.g.,* soil material, waste, sludge, attention should be focused on the possible entry of pathogens into these built soils which are intended for the public, in particular the construction of housing or recreational activities (*e.g.,* parks, gardens). So far, there are no data available on the risks about viruses, the attention having been mainly focused on the risks of introduction of pollutants (*e.g.,* metals).

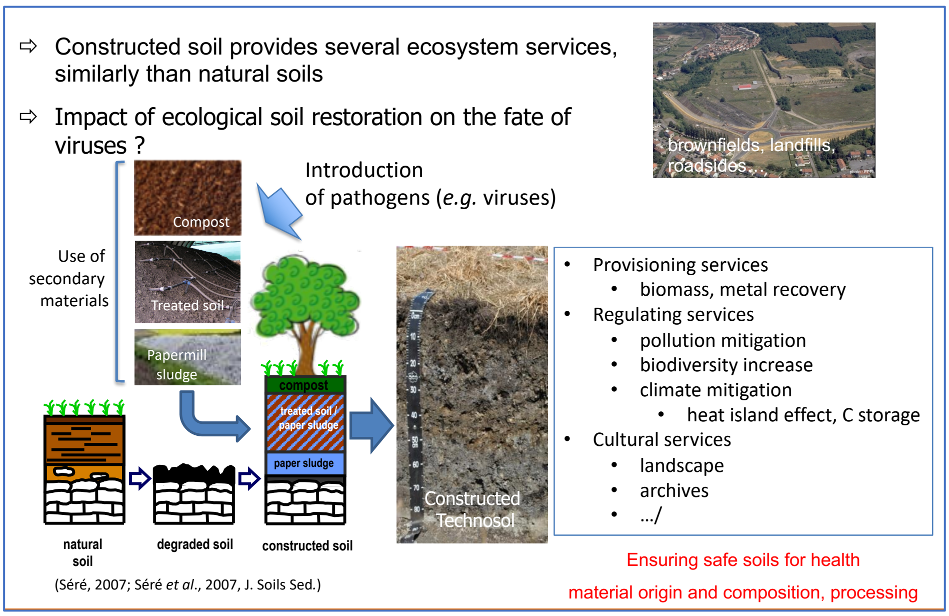


Figure 24. General strategy for soil construction

f) Conclusion on impact of soil management

In cities, soils are subject to frequent changes, and their properties and functions change because of these actions. These actions could likely modify the fate of pathogens, including viruses, in soils and their impact on the health of populations. But this hypothesis is not yet documented, and it is not possible to say that these practices, in particular soil construction, can represent a new risk of the spread of viruses and the entry of new strains. During the pandemic, various practices have been implemented to reduce the risk of infection of populations. Some of these practices, which use disinfectants on a large scale, could pose a threat to populations and water quality. It is necessary to deepen this question which has important repercussions in terms of the management of urban areas in times of pandemic and secondary risks for populations and aquatic ecosystems. Finally, among the current practices that have become essential for the management of urban space, in particular the cleaning of surfaces, the use of certain technologies, *e.g.,* leaf-blowing, could be at the origin of new transmission routes, beside their impact on the quality of life in the city (*e.g.,* noise, GES emissions). But this assumption requires further studies to support or invalidate it and promote actions to change the procedures and tools.

II. Recommendations for research actions

The review of the literature, albeit partial, makes it possible to identify a series of questions relating to the future of SARS-CoV-2 in urban soils. These questions are important not only because they concern a densely populated environment with which people are in direct contact with the soil and with the emissions that come from it, but also because it concerns soils whose properties are very specific. Indeed, urban soils develop under the main influence of anthropogenic actions, which determine the parent materials and the conditions of evolution (*e.g.,* compaction, temperature, water management, sealing). Thus, as a primordial compartment of the urban ecosystem, soils constitute a reservoir of contaminants, pathogens, including viruses, which it is essential to know better because of the increased risks of pandemics and, more generally, of human health in a predominantly urbanized world. From the analysis of the literature conducted in this report, the following series of questions emerged, organized according to the plan initially adopted.

1. Questions emerging from the review

a) Sources and characteristics of virus contaminating urban soils

The main ways of virus spread are aerosols and droplets, but all the environmental compartments like water, air, and soil must be monitored to control the spread of the infection.

- As wastewater effluents and sewage sludge bear a large range of contaminants and pathogens, do we have the proper tools and procedures to monitor their safety before their application in soils to prevent the SARS-CoV-2 transfer to other environmental compartments?
- Wastewater infrastructures are not always optimal to deal with contaminants, including viruses.
    - Are the wastewater collection systems safe enough to prevent the dispersion of contaminated wastewater in the environment (*e.g.,* soils)?
    - Are the wastewater treatment plants adapted to deal with virus contamination in the case of a pandemics?
    - Are the funds dedicated to wastewater and waste management in cities sufficient to improve their efficacy and deal with emergency situations such as the one induced by the emergence of the SARS-CoV-2 virus?

b) Characteristics of urban soils

The wide variety of substrates and habitats makes urban soils (*i.e.,* SUITMAs) very specific environments where the processes that control the fate of viruses cannot be inferred solely from knowledge acquired in other soils. It is therefore necessary to carry out dedicated research to understand the impact of soil functioning on the fate of viruses and to provide relevant soil management recommendations to minimize the risks of transfer to other compartments and people. The questions that arise from the literature analysis are:

- Do the composition and properties of soils confer a specific fate of viruses in urban soils?
  - What are the main factors that determine the fate of viruses in urban soils?
    - For example, is the generally high pH of urban soils a factor of inactivation, of immobilization?
  - Does compaction likely interfere in the fate and survival of viruses in soils?
  - Is a typology of urban soils according to their impact on the fate of the virus feasible?
- Are heat island effects in urban areas likely to interact with viruses and change their fate?
- What are the relationships between plants and pathogenic viruses such as SARS-CoV-2?
  - How plants growing in urban environments can contribute to the transfer of diseases to populations?

c) Inactivation of viruses

Viruses residing on surfaces can be inactivated by chemicals and by disinfecting irradiation, and obviously also by physical means such as heat.

- As almost all tests have used surface located viruses,
  - how inactivation with the same means would work in the soil matrix or in solid waste fractions?
  - How the phenomena operate in urban soils under real conditions (*e.g.,* temperature)
- How is virus laden waste safe?
- How is the virus affected by soil microbes?
- To which extent soil moisture and protection against irradiation may promote virus survival?

d) Transport in the soil profile

Viruses and specifically SARS-COV-2 virus is likely to be transported into soils, depending on geochemical and hydrogeological conditions, and contaminate groundwater.

- How the collection of knowledge about the fate of other viruses in soils would contribute to understand the coupling between transport and inactivation of the virus, and thus predict the risks of long-distance transport, and develop strategies for treating contaminated water?
- How would SARS-CoV-2 behave under unsaturated conditions? This would require transport studies at several scales, from model situations under controlled conditions (laboratory column, saturated conditions) to real situations with pilot-sized lysimeters.
- How would compaction impact the survival and transport of SARS-CoV-2?
- How would microplastics, generated by masks for example, and which may bear the virus impact transport in soils?

e) Emission of airborne particles and transport

Airborne virus particles are considered the main route of spread of infection in the case of SARS-CoV-2. In outdoor conditions the infective dose is rapidly diluted by the wind. These issues have been and are currently extensively studied in a variety of local conditions. But there are a set of important issues that were not addressed so far:

- Could SARS-CoV-2 and similar viruses be aerosolized by wind gusts, by physical agitation, or by splashing water, from wet ponds or dry soil?
    - May wet medical or household waste, where virus density may be high and conditions suitable for virus survival, pose a threat?
    - Dry conditions – street dust etc. is less likely to maintain infective virus populations, but this issue was not tested. Can dissemination from dry sources be excluded without testing?
- In industrialized countries medical waste is properly taken care of, while in developing countries this may not be the case. Furthermore, bodily fluids – also others than nasal mucus – from infected persons may be a source of airborne infective particles even when taking the route via soil or storm water ponds. Are scientific data sufficient to assess these risks, and propose proper management procedures?

f) Impact of soil management on virus transmission and on soil functions

In cities, soils are subject to frequent changes, regular management procedures, and management procedures specifically implemented during the pandemics. These actions could likely modify the fate of viruses in urban soils and their impact on the health of populations.

- To which extent soil construction which is developed to restore ecosystems would contribute to the entry of viruses in the urban environment, then contaminate the population?
- How soil construction should be designed to minimize risks connected to the spread of viruses in cities and more generally the spread of contaminants?
- What is the impact of disinfection procedures on soil quality and functioning? How can it contribute to the contamination of groundwater affect surface water and drinking water quality?
- How could current practices to manage cities, *e.g.,* street cleaning with leaf-blowing, affect the transmission routes of viruses to the population?

2. Potential research proposal

From the above questions, a comprehensive research proposal was built to bring information to understand the routes, fate, and impact of viruses in the urban environment, stressing on the soil compartment (Figure 25). Such research is necessary to propose relevant recommendations to minimize risks of dissemination of viruses in the urban environment, regarding wastewater and sewage management, solid waste management, street cleaning and disinfection, soil construction for ecosystem restoration.

- First, the monitoring of potential sources should be assessed, with the development of methods adapted to complex matrices like soil material. This would allow the continuous detection of viruses in water, especially SARS-CoV-2, sludge, aerosols, solid wastes, and soils.

- Then research should be carried out to characterize and model the mechanisms and processes that affect the fate of the virus in urban soils (inactivation, immobilization, transport), considering their specificity regarding their composition and functioning.
- A special attention should be put on the effect of plants, their interactions with viruses, and their role in the cycle of the viruses in urban soils (*e.g.,* soils amended with wastewater, or where medical waste is disposed of).
- From a thorough analysis of the processes and mechanisms, the modelling of the fate in the soil-plant system could be developed.
- Finally, on a practical aspect, the research would provide useful information to elaborate recommendations to manage urban soils to minimize risks related to dangerous viruses, and their dissemination.

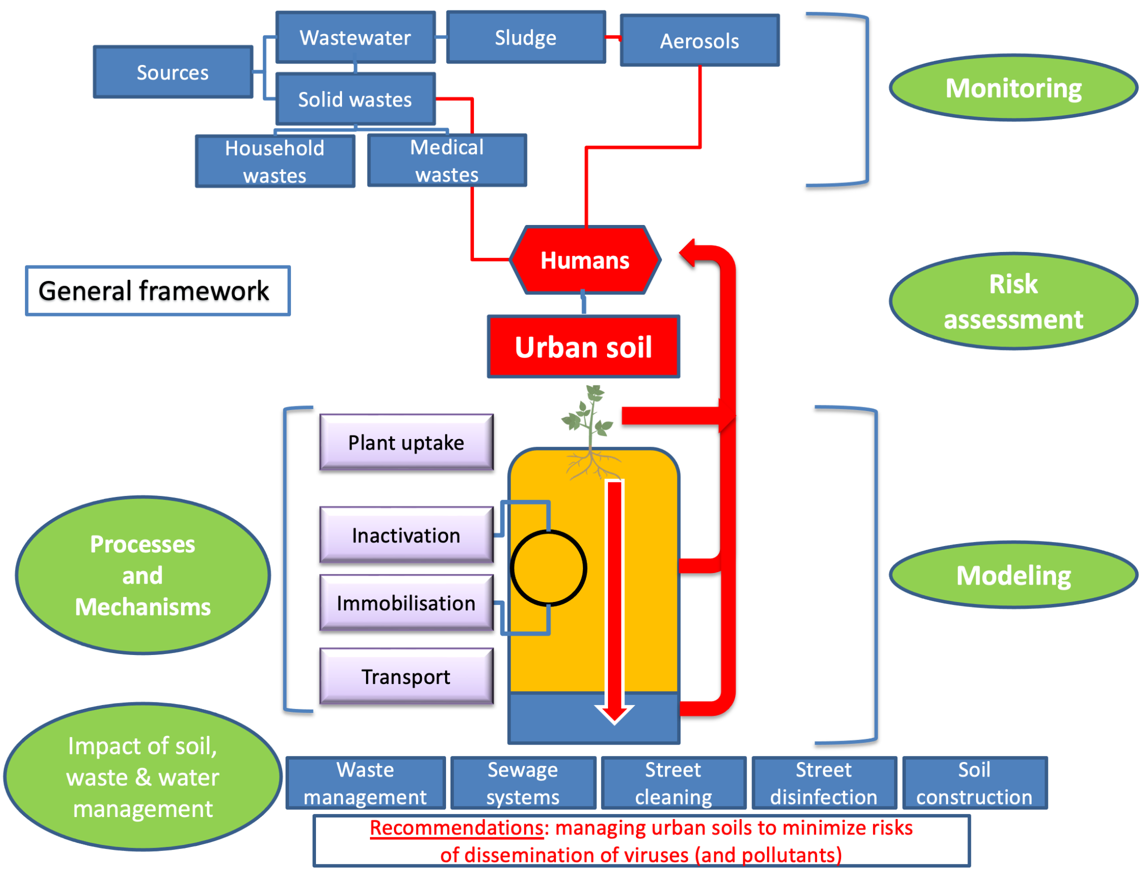


Figure 25. Are urban soils a potential source and/or well for SARS-CoV-2?

This general framework identifies potential work packages for a research proposal. To go further, a discussion should occur to identify the tasks which should be undertaken to meet the objectives.

III. Recommendations for decision makers and community managers to minimize the risk of the virus spreading from urban soils

Soil is an essential component of the urban ecosystem. It is the physical support of human activities, but also the receptacle of a wide range of compounds, ranging from chemical pollutants to viruses. The SARS-CoV-2 pandemic has highlighted the risks of transmission of viral particles from various sources, air, soils, waste, wastewater, aerosols, and contaminated surfaces. Urban soils also represent a potential source of contamination of populations by various organisms (viruses, bacteria), but their contribution to the increase in virus infections has not yet been clearly assessed.

The present literature review, which focused on knowledge gained for SARS-CoV-2, and other similar viruses (*e.g.,* surrogates such as noroviruses), showed that viruses can be inactivated or immobilized in urban soils, but can also be transferred to the air as dust particles and to groundwater. The fate of viruses depends on several factors related to soil composition and soil management practices used in cities.

Vigilance should be directed towards the following points:

- The formation of **aerosols** from dust can constitute a preferential route for the transfer of viruses to populations.
- Soil and water can also be contaminated because of the uncontrolled dumping of **medical waste**.
- The **disinfection** practices implemented during the pandemic, such as the direct application of disinfectants to the soil, are a threat to the chemical quality of surface water and groundwater and can significantly affect the functioning and survival of soil organisms.
- The use of **wastewater** for the irrigation of crops, particularly vegetables, is a way to consider even if the risks of viruses transfer from the soil to the consumable parts of **plants** are not fully established yet.

Overall, the knowledge acquired to date about the fate of the virus in urban soils remains insufficient and sometimes contradictory and needs to be consolidated for correct risk assessment. Nevertheless, from the findings published so far, it is possible to identify some **preliminary guidelines** for the establishment of recommendations intended to reduce the risks of contamination of populations from urban soils, and degradation of terrestrial and aquatic ecosystems caused by certain practices implemented during the pandemic.

One of the major ways of infecting populations from contaminated soils being aerosols, it is essential to avoid or at least reduce the emission of fine particles and their suspension in the air.

- **Washing** streets and sidewalks during **dry periods** can significantly reduce these emissions, with the washing water then being sent to treatment plants.
- During dry weather and epidemics (*e.g.,* covid, flu), by reducing the inhalation of fine particles, wearing a **mask** outside could help protect populations against infection.

- The frequent use of **urban equipment** which induces the production of large quantities of **dust**, such as leaf blowers, should be controlled or even forbidden; these practices are likely to transport not only viruses but also other biological and chemical contaminants to environmental targets (*e.g.,* water) and to populations.
- The effectiveness of **disinfectants** applied directly to soils on inactivating viruses has not been fully proven, while a detrimental effect on the ground surface is probable. Also, their action is probably limited deeper within the soil profile. In addition, this practice leads to the introduction into the soil of compounds that degrade water quality and disturb the biological functioning of aquatic ecosystems, with runoff water from treated surfaces. This practice is therefore not to be recommended because of the **chemical risks** it generates. Additionally, the ability of soil to inactivate viruses could be altered because of altered soil functions.
- All environmental compartments like water, air and soil on which viruses should be **monitored** to control the risks of spreading during a pandemic. Screening should be conducted on wastewater **effluents** and sewage sludge before their application to soils.
- In the event of a pandemic, it then seems necessary to carry out specific **analytical** checks for the presence of viruses. Systematic analysis outside these periods does not seem necessary.
- In addition, waste management, especially **medical waste**, is of utmost importance, in general and in times of pandemic. The soil should not be the receptacle for face masks and other materials that carry virus particles. Therefore, municipalities must raise public awareness of personal responsibility regarding the uncontrolled dumping of masks on the streets and the disposal of covid test kits on trash cans that end up in sanitary landfills.
- The **workforce that manages urban waste** is particularly exposed and must be protected as such.
- About parks and playgrounds for **children** (*e.g.,* sandboxes), the same general recommendations relating to the risks of soil contamination by different substances apply.
- While it is difficult to **prioritize the risks** according to the sources (air, water, soil, medical waste), it is important to consider that the urban soil constitutes a compartment to be considered in the same way as solid waste, and liquid effluents. But more information is needed on the risks associated with urban soils to establish prioritization.
- Many different **departments of public authority** need to be involved, from environment, health, to economic development. There is a need for interdisciplinary engagement and synergies in terms of funding and planning.
- Finally, it is important for the public authorities to better direct **public funding** to be able to benefit from more relevant information and make the right decisions regarding public health and in the event of a pandemic. For this, many questions that have been raised in the chapter "Recommendations for research" must be studied. Most of these questions can be answered, provided that the financial means are invested by the public authorities.
- In general, the pandemic situation is an opportunity to initiate operations to **inform citizens about the role of soils** in the functioning of the urban ecosystem and more particularly their importance in the processes that control the future of viruses and their transfer to populations. Providing sufficient information is available, the **fate of viruses** in the urban ecosystem would be presented, with a focus on the soil, then a description

of the fate of viruses and other contaminants. This could allow everyone to understand the risk of infection related to soil contamination. This would make it possible to present the advantages (services) that soils provide in terms of contamination attenuation (*e.g.,* inactivation, immobilization, and transport of viruses and chemical contaminants) and to highlight their importance for the control of health safety in the city.

These recommendations are part of the more general framework of the prevention of risks related to soil contamination. They are not specific to viruses and, on the contrary, have a broad scope, including biological and chemical contaminants. They also illustrate that soils function as a reactor within which various transformations of viral particles take place (*e.g.,* inactivation, immobilization, transport). Information is one of the keys that would make it possible to better manage soils with a view to increasing the ecosystem services they provide to the urban environment and, in the event of a pandemic, to dispelling doubts regarding populations. However, scientific knowledge remains fragmentary about the complexity of the processes and situations encountered in soils. Also, it is essential to set up research programs directly dedicated to these questions which are crucial in times of crisis and to provide decision-makers with the best and most recent information.

IV. References

Adelodun, B., Fidelis Odedishemi Ajibade, AbdulGafar Olatunji Tiamiyu, Nathaniel Azubuike Nwogwu, Rahmat Gbemisola Ibrahim, Pankaj Kumar, Vinod Kumar, Golden Odey, Krishna Kumar Yadav, Afzal Husain Khan, Marina M.S. Cabral-Pinto, Kola Yusuff Kareem, Hashim Olalekan Bakare, Temitope Fausat Ajibade, Quadri Noorulhasan Naveed, Saiful Islam, Oluniyi Olatunji Fadare, Kyung Sook Choi. (2021). Monitoring the presence and persistence of SARS-CoV-2 in water-food-environmental compartments: State of the knowledge and research needs, *Environmental Research*, 200, 111373, ISSN 0013-9351, https://doi.org/10.1016/j.envres.2021.111373.

Albert S, Alberto A. Amarilla, Ben Trollope, Julian D.J. Sng, Yin Xiang Setoh, Nathaniel Deering, Naphak Modhiran, Sung-Hsia Weng, Maria C. Melo, Nicholas Hutley, Avik Nandy, Michael J. Furlong, Paul R. Young, Daniel Watterson, Alistair R. Grinham, Alexander A. Khromykh. 2021. Assessing the potential of unmanned aerial vehicle spraying of aqueous ozone as an outdoor disinfectant for SARS-CoV-2. *Environmental Research*, 196, 110944, ISSN 0013-9351, https://doi.org/10.1016/j.envres.2021.110944.

Anand, U., Adelodun, B., Pivato, A., Suresh, S., Indari, O., Jakhmola, S., Jha, H.C., Jha, P. K., Tripathi, V., Di Maria, F., 2021a. A review of the presence of SARS-CoV-2 RNA in wastewater and airborne particulates and its use for virus spreading surveillance. *Environ. Res.* 196, 110929. https://doi.org/10.1016/j.envres.2021.110929.

Assis, M., Simoes, L.G.P., Tremiliosi, G.C., Coelho, D., Minozzi, D.T., Santos, R.I., Vilela, D.C.B., do Santos, J.R., Ribeiro, L.K., Rosa, I.L.V., *et al.,* (2021). SiO_2-Ag Composite as a Highly Virucidal Material: A Roadmap That Rapidly Eliminates SARS-CoV-2. *Nanomaterials*, 11, 638.

Bai, H., 2017. Bio-colloidal transfer in saturated and unsaturated porous media: influence of the physical heterogeneity of the porous medium and cell properties on bacteria transport and deposition mechanisms. PhD dissertation, Université Technologique de Compiègne. 190 p.

Bai, H., Cochet, N., Pauss, A., Lamy, E., 2016. Bacteria cell properties and grain size impact on bacteria transport and deposition in porous media. Colloids Surf. B139, 148–155.

Balboa, S., Mauricio-Iglesias, M., Rodriguez, S., Martínez-Lamas, L., Vasallo, F.J., Regueiro, B., Lema, J.M., 2020. The Fate of SARS-COV-2 in Wastewater Treatment Plants Points Out the Sludge Line as a Suitable Spot for Incidence Monitoring. https://doi.org/10.1101/2020.05.25.20112706 medRxiv.

Behzadinasab, S.; Chin, A.; Hosseini, M.; Poon, L.; Ducker, W.A. A Surface Coating That Rapidly Inactivates SARS-CoV-2. ACS *Appl. Mater. Interfaces* 2020, 12, 34723–34727.

Betancourt W.Q., Schijven J., Regnery J., Wing A., Morrison C.M., Drewes J.E., Gerba C.P., 2019. Variable non-linear removal of viruses during transport through a saturated soil column. *J. Contam. Hydrol*. 223, 103479.

Blanco, A., Abid, I., Al-Otaibi, N., Perez-Rodriguez, F.J., Fuentes, C., Guix, S., Pinto, R.M., Bosch, A., 2019. Glass wool concentration optimization for the detection of enveloped and non-enveloped waterborne viruses. *Food Environ. Virol*. 11 (2),184–192.

Bosch, A., Pint´o, R.M., Abad, F.X., 2006. Survival and transport of enteric viruses in the environment. In*: Viruses in Foods*. https://doi.org/10.1007/0-387-29251-9_6.

Bradford, S.A., Feike, L.J., Schijven, J., Torkzaban, S., 2017. Critical role of preferential flow in field-scale pathogen transport and retention. *Vadose Zone J*. 16 (4), 1-13.

Breitbart, M., Rohwer, F., 2005. Here a virus, there a virus, everywhere the same virus? *Trends Microbiol*. 13, 278–284. https://doi.org/10.1016/j.tim.2005.04.003.

Burghardt W, Morel JL, Zhang GL. 2015. Development of the soil research about urban, industrial, traffic, mining, and military areas (SUITMA). *Soil Science and Plant Nutrition*, 3-21

Cao, J., Zhang, Y., Chen, Q. *et al.,* 2021 Ozone Gas Inhibits SARS-CoV-2 Transmission and Provides Possible Control Measures. *Aerosol Sci Eng* 5:516–523. https://doi.org/10.1007/s41810-021-00118-1)

Cao, H., Tsai, F.T.C., Rusch, K.A., 2010. Salinity and soluble organic matter on virus sorption in sand and soil columns. *Groundwater* 48 (1), 42–52.

Chirizzi D, Conte M, Feltracco M, Dinoi A, Gregoris E, Barbaro E, La Bella G, Ciccarese G, La Salandra G, Gambaro A, Contini D (2021). SARS-CoV-2 concentrations and virus-laden aerosol size distributions in outdoor air in north and south of Italy. *Environ Int* 146:106255

Chrysikopoulos, C.V., Sim, Y., 1996. One-dimensional virus transport in homogeneous porous media with time-dependent distribution coefficient. *J. Hydrol.* 185, 199-219.

Chrysikopoulos, C.V., Aravantinou, A.F., 2014. Virus attachment onto quartz sand: Role of grain size and temperature. *J. Environ. Chem. Eng.* 2 (2), 796–801

Curtis L. (2021). PM2.5, NO_2, wildfires, and other environmental exposures are linked to higher Covid 19 incidence, severity, and death rates. *Environmental Science and Pollution Research* 28: 54429-54447.

de Kimpe C., Morel J.L. 2000. Urban soils: a growing concern. *Soil Science*, 165:31-40.

de Rooij MMT, Hakze-Van der Honing RW, Hulst MM, Harders F, Engelsma M, van de Hoef W, Meliefste K, Nieuwenweg S, Oude Munnink BB, van Schothorst I, Sikkema RS, van der Spek AN, Spierenburg M, Spithoven J, Bouwstra R, Molenaar RJ, Koopmans M, Stegeman A, van der Poel WHM, Smit LAM. Occupational and environmental exposure to SARS-CoV-2 in and around infected mink farms. *Occup Environ Med*. 2021, 78:893-899. doi: 10.1136/oemed-2021-107443.

Du Y.J., Wu J., Bo Y.L. Jiang N.J. 2020. Effects of acid rain on physical, mechanical, and chemical properties of GGBS–MgO solidified/ stabilized Pb-contaminated clayey soil. *Acta Geotechnica* 15:23–932, https://doi.org/10.1007/s11440-019-00793-y.

El-Ramady H, Brevik EC, Elbasiouny H, Elbehiry F, Amer M, Elsakhawy T, Omara AE, Mosa AA, El-Ghamry AM, Abdalla N, Rezes S. Planning for disposal of COVID-19 pandemic wastes in developing countries: a review of current challenges. *Environmental Monitoring and Assessment*. 2021 Sep;193(9):1-15.

Farooq S., Tizaoui C. 2022. A critical review on the inactivation of surface and airborne SARS-CoV-2 virus by ozone gas, *Critical Reviews in Environmental Science and Technology*, DOI:10.1080/10643389.2022.2043094

Fedorenko A, Grinberg M, Orevi T, Kashtan, N 2020. Survival of the enveloped bacteriophage Phi6 (a surrogate for SARS-CoV-2) in evaporated saliva microdroplets deposited on glass surfaces. *Scientific Reports*, 10:22419 DOI10.1038/s41598-020-79625-z

Feng, H.R., Ruan, Y.F., Wu, R.B., Zhang, H.Y., Lam, P.K.S., 2019. Occurrence of disinfection by-products in sewage treatment plants and the marine environment in Hong Kong. *Ecotoxicol. Environ. Saf.* 181, 404–411.

Flury, M., Aramrak, S., 2017. Role of air-water interfaces in colloid transport in porous media: A review. *Water Resour. Res.* 53 (7), 5247–5275.

Foladori, P., Cutrupi, F., Segata, N., Manara, S., Pinto, F., Malpei, F., Bruni, L., La Rosa, G., 2020. SARS-CoV-2 from faeces to wastewater treatment: what do we know? A review. *Science of the. Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.140444.

Gargiulo, G., Bradford, S.A., Simunek, J., Ustohal, P., Vereecken, H., Klumpp, E., 2008. Bacteria transport and deposition under unsaturated flow conditions: the role of water content and bacteria surface hydrophobicity. *Vadose Zone J.* 7(2), 406–419.

Gholipour, S., Ghalhari, M.R., Nikaeenc, M., Rabbani, D., Pakzad, P., Miranzadeh, M.G., 2022. Occurrence of viruses in sewage sludge: A systematic review. *Science of the Total Environment*. 824, 153886

Gorguner, M., S. Aslan, T. Inandi, Z. Cakir (2004). Reactive airways dysfunction syndrome in housewives due to a bleach-hydrochloric acid mixture. *Inhal. Toxicol.*, 16, 87-91

Guti´errez, R.A., Buchy, P., 2012. Contaminated soil and transmission of influenza virus (H5N1). *Emerg. Infect. Dis.* 18, 1530.

Han J., He S. 2021. Urban flooding events pose risks of virus spread during the novel coronavirus (COVID-19) pandemic. *Science of the. Total Environment.*

Haque M.A., Chen B. 2019 Research progresses on magnesium phosphate cement: a review. *Construction and Building Materials* 211:885–898, https://doi.org/10.1016/j.conbuildmat.2019.03.304.

Herman, J., Biegel, B., Huang, L., 2020. Inactivation times from 290 to 315 nm UVB in sunlight for SARS coronaviruses CoV and CoV-2 using OMI satellite data for the sunlit. *Earth. Air Qual. Atmos. Heal.* https://doi.org/10.1007/s11869-020-00927-2.

Heyde B.J., Anders A., Siebe C., Siemens J. Mulder I. 2021 Quaternary alkylammonium disinfectant concentrations in soils rise exponentially after long-term wastewater irrigation. *Environ. Res. Lett.* 16:064002 https://doi.org/10.1088/1748-9326/abf0cf

Hora, P.I., S.G. Pati, P.J. McNamara, W.A. Arnold. Increased use of quaternary ammonium compounds during the SARS-CoV-2 pandemic and beyond: consideration of environmental implications. *Environ. Sci. Technol. Lett.*, 7 (9) (2020), pp. 622-631

Horswell, J., Hewitt, J., Prosser, J., Van Schaik, A., Croucher, D., MacDonald, C., Burford, P., Susarla, P., Bickers, P., Speir, T., 2010. Mobility and survival of Salmonella Typhimurium and human adenovirus from spiked sewage sludge applied to soil columns. *J. Appl. Microbiol.* https://doi.org/10.1111/j.1365-2672.2009.04416.x.

Hosseini, M.; Behzadinasab, S.; Chin, A.W.H.; Poon, L.L.M.; Ducker, W.A. (2021a). Reduction of Infectivity of SARS-CoV-2 by Zinc Oxide Coatings. *ACS Biomater. Sci. Eng.*, 7, 5022–5027.

Hosseini, M.; Chin, A.W.H.; Behzadinasab, S.; Poon, L.L.M.; Ducker, W.A. (2021b). Cupric Oxide Coating That Rapidly Reduces Infection by SARS-CoV-2 via Solids. *ACS Appl. Mater. Interfaces* 2021, 13, 5919–5928.

Huot, H, Simonnot, MO, Morel, JL. 2015. Pedogenic trends in soils formed in technogenic parent materials. *Soil Science*, 180:182-192

Iyer, M., Tiwari, S., Renu, K., Pasha, M.Y., Pandit, S., Singh, B., Raj, N., Krothapalli, S., Kwak, H.J., Balasubramanian, V., Jang, S., Bin, G., D, K., Uttpal, A., Narayanasamy, A., Kinoshita, M., Subramaniam, M.D., Nachimuthu, S.K., Roy, A., Valsala Gopalakrishnan, A., Ramakrishnan, P., Cho, S.G., Vellingiri, B., 2021. Environmental survival of SARS-CoV-2 – a solid waste perspective. *Environ. Res.* 197, 111015. https://doi.org/10.1016/j.envres.2021.111015.

Jacobs, A., Lafolie, F., Herry, J.M., Debroux, M., 2007. Kinetic adhesion of bacterial cells to sand: Cell surface properties and adhesion rate. *Colloids Surf.* B 59 (1), 35–45.

Jain, R., 2003. Horizontal gene transfer accelerates genome innovation and evolution. *Mol. Biol. Evol.* 20, 1598–1602. https://doi.org/10.1093/molbev/msg154.

Jiang, S.C., Bai, B., 2018. Influence of particle shape on the suspended particle transport and deposition in porous media. *Rock Soil Mech.* 39 (6), 2043–2051

Jones, J.B., Jackson, L.E., Balogh, B., Obradovic, A., Iriarte, F.B., Momol, M.T., 2007. Bacteriophages for plant disease control. *Annu. Rev. Phytopathol.* 45, 245–262. https://doi.org/10.1146/annurev.phyto.45.062806.094411.

Kampf, G., D. Todt, S. Pfaender, E. Steinmann. Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. *J. Hosp. Infect.*, 104 (3) (2020), pp. 246-251

Keikhosravi, G., Fadavi, S.F. (2021). Impact of the inversion and air pollution on the number of patients with Covid-19 in the metropolitan city of Tehran. *Urban Climate* 37:100867.

Kida K., Kawahigashi M., 2015. Influence of asphalt pavement construction processes on urban soil formation in Tokyo, *Soil Science and Plant Nutrition*, 61:sup1, 135-146, DOI: 10.1080/00380768.2015.1048182

Kim, M.-K., Kim, S.-B., Park, S.-J., 2008. Bacteria transport in an unsaturated porous media: incorporation of air-water interface area model into transport modelling. *Hydrol. Process.* 22 (13), 2370–2376.

Kokkinos, P., Syngouna, V.I., Tselepi, M.A., Bellou, M., Chrysikopoulos, C.V., Vantarakis, A., 2015. Transport of human adenoviruses in water saturated laboratory columns. *Food Environ. Virol.* 7 (2), 122–131.

Kumar, M., Thakur, A.K., Mazumder, P., Kuroda, K., Mohapatra, S., Rinklebe, J., Ramanathan, A., Cetecioglu, Z., Jain, S., Tyagi, V.K., Gikas, P., Chakraborty, S., Tahmidul Islam, M., Ahmad, A., Shah, A.V., Patel, A.K., Watanabe, T., Vithanage, M., Bibby, K., Kitajima, M., Bhattacharya, P. 2020. Frontier review on the propensity and repercussion of SARS-CoV-2 migration to aquatic environment. *J. Hazard. Mater. Lett.* 1, 100001. https://doi.org/10.1016/j.hazl.2020.100001.

Kuzyakov, Y., Mason-Jones, K., 2018. Viruses in soil: Nano-scale undead drivers of microbial life, biogeochemical turnover, and ecosystem functions. *Soil Biol Biochem,* 127:305–317. https://doi.org/10.1016/j.soilbio.2018.09.032.

Kwak J.I., An Y.J. 2021. Post COVID-19 pandemic: Biofragmentation and soil ecotoxicological effects of microplastics derived from face masks. *Journal of Hazardous Materials*, 416:126169.

Lal R.A. 2020a. Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. *Food Security*, 12:871–876, https://doi.org/10.1007/s12571-020-01058-3

Lal R.A. 2020b. Soil science beyond COVID-19. *Journal of Soil and Water Conservatio*n 75:79A-81A.

Lamastra, L., Suciu, N.A., Trevisan, M., 2018. Sewage sludge for sustainable agriculture: contaminants' contents and potential use as fertilizer. *Chem. Biol. Technol. Agric.* 5, 10. https://doi.org/10.1186/s40538-018-0122-3.

Laurent F., Cebron A., Schwartz C., Leyval C. 2012. Oxydation of a PAH polluted soil using modified Fenton reaction in unsaturated condition affects biological and physico-chemical properties. *Chemosphere,* 86, 659-664.

Levin MJ, Kim KHJ, Morel JL, Burghardt W, Charzynski P, Shaw RK (eds) 2016. Soils within cities - Global approaches to their sustainable management. *Catena Soil Science*, ISBN 978-3-510-65411-, 235 p.

Li L, Li Q, Huang L, Wang Q, Zhu A, Xu J, Liu Z, Li H, Shi L, Li R, Azari M, Wang Y, Zhang X, Liu Z, Zhu Y, Zhang K, Xue S, Ooi MCG, Zhang D, Chan A (2020) Air quality changes during the Covid-19 lockdown over the Yangtze River Delta Region: an insight into the impact of human activity pattern changes on air pollution variation. *Science of the. Total Environment* 732:139282

Lopman, B.; Gastañaduy, P.; Park, G.W.; Hall, A.J.; Parashar, U.D.; Vinjé, J. Environmental Transmission of Norovirus Gastroenteritis. *Curr. Opin. Virol.* 2012, 2, 96–102.

Ma, H., Bolster, C., Johnson, W.P., Li, K., Pazmino, E., Camacho, K.M., Anselmo, A.C., Mitragotri, S., 2020. Coupled influences of particle shape, surface property and flow hydrodynamics on rod-shaped colloid transport in porous media. J. Colloid Interface Sci. 577, 471–480.

Malmgren *et al*, 2022. Spread and survival of enveloped virus particles in outdoor conditions – Bacteriophage Phi6 used as substitute for Coronaviruses. *Manuscript in preparation.*

Mancuso, G.; Perulli, G.D.; Lavrni´c, S.; Morandi, B.; Toscano, A. 2021. SARS-CoV-2 from Urban to Rural Water Environment: Occurrence, Persistence, Fate, and Influence on Agriculture Irrigation. A Review. *Water*, 13, 764. https://doi.org/10.3390/w13060764

Mantlo, E.K.; Paessler, S.; Seregin, A.; Mitchell, A. 2021. Luminore CopperTouch Surface Coating Effectively Inactivates SARS-CoV-2, Ebola Virus, and Marburg Virus in Vitro. *Antimicrob. Agents Chemother*. 65, e01390-20

Martínez-Puchol, S., Rusi˜nol, M., Fern´andez-Cassi, X., Timoneda, N., Itarte, M., Andr´es, C., Ant´on, A., Abril, J.F., Girones, R., Bofill-Mas, S., 2020. Characterisation of the sewage virome: comparison of NGS tools and occurrence of significant pathogens. *Science of the. Total Environment*. 713, 136604. https://doi.org/10.1016/j. scitotenv.2020.136604.

Medina-Ramón, M., J.P. Zock, M. Kogevinas, J. Sunyer, Y. Torralba, A. Borrell, F. Burgos, J.M. Antó. (2005) Asthma, chronic bronchitis, and exposure to irritant agents in occupational domestic cleaning: a nested case-control study. *Occup. Environ. Med.,* 62:598-606

Michen, B., Graule, T. (2010). Isoelectric points of viruses. *J Appl Microbiol*. https://doi. org/10.1111/j.1365-2672.2010.04663.x.

Mlcochova, P.; Chadha, A.; Hesselhoj, T.; Fraternali, F.; Ramsden, J.J.; Gupta, R.K. (2020) Extended In Vitro Inactivation of SARS-CoV-2 by Titanium Dioxide Surface Coating. bioRxiv, 1–10.

Mohan, S.V., Hemalatha, M., Kopperi, H., Ranjith, I., Kumar, A.K. (2021). SARS-CoV-2 in environmental perspective: occurrence, persistence, surveillance, inactivation, and challenges. *Chem Eng J*. 405, 126893. https://doi.org/10.1016/j.cej.2020.126893.

Mohanty, S.K., Boehm, A.B. (2014a). *Escherichia coli* removal in biochar-augmented biofilter: effect of infiltration rate, initial bacterial concentration, biochar particle size, and presence of compost. Environ. Sci. Technol. 48 (19), 11535–11542.

Mohanty, S.K., Cantrell, K.B., Nelson, K.L., Boehm, A.B. (2014b). Efficacy of biochar to remove *Escherichia coli* from stormwater under steady and intermittent flow. Water Res. 61, 288–296.

Morel JL, Chenu C, Lorenz K. (2015). Ecosystem services provided by soils of urban, industrial, traffic, mining, and military areas (SUITMAs). *Journal of Soils and Sediments*, 15:1659-1666

Moresco, V., Olivera, D.M., Weidmann, M., Matallana-Surget, S., Quilliam, R.S. (2021). Survival of human enteric and respiratory viruses on plastics in soil, freshwater, and marine environments. Environ. Res. 199, 111367.

Mosselhy, D.A.; Kareinen, L.; Kivistö, I.; Virtanen, J.; Loikkanen, E.; Ge, Y.; Maunula, L.; Sironen, T. (2022) Inhibition of SARS-CoV-2 Alpha Variant and Murine Noroviruses on Copper-Silver Nanocomposite Surfaces. *Nanomaterials*, 12, 1037. https://doi.org/10.3390/ nano12071037

Nehls, T., Shaw, R. (2015). Black Carbon in Soils: Relevance, Analysis, Distribution. *Soil Horizons, Soil Science Society of America,* 51:79-84

Nehls, T., Rokia, S., Mekiffer, B., Schwartz, C., Wessolek, G. (2013). Contribution of bricks to urban soil properties. *Journal of Soils and Sediments*. 13: 575-584. DOI: 10.1007/s11368-012-0559-0

Nú˜nez-Delgado, A., (2020)a. What do we know about the SARS-CoV-2 coronavirus in the environment? *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.138647.

Nú˜nez-Delgado A. (2020)b. SARS-CoV-2 in soils. *Environmental Research*, 190:110045

Oksanen, L; Auvinen, M; Kuula, J; Malmgren, R; Romantschuk, M; Hyvärinen, A; Laitinen, S; Maunula, L; Sanmark, E; Geneid, A; Sofieva, S; Salokas, J; Veskiväli, H; Sironen, T; Grönholm, T; Hellsten, A; Atanasova, N (2022). Combining Phi6 as a surrogate virus and computational large-eddy simulations to study airborne transmission of SARS-CoV-2 in a restaurant. *Indoor Air* (in press).

Papirio, S., Zou, G., Ylinen, A., Di Capua, F., Pirozzi, F., Puhakka, J.A. (2014). Effect of arsenic on nitrification of simulated mining water. *Bioresour Technol*. 164, 149–154. https://doi.org/10.1016/j.biortech.2014.04.072.

Parveen N., Chowdhury S., Goel S. (2021). Environmental impacts of the widespread use of chlorine-based disinfectants during the COVID-19 pandemic. *Environmental Science and Pollution Research* https://doi.org/10.1007/s11356-021-18316-2

Patel, M., Chaubey, A.K., Pittman, C.U., Mlsna, T., Mohan, D. (2020). Coronavirus (SARS-CoV-2) in the environment: occurrence, persistence, analysis in aquatic systems and possible management. *Science of the Total Environment*. https://doi.org/10.1016/j. scitotenv.2020.142698.

Paul, D., Kolar, P., Hall, S.G. (2021). A review of the impact of environmental factors on the fate and transport of coronaviruses in aqueous environments. Clean.Water 4 (1), 7.

Pietramellara G., Pathan *S.I.,* Datta R., Vranová V., Ceccherini M.T., Nannipieri P. (2021). Perspective on the status and behaviour of SARS-CoV-2 in soil. *Saudi Journal of Biological Sciences*

Qiao F., Chau C.K., Li Z. (2010). Property evaluation of magnesium phosphate cement mortar as patch repair material. Construction and Building Materials 24:695–700, https://doi.org/10.1016/j.

Qin, Y.Q., Wen, Z., Zhang, W.J., Chai, J.F., Liu, D., Wu, S.Y. (2020). Different roles of silica nanoparticles played in virus transport in saturated and unsaturated porous media. Environ. Pollut. 259, 113861.

Rahman, M.M., Bodrud-Doza, M., Griffiths, M.D., Mamun, M.A. (2020). Biomedical waste amid COVID-19: perspectives from Bangladesh. *Lancet Glob Heal* https://doi.org/ 10.1016/S2214-109X(20)30349-1.

Ratnesar-Shumate, S., Williams G., Green B., Krause M., Holland B., Wood S., Bohannon J., Boydston J., Freeburger D., Hooper I., Beck K., Yeager J., Altamura L.A., Biryukov J., Yolitz J., Schuit M., Wahl V., Hevey M., Dabisch P. (2020). Simulated Sunlight Rapidly Inactivates SARS-CoV-2 on Surfaces, *The Journal of Infectious Diseases*, 222:214–222, https://doi.org/10.1093/infdis/jiaa274

Rees, F., Dagois, R., Derrien, D., Fiorelli, J-L., Watteau, F., Morel, J.L., Schwartz, C., Simonnot, M-O., Séré, G. (2018) Storage of carbon in constructed technosols: *in situ* monitoring over a decade. *Geoderma* 337:641-648

Regenmortel, M.H.V. (2000). Introduction to the species concept in virus taxonomy. In virus taxonomy. Seventh report of the international committee on taxonomy of viruses. In: *Biological Centrifugation*.

Rossiter, D.G. (2007). Classification of Urban and Industrial Soils in the World Reference Base for Soil Resources. *Journal of Soils and Sediments* 7: 96-100

Sagripanti, J.-L., Lytle, C.D. (2020) Estimated Inactivation of Coronaviruses by Solar Radiation With Special Reference to COVID-19. *Photochem Photobiol*, 96: 731-737. https://doi.org/10.1111/php.13293

Salokas *et al*. *(*2022). Removal of airborne virus particles from indoor spaces using filtration – bacteriophage Phi6 used as substitute for Coronavirus. *Manuscript in preparation*.

Sarkar, M., Saha, S. (2020). Structural insight into the role of novel SARS-CoV-2 E protein: A potential target for vaccine development and other therapeutic strategies. *PLoS ONE* 15, (8) e0237300.

Sasidharan, S., Torkzaban, S., Bradford, S.A., Cook, P.G., Gupta, V.V.S.R. (2017). Temperature dependency of virus and nanoparticle transport and retention in saturated porous media. *J. Contaminant Hydrol*. 196, 10–20.

Schijven, J.K., Hassanizadeh, S. (2000). Removal of viruses by soil passage: overview of modeling, processes, and parameters. *Crit. Rev. Environ. Sci. Technol*. 30 (1), 49-127.

Schinner, T., Letzner, A., Liedtke, S., Castro, F.D., Eydelnant, I.A., Tufenkji, N. (2010). Transport of selected bacterial pathogens in agricultural soil and quartz sand. *Water Res*. 44 (4), 1182–1192.

Sen, K.T., Khilar, K.C., 2006. Review on subsurface colloids and colloid associated contaminant transport in saturated porous media. *Adv. Colloid Interface Sci*. 119 (2e3), 71e96.

Séré G., Schwartz C., Ouvrard S., Sauvage C., Renat J.C., Morel J.L. (2008). Soil Construction: A Step for Ecological Reclamation of Derelict Lands. *Journal of Soils and Sediments*, 8:130-136

Shao, LY; Ge, SY; Jones, T; Santosh, M; Silva, LFO; Cao, YX; Oliveira, MLS; Zhang, MY; BeruBe, K. (2021). *Geoscience Frontiers* 12:101189; DOI10.1016/j.gsf.2021.101189

Tang C.S., Paleologos E.K., Vitone Y.J. *et al*. (2021). Environmental geotechnics: challenges and opportunities in the post-Covid-19 world. *Environmental Geotechnics* 8:172–192. https://doi.org/10.1680/jenge.20.00054

Tung NT, Cheng PC, Chi KH, Hsiao TC, Jones T, BeruBe K, Ho KF, Chuang HC (2021) Particulate matter and SARS-CoV-2: a possible model of Covid-19 transmission. *Science of the. Total Environment* 750:141532

Turgeon N, Toulouse MJ, Martel B, Moineau S, Duchaine C. (2014) Comparison of Five Bacteriophages as Models for Viral Aerosol Studies. *Applied and Environmental Microbiology* 80 4242–4250.

Vasenev, V., Dovletyarova, E., Cheng, Z., Prokof'eva, T.V., Morel, J.L., Ananyeva, N.D. (2018). Urbanization: Challenge and Opportunity for Soil Functions and Ecosystem Services. Springer ISBN 978-3-319-89601-4

Vaverková M.D., Paleologos E.K., Dominijanni A. *et al.,* (2021). Municipal solid waste management under Covid-19: challenges and recommendations. *Environmental Geotechnics* 8:217–232, https://doi.org/10.1680/jenge.20.00082

Vidal Beaudet, L., Rokia, S., Nehls, T., Schwartz, C. 2016. Aggregation and availability of phosphorus in a Technosol constructed from urban wastes. *Journal of Soils and Sediments*, 10.1007/s11368-016-1469-3

Walshe, G.E., Pang, L., Flury, M., Close, M.E., Flintoft, M. (2010). Effects of pH, ionic strength, dissolved organic matter, and flow rate on the co-transport of MS2 bacteriophages with kaolinite in gravel aquifer media. Water Res. 44:1255–1269.

Wigginton, K.R., Pecson, B.M., Sigstam T.r., Bosshard F., Kohn T. (2012) Virus inactivation mechanisms: impact of disinfectants on virus function and structural integrity. *Environ. Sci. Technol.*, 46 :12069-12078

Wigginton, K.R., Boehm, A.B. (2020). Environmental engineers and scientists have important roles to play in stemming outbreaks and pandemics caused by enveloped viruses. *Environ Sci Technol.* https://doi.org/10.1021/acs.est.0c01476.

Wiktorczyk-Kapischke N., Grudlewska-Buda K., Wałecka-Zacharska E., Kwiecińska-Piróg J., Radtkec L., Gospodarek-Komkowska E., Skowron K. (2021). SARS-CoV-2 in the environment - Non-droplet spreading routes. *Science of the. Total Environment*, 770:145260

Wong, K., Voice, T.C., Xagoraraki, I. (2013). Effect of Organic Carbon on Sorption of Human Adenovirus to Soil Particles and Laboratory Containers. *Water Research*, https://doi.org/ 10.1016/j.watres.2013.03.029.

Wong, K., Bouchard, D., Molina, M. (2014). Relative transport of human adenovirus and MS2 in porous media. *Colloids Surf. B* 122, 778–784.

Xia W.Y., Du Y.J., Li F.S. *et al*. (2019). In-situ solidification/stabilization of heavy metals contaminated site soil using a dry jet mixing method and new hydroxyapatite based binder. *Journal of Hazardous Materials* 369: 353–361, https://doi.org/10.1016/j.jhazmat.2019.02.031.

Yan, L.J., Herrmann, M., Kampe, B., Lehmann, R., Totsche, K.U., Kusel, K., 2020. Environmental selection shapes the formation of near-surface groundwater microbiomes. *Water Res*. 170, 115341.

Yates, M.V., Yates, S.R., (1998). Virus survival and transport in groundwater. *Water Sci. Technol.* 20 (11/12), 301-307.

Zand, A.D., Heir, A.V. (2020). Emerging challenges in urban waste management in Tehran, Iran during the COVID-19 pandemic. *Resour Conserv Recycl* 162, 105051. https://doi.org/10.1016/j.resconrec.2020.105051.

Zhang, W., Chai, J., Li, S., Wang, X., Wu, S., Liang, Z., Jat Baloch, M.Y., Silva, L.F.O., Zhang, D. (2022). Physiological characteristics, geochemical properties and hydrological variables influencing pathogen migration in subsurface system: What we know or not? *Geoscience Frontiers* 13(6), 101346.

Zhang, W.J., Li, S., Wang, S., Lei, L.C., Yu, X.P., Ma, T.Y., 2018. Transport of *Escherichia coli* phage through saturated porous media considering managed aquifer recharge. *Environ. Sci. Pollut.* Res. 25 (7), 6497–6513.

Zhang, W., Morales, V.L., Cakmak, M.E., Salvucci, A.E., Geohring, L.D., Hay, A.G., Parlange, J.Y., Steenhuis, T.S. (2010). Colloid transport and retention in unsaturated porous media: effect of colloid input concentration. *Environ. Sci. & Technol.* 44 (13), 4965e4972.

Zhang, W.J., Wu, S.Y., Qin, Y.Q., Li, S., Lei, L.C., Sun, S.M., Yang, Y.S., 2021. Deposition and mobilization of viruses in unsaturated porous media: Roles of different interfaces and straining. *Environ. Pollut.* 270, 116072.

Zhang, D., Yang, Y., Huang, X., Jiang, J., Li, M., Zhang, X., Ling, H., Li, J., Liu, Y., Li, G., Li, W., Yi, C., Zhang, T., Jiang, Y., Xiong, Y., Hu, Z., Wang, X., Deng, S., Zhao, P., Qu, J., He, Z., Wang, X., Deng, S., Zhao, P., Qu, J., 2020. SARS-CoV-2 spillover into hospital outdoor environments. medRxiv. https://doi.org/10.1101/ 2020.05.12.20097105, 2020.05.12.20097105.

Zhang P., Wang K., Li Q., Wang J., Ling Y. 2020. Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders – a review. *Journal of Cleaner Production* 258: article 120896, https://doi.org/10.1016/j.jclepro.2020.120896.

Zoran, MA, Savastru, RS, Savastru, DM, Tautan, MN, Baschir, LA, Tenciu, DV. 2021. Exploring the linkage between seasonality of environmental factors and COVID-19 waves in Madrid, Spain, *Process Safety and Environmental Protection*, 152:583-600, ISSN 0957-5820, https://doi.org/10.1016/j.psep.2021.06.043.