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A review of compaction effect on subsurface processes in soil: Implications on stormwater treatment in roadside compacted soil

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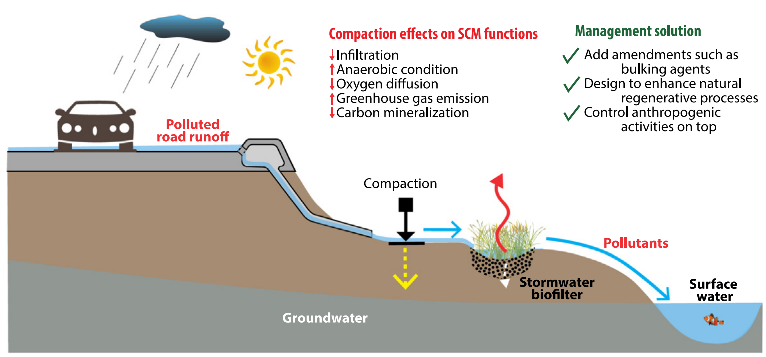
HIGHLIGHTS

- Compaction decreased infiltration capacity but adding sand restored the capacity.
- Moderate compaction appeared to have a limited impact on root biomass.
- Compaction could reduce plant uptake of N and P and increase nutrient export.
- Compaction decreased oxygen diffusion by 36.2 %.
- Compaction would increase emission of greenhouse gases from soils.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable cities require spacious infrastructures such as roadways to serve multiple functions, including transportation and water treatment. This can be achieved by installing stormwater control measures (SCM) such as biofilters and swales on the roadside compacted soil, but compacted soil limits infiltration and other functions of SCM. Understanding the effect of compaction on subsurface processes could help design SCM that could alleviate the negative impacts of compaction. Therefore, we synthesize reported data on compaction effects on subsurface processes, including infiltration rate, plant health, root microbiome, and biochemical processes. The results show that compaction could reduce runoff infiltration rate, but adding sand to roadside soil could alleviate the negative impact of compaction. Compaction could decrease the oxygen diffusion rate in the root zone, thereby affecting plant root activities, vegetation establishment, and microbial functions in SCM. The impacts of compaction on carbon mineralization rate and root biomass vary widely based on soil type, aeration status, plant species, and inherent soil compaction level. As these processes are critical in maintaining the long-term functions of SCM, the analysis would help develop strategies to alleviate the negative impacts of compaction and turn road infrastructure into a water solution in sustainable cities.

Contents

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1. Introduction

For a city to be sustainable, critical natural resources such as water and land must be managed without depleting or degrading them (Chang et al., 2020). By 2050, 70 % of the world's population is projected to live in urban areas, which are severely water-stressed in many regions (Ahmadi et al., 2020; He et al., 2021; United Nations, 2018). Further, the development of new urbanization infrastructures such as roads, metro, railways, and buildings causes environmental degradation, resource depletion, and ecological footprint. Impervious cover and compaction of the soils during urban development not only limit natural infiltration and recharge of groundwater (Pitt et al., 2008; Edmondson et al., 2011), but also increase flooding severity and pollution of surface waters (dos Santos et al., 2021; McGrane, 2016; Müller et al., 2020; Pour et al., 2020). Among all types of urban development, roads contribute to a large fraction of impervious areas (Frazer, 2005; Vogler and Vukomanovic, 2021). However, road expansion is necessary during the city's expansion as efficient roadways are an integral part of a nation's economy. For sustainable development, road infrastructure needs to serve multiple functions (Marcucci and Jordan, 2013). Installing stormwater control measures such as biofilters and swales on the roadside could enhance the infiltration and treatment of stormwater (Cheng and Wang, 2018; Rivers et al., 2021; Sileshi et al., 2012; Winston et al., 2012). Roadside SCM could also provide other benefits, including carbon sequestration and ecological habitat restoration (Alam et al., 2021; Kavehei et al., 2018; Prudencio and Null, 2018; Säumel et al., 2016). Treatment and reuse of contaminated road runoff can transform the nation's road infrastructure from a leading cause of water pollution to a network of water solutions to solve water scarcity issues in urban areas.

With few exceptions, most SCM consists of two components: highly permeable soil or filter media layer to maximize infiltration and pollutant removal and vegetation on top for aesthetics and multiple benefits (Feng et al., 2022; Kim, 2018; Liu et al., 2021; Pitt et al., 2022; Roy-Poirier et al., 2010). The filter media increase stormwater infiltration by providing physical conduits (Grebel et al., 2013), help remove pollutants by facilitating physical and biochemical processes (Davis et al., 2009; LeFevre et al., 2015), and provide ecosystem benefits via vegetation (Ebrahimian et al., 2020; Marando et al., 2022; Pitt et al., 2002). Road banks are typically required to be compacted to 85–90 % of their capacity to prevent landslides and increase soil stability and bearing capacity. Further soil-based stormwater control measures installed in the Clear Recovery Zone could also be compacted due to construction activities such as excavation, mixing, stockpiling, equipment storage, and equipment traffic. So, the unavoidable compaction of filter media or soil in SCM can affect all critical functions of SCM as described above (Fig. 1). Compaction has a direct impact on infiltration and an indirect impact on pore water quality or the exchange of gas and nutrients between infiltrating stormwater and pore water. Compaction could modify the pore structure and connectivity and reduce infiltration rate or hydraulic conductivity (Pitt et al., 2008; Sileshi et al., 2015). Compaction could restrict the oxygen and water supply to the roots (Tracy et al., 2011; Watson and Kelsey, 2006), which could negatively impact vegetation and the rhizosphere microbial community (Colombi and Keller, 2019; Mossadeghi-Björklund et al., 2019). Poor vegetation establishment could influence pollutant removal processes (Muerdter et al., 2018). Low oxygen supply through the filter layer could help develop anaerobic conditions and alter the microbial communities (Danfoura and Gurdak, 2016; Minett et al., 2013). The changing redox condition and microbial communities could affect nutrient uptake and release (Jonasson et al., 1999), contaminant degradation (Biswal et al., 2021; Payne et al., 2014), and the release of greenhouse gases (Grover et al., 2013; Payne et al., 2017). Reduced aeration and increased anaerobic conditions within biofilters could enhance CH_4 and N_2O production (Antille et al., 2015; Payne et al., 2017). Unlike numerous studies on the compaction effect on soil function in agricultural and forest ecosystems, only a few studies have examined the extent to which compaction could affect some of the SCM functions. Some of them were conducted in controlled laboratory conditions (Ghavanloughajar et al., 2020; Le et al., 2020; Moore, 2008; Wen et al., 2020), and others were conducted in field conditions (Galli et al., 2021; Pitt et al., 2008, 2002; Schwartz and Smith, 2021; Sileshi et al., 2015, 2012). However, these studies mainly focused on the effect of compaction on infiltration or water retention behavior, ignoring the impacts of compaction on the processes that could affect pollutant removal or biodegradation. These processes relevant for SCM are rarely monitored in agriculture and forest ecosystems. Thus, it is critical to inform how compaction could affect these processes in SCM based on understanding the same in agricultural systems and identifying potential knowledge gaps unique to SCM.

The aims of the study are to synthesize the published data on the compaction effect in order to estimate the extent to which compaction could affect different processes in the subsurface and the functions of SCM, including infiltration capacity, root health, and microbial processes. Despite the importance of compaction, no review to date has analyzed the potential impacts of compaction on SCM functions. A few review articles described the effect of compaction on agriculture (Hamza and Anderson, 2005; Nawaz et al., 2013; Shah et al., 2017) and forest ecosystems (Cambi et al., 2015; Mariotti et al., 2020), where understanding the impact of compaction on plant health was the primary objective. In contrast, the main functions of SCM are infiltration and pollutant removal. Thus, the analysis could inform the design of stormwater treatment systems on the roadside where the soil is compacted according to the design guidelines for roadways.

2. Data collection

Data were collected from stormwater systems, agricultural soil, and forest ecosystem to understand the impact of compaction on different

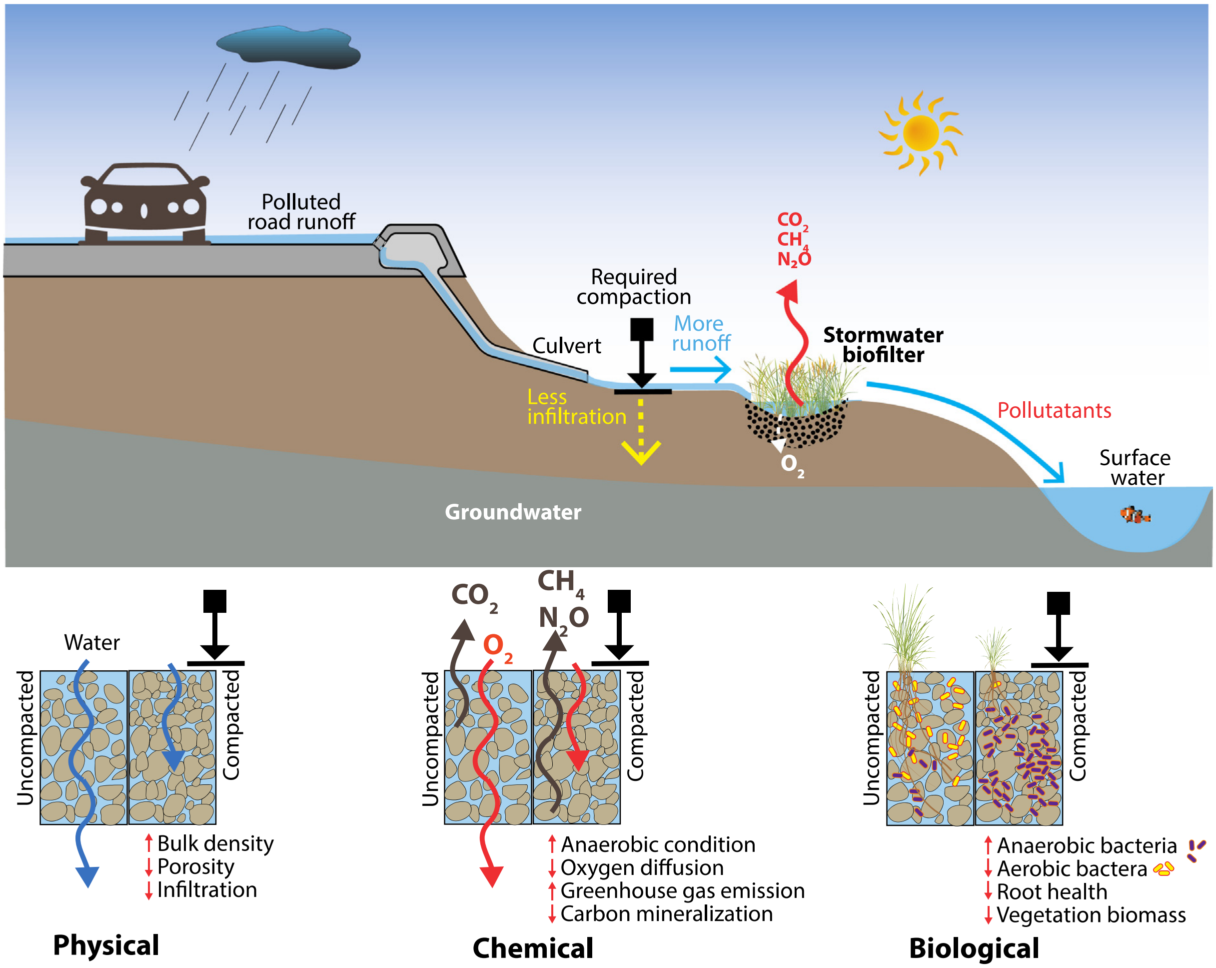

Fig. 1. Potential impacts of compaction on the performance of roadside stormwater control measures. Compaction could affect physical, chemical, and biological processes in subsurface soil. Compaction could increase bulk density, reduce infiltration rate, and decrease aeration. Compaction could induce an anaerobic environment and alter microbial communities in a way that could increase greenhouse gas emissions. Compaction could also affect vegetation health in SCM by blocking root growth and reducing nutrient uptake. All these processes could affect the water quantity, and quality of stormwater discharged into surface waters originating from road surfaces during rainfall events.

biochemical processes, as limited data is available on stormwater systems. The three key functions of SCM are infiltration rate, pollutant retention, and degradation. The subsurface processes in agricultural soil and forest ecosystem are relevant to understanding the impact of compaction on SCM functions. Reported research articles were searched in Web of Science using keywords including compaction, stormwater control measures, biofiltration, bulk density, infiltration rate, oxygen diffusion rate, root biomass, carbon mineralization, nutrient cycling, greenhouse gas emission, nitrous oxide, methane, pasture, and agriculture. All studies cataloged in the database before December 24, 2021, were included in the analysis. The search resulted in a total of 1248 articles, of which 136 articles were selected after reading the titles and abstract, where the impact of compaction on key subsurface functions was reported. After further analysis of reported data in those articles, a total of 34 articles were selected, where data was available to link compaction with the subsurface functions (Table S1). The change in bulk density was used as a measure of compaction to quantify the effect of sand addition on the soil response to compaction. The collected data was divided into two categories: compacted and uncompacted. The data from each category was compared against others to find significance difference in the observed effect of compaction using one-way analysis of variance (ANOVA). The significance of differences between two specific means was assessed with Tukey HSD post-hoc comparison, where the difference is assumed to be significant if the $p\text{-value} < 0.05$. The details of the data collection framework and analysis flow are shown in Fig. S1 (Supplementary Materials). The complete dataset used in the analysis is provided in an online open-access repository, Figshare (Das et al., 2022).

3. Compaction impacts: data analysis and opportunities

Data analysis on how compaction could affect some of the processes in SCM could help identify specific research gaps or opportunities. This section analyzed data from available data to inform the extent to which compaction could affect specific processes or parameters in SCM and identify specific research gaps. Briefly, the compaction of biofilter media changes the pore size distribution and pore connectivity, which in turn decreases the infiltration rate (Pitt et al., 2008). A decrease in infiltration could indirectly affect other functions of biofilter, such as oxygen diffusion, root growth and vegetation establishment, microbial activities, and biochemical process related to pollutant removal.

3.1. Infiltration rate

Soil compaction can decrease the infiltration rate, which is the primary function of SCM. Compaction could reduce the pore spaces, thereby decreasing natural infiltration rates (Gregory et al., 2006; Nawaz et al., 2013; Yang and Zhang, 2011). The analysis of data from both laboratory and field compaction studies (Das et al., 2022; Gregory et al., 2006; Pearson et al., 2013; Schwartz and Smith, 2021) showed that compaction reduced the infiltration rate in soil by two orders of magnitude (Fig. 2a), whereas compaction of sand or sandy soil did not significantly ($p = 0.089$) affect the infiltration rate. Based on the median value, compaction increased the soil's average bulk density by 18 % (Fig. 2b) and decreased the infiltration rate by 91 % (Fig. 2a). Comparison of median infiltration capacity of compacted soil (2.64 $mm.hr^{-1}$) vs. sand (58.98 $mm.hr^{-1}$) (Fig. 2a) indicates that the addition of sand to the urban soil could increase the infiltration rate by 22-fold despite compaction. Bulk density of compacted soil and sand mixture was increased significantly due to change in the pore volume of the media mixture as the fine size of soil particles could slip into macropores created by sand packing during compaction. However, the infiltration did not change much, as sand withstands compaction better than soil aggregate without breaking down and preserves macropore flow, which collectively helped to maintain better pore space than only soil media. The infiltration rate of compacted sand varied in a wide range due to different amounts of sand fraction presented in the sand-soil mixture. As the filter media used in SCM is typically sandy soil or a mixture of sand and soil (Tirpak et al., 2021), the compaction effect could be less detrimental than that observed in soil. Heavily compacted soils contain few large pores, thereby lowering infiltration rates (Itsukushima et al., 2021). In contrast, the presence of sand restricts the compression of some of these pore paths, thereby alleviating the negative impact of compaction. Thus, sand should be used as an effective bulking agent in stormwater infrastructure. The reported infiltration rates through compacted soil and sand are highly variable, possibly because the degree of compaction and soil types varied between the studies. The infiltration rate in compacted soil could change with the degree of compaction, soil textural class, soil moisture content, and ponded water depth (Pearson et al., 2013; Pitt et al., 2002; Sileshi et al., 2015). In sandy soil, the degree of compaction is the leading cause of infiltration reduction, whereas, in clayey soils, both the compaction level and antecedent moisture conditions were important (Pitt et al., 2008, 2002). Compaction decreases soil-saturated hydraulic conductivity by reducing macropores, which play a crucial role in soil drainage. Collectively, these results indicate that amount of sand may determine the negative impact of compaction on the infiltration capacity of roadside SCM.

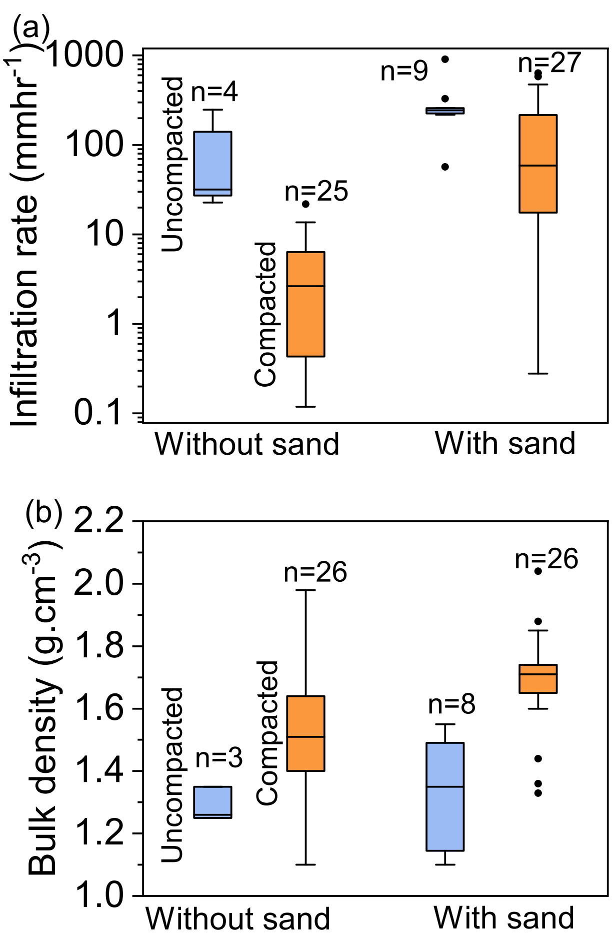

Fig. 2. (a) Effect of compaction on infiltration rate of soil amended with sand. Infiltration rate is in log scale; (b) Effect of compaction on bulk density. In the analyzed data set, soil with sand amendment bulk densities ranged from 1.1 to 1.98 $g.cm^{-3}$, where 53 % of the data had a bulk density >1.5 $g.cm^{-3}$. Soil with sand amendment bulk densities ranged from 1.3 to 2.04 $g\ cm^{-3,}$ where 80 % of the data had a bulk density larger than 1.5 $g.cm^{-3}$. Here clayey and silty soils are classified as soil without sand amendment, and all sandy soils are classified as soil with sand. Data were collected from 8 peer-reviewed articles. n is the number of data points reviewed.

Opportunities: A decrease in infiltration rate in SCM can be attributed to both compaction and clogging with sediments, but the relative importance of either is rarely studied. Compaction could also accelerate the clogging rate. Future studies should measure compaction and examine their contribution to decreasing infiltration in SCM. The analysis also reveals that sand can be an effective amendment to alleviate the negative impact of compaction. Yet the quantity of sand needed for specific soil types based on their grain size distribution is unknown. The grain size of sands determines the size of pore space between them, which in turn determines whether fine soil particles displace into the pores during compaction and lower overall hydraulic conductivity. Typically, coarse or medium size sands are used, and the presence of a higher percentage of fine (<100 μm) sands could limit the benefits of sand in increasing hydraulic conductivity (Glover and Luo, 2020). So, future studies should determine the relative size of the sand compared to soil grain size to achieve desirable hydraulic conductivity in different soil types. Future experiments could help validate models if hydraulic conductivity can be predicted based on compaction level and grain size distribution of sand and soil. While the addition of sand can restore the infiltration capacity of compacted soil, it has a limited capacity to remove pollutants (Tirpak et al., 2021). Therefore, future studies should examine the effects of sand addition on pollutant removal or transport in SCM and explore other types of bulking agents or amendments such as biochar, clay aggregate, and crushed cinder with higher pollutant removal capacity (Kuoppamäki et al., 2021; Mlih et al., 2020; Mohanty et al., 2018). The performance of these bulking material mixtures needs to be evaluated to decide their optimum size, the amounts required to improve infiltration, and how compaction affects the amendment's physical integrity and pollutant removal capacity.

3.2. Aeration or oxygen diffusion

The effect of different vehicle passes on soil aeration conditions was quantified in a few field experiments (Czyż, 2004; Czyz et al., 2001; Lipiec et al., 2012). The analysis of the results from these studies shows that compaction could decrease the oxygen diffusion rate by 36.8 % and increase the bulk density by 33.3 % based on median values (Fig. 3). When the diffusion rate decreased below 35 μg $O_2\ m^{-2}{\cdot}s^{-1}$, aeration can be considered a limiting factor in the subsurface (Szafranek-Nakonieczna and Stępniewska, 2015). The result indicates that compaction could reduce the diffusion rate to near this threshold in the vadose zone, which could limit root growth and alter microbial communities (Watson and Kelsey, 2006). Thus, compaction of the subsurface soil could affect the amount of oxygen the root zone has access to either directly by gas exchange from the atmosphere or via dissolved oxygen in stormwater. Both processes require oxygen diffusion, which is often used as an indicator of the aeration capacity (Czyż, 2004). Compaction reduces macropore spaces, which could restrict oxygen diffusion and limit the exchange of oxygenated stormwater with anoxic pore water. However, sand is typically added to filter media used in SCM, which can lower the negative impact of compaction on oxygen diffusivity. Transport of oxygen was monitored within biofilter media in relation to pollutant degradation, microbial community development, and root health (Minett et al., 2013; Subramaniam et al., 2016).

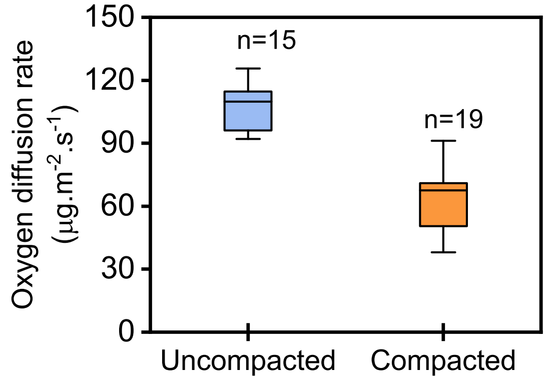

Fig. 3. Effects of compaction on oxygen diffusion rate in soil under field experiments, the bulk density of uncompacted soil: 1.23–1.54 $g.cm^{-3}$ and compacted soil 1.58–1.71 $g.cm^{-3}$. Data were collected from 3 peer-reviewed articles (Czyż, 2004; Czyz et al., 2001; Lipiec et al., 2012). n is the number of data points used.

However, no study has directly examined changes in oxygen diffusion rate as a function of the degree of compaction in stormwater biofilter systems. Analysis of synthesized data also revealed a wide variation in the measured oxygen diffusion rate in compacted soils compared to uncompacted soil, possibly due to different degrees of compaction and soil types that determine the porosity around the soil root system (Neira et al., 2015). However, the results did not account for the change in the concentration gradient that can also affect the diffusion rate. The diffusion rate can be higher when a large oxygen concentration gradient is created between macropores with fresh stormwater and anoxic zones in the submerged organic layer, where microbial activity could deplete oxygen. Higher moisture content could reduce aeration as diffusion of oxygen through water is much slower than the supply of gaseous oxygen through dry pores (Kechavarzi et al., 2010). So, antecedent drying days could affect dry pore distribution in soil and increase oxygen diffusion through pore water connected with dry pores. So, the compacted SCM experienced a longer antecedent drying period could have better oxygen diffusion into trapped pore water (Cho et al., 2011). Thus, a combination of compaction and saturation could limit oxygen supply and impair root growth in biofilters. Oxygen concentration can affect many biochemical processes in the root zone, including nitrogen and phosphorus cycling (Moreau et al., 2019).

Opportunities: Compaction could lower the oxygen transport in biofilter media, indirectly impacting vegetation establishment and pollutant degradation. Yet, no study to date has directly quantified the compaction impact on oxygen diffusion rate and its effect on pollutant removal. Among the study that measured oxygen concentration in-situ in different (Bittig et al., 2018; Elberling et al., 2011; Reiser et al., 2020; Song et al., 2019), most of the studies did not have appropriate controls or measured oxygen diffusion before compaction. Thus, future studies should use appropriate control in the same setup to estimate the effect of compaction in the short and long-term using in-situ probes. The anoxic condition created by compaction can increase the dissolution of iron, which typically releases nutrients such as phosphate (Herndon et al., 2019). Anoxic conditions could also promote denitrification (Subramaniam et al., 2016). Thus, future studies should examine whether the compaction of filter media in SCM can result in the net release or removal of nutrients such as nitrogen. Amendments could be added to improve aeration and oxygen diffusion in subsurface soil. So, future research should explore the suitability of amendments such as biochar, pumice, clay aggregate, and perlite to improve aeration status in compacted biofilter. Certain submerged plant species like *Lobelia dortmanna, rice, Eriophorum angustifolium, and seagrasses* can transfer oxygen from shoot to root via aerenchyma cell, and the oxygen in the root tip diffuses radially into the root zone (Liu et al., 2020; Rehman et al., 2017). So, future research should examine the suitability of plant species in compacted biofilters that can supply oxygen in the rhizosphere zone.

3.3. Plant functions

The analysis of limited available dataset on dry root biomass showed that there was no significant difference between biomass in compacted and non-compacted soil (Fig. 4a). The result reveals that compaction increased the bulk density from 1 to 2 $g.cm^{-3}$, resulting in the root biomass change from −75 % to +97 % (Fig. 4b). Nearly 70 % of the data shows a negative effect of compaction. This unexpected outcome resulted due to smaller data sets and a wide variation in experimental conditions with many confounding factors such as plant types, soil type, and compaction level. For instance, a moderate level of compaction resulted in a net root biomass growth compared to no-compaction control in *Acer Cappadocium*, whereas a severe compaction level decreased root growth (Jourgholami, 2018).

As plants in SCM play a critical role in transforming contaminants accumulated in the biofilters (Mehmood et al., 2021; Muerdter et al., 2018; Payne et al., 2018), compaction could negatively affect SCM function by influencing the vegetation establishment (Correa et al., 2019; Picchio et al., 2019; Tracy et al., 2011). Compaction could hinder the plant functions such as nutrient uptake and transpiration by affecting root traits and root microbiome (Longepierre et al., 2021; Mariotti et al., 2020). Poor gas diffusion in compacted soil enhanced root-secreted volatile ethylene hormone concentration in the rhizosphere, triggering plant hormone response and restricting root growth (Pandey et al., 2021). Rhizosphere

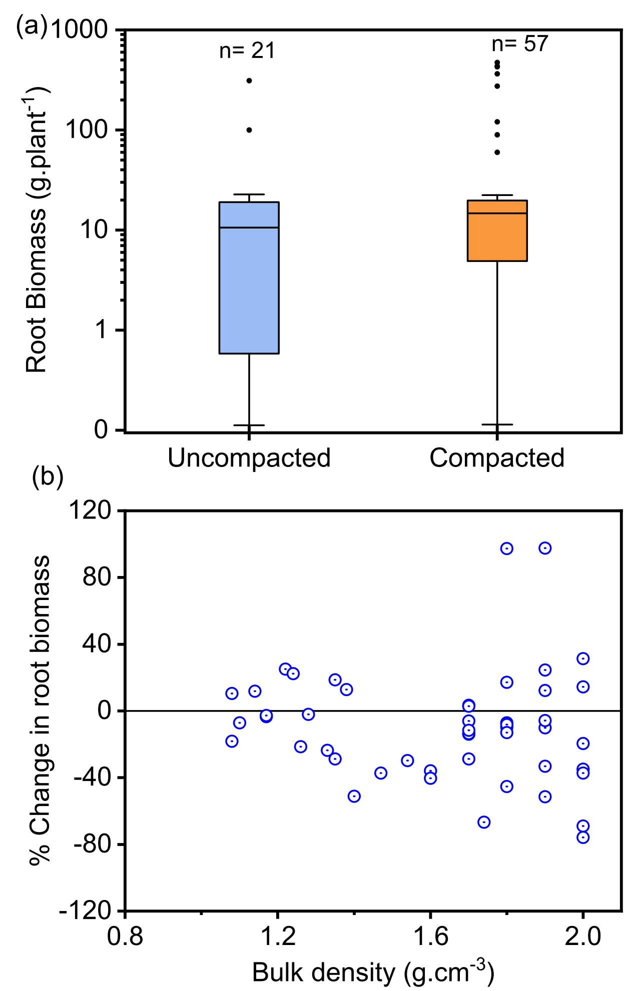

Fig. 4. (a) Effects of compaction on root biomass. Based on a limited dataset, the root biomass did not significantly change after compaction ($p > 0.05$). The bulk density of soils in the reported studies ranged between 0.9 and 2.1 $g.cm^{-3}$; (b) Changes in root biomass because of compaction. 70 % of data points show a negative effect of compaction on biomass production. Data were collected from 11 peer-reviewed articles, and n is the number of data points reviewed.

microorganisms can degrade contaminants accumulated in the filter media (Chaudhry et al., 2005; Hoang et al., 2021; Read et al., 2009), thereby recharging the adsorption capacity of filter media. Plant roots can also enhance stormwater infiltration by maintaining high hydraulic conductivity through the pore paths created after root death (Bartens et al., 2008; Hatt et al., 2009). Plants with extensive root systems improve contaminants removal performance (Hermawan et al., 2019; Palacios et al., 2021). Thus, any changes in root health by compaction could affect all these functions. Poor root growth means less access to plant-available water and nutrients, which could significantly reduce above-ground plant growth such as the growth of leaf and stem and plant height (Colombi et al., 2018; Mariotti et al., 2020). Poor aeration and reduced root growth, which are typical symptoms of compacted soil, can disrupt the rhizosphere biochemical environment, which further reduces the nutrient uptakes and alters the microbial degradation of pollutants (LeFevre et al., 2012; Mehmood et al., 2021; Muerdter et al., 2018).

Opportunities: Unlike soil, biofilter media could be composed of materials of different densities (Tirpak et al., 2021). For example, sand or soil is often mixed with amendments such as compost or biochar, which are lighter materials. The addition of these amendments can decrease the bulk density of soil (Ghavanloughajar et al., 2020). Thus, changes in bulk density in biofilter media due to compaction can be different from changes in bulk density in soil. Consequently, bulk density may not explain the degree of compaction in SCM media when compared with other studies that used soil without amendment. Thus, studies examining the extent of compaction should not use changes in bulk density as an indicator of the degree of compaction that occurred in SCM after their installation. The effect of compaction on functions of plants relevant to SCM, such as pollutant removal, plant establishment, and development of rhizosphere, is not well understood (Burr-Hersey et al., 2020; Hatt et al., 2009; Kranz et al., 2022). In particular, the effect of compaction on plants' ability to remove pollutants in SCM is understudied (Hatt et al., 2008). Compaction can also trigger plant biochemical metabolic processes, such as the release of root exudates (Badri and Vivanco, 2009). Changes in rhizosphere biochemistry can influence pollutant degradation (LeFevre et al., 2013; Muerdter and LeFevre, 2019). Mechanistic studies linking compaction level and changes in root rhizosphere chemistry are needed. For instance, certain plant species with deep rooting systems can tolerate high compaction levels and low oxygen concentrations and alleviate the compaction (Ampoorter et al., 2011; Colombi and Walter, 2017). Plant species resistant to waterlogging conditions would sometimes be helpful to combat compaction effects (Jourgholami et al., 2020, 2019). The suitability of such plant species in SCM needs to be explored further. Compaction-tolerant plant species are developed through genetic manipulation for better crop growth (Colombi and Keller, 2019). This type of work can be extended to improve SCM vegetation physiological traits to alleviate the negative impacts of compaction (Correa et al., 2019).

3.4. Carbon mineralization

To examine carbon mineralization in the field, researchers measure CO_2 emission in the field or lab incubation studies where the soil is typically repacked to field density (Chen et al., 2016). Thus, compaction can be integrated into laboratory studies to understand its impact on the carbon mineralization rate. Based on limited available data (Das et al., 2022), compaction increased bulk density by 11.5–17.7 % and altered carbon mineralization rate between −36.2 to 91.9 % (Fig. 5) compared to uncompacted soil (Jourgholami et al., 2019; Kan et al., 2020; Nazari et al., 2020). The carbon mineralization rates in compacted and uncompacted soils were not significantly different, potentially due to the high variability of the limited data set. The wide variation in carbon mineralization has been attributed to the degree of compaction, pore size distribution, soil type difference, and variability in the microbial community. As compaction increases bulk density and decreases macropores, they can be used as indicators to determine when compaction could negatively affect the carbon mineralization rate. Based on the analyzed data, when the bulk density value exceeds 1.6 g cm^{-3}, the carbon mineralization process is significantly reduced (Chen et al., 2016; Taboada et al., 1998). Compaction

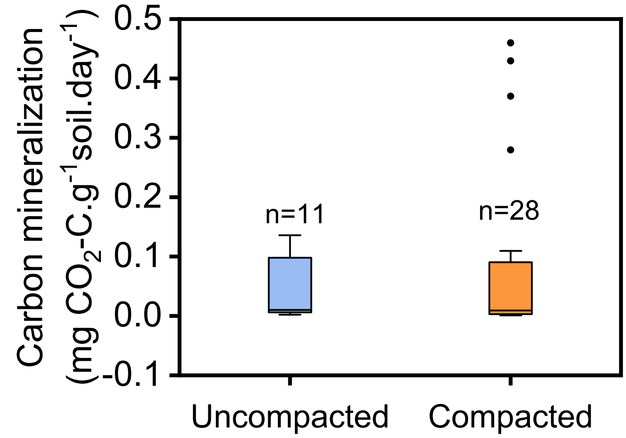

Fig. 5. Effects of soil compaction on the rate of carbon mineralization. The bulk density of non-compacted soil ranges between 1.01 and 1.46 g.cm^{-3} and compacted soil between 1.11 and 1.65 g.cm^{-3}. The carbon mineralization rate is not significantly ($p > 0.05$) different between compacted and non-compacted soils. Data were collected from 6 peer-reviewed articles. n is the number of data points reviewed.

reduces the large macropores (>150 μm) and increases the small macropores (15–150 μm) fraction, and this small macropore is desirable for microbial activities (Chen et al., 2016; Yoo et al., 2006) and increases carbon mineralization rate. However, the further reduction of small macropores can hinder the soil microbial activities (Chen et al., 2016; Strong et al., 2004; Taboada et al., 1998) and, eventually, the mineralization rate. The small-size macropores are the major habitable space for the microorganisms because it permits the exchange of water, gas, and nutrients while retaining water during a short drying period. The reduction of small-size macropores reduces microbial activities. Thus, pore size distribution should be monitored in all compaction studies to understand better to link between compaction and mineralization of carbon in SCM.

Opportunities: The second most important function of SCM is to remove pollutants from stormwater, and biodegradation is a critical pathway to transform and degrade the accumulated organic pollutants (Biswal et al., 2021; LeFevre et al., 2015; Mehmood et al., 2021). Compaction could affect these processes by affecting microbial activities and redox environments (Gougoulias et al., 2014; Keiluweit et al., 2017), and by limiting the oxygen supply in the rhizosphere (Beylich et al., 2010). Yet, most reported studies on SCM rarely monitored these processes in compacted soil or at different degrees of compaction. Furthermore, the fate of the group of microorganisms that serves a specific function or mineralization of other elements such as N, P, and S was rarely monitored in those studies. Most studies measured carbon mineralization, enzymatic activities, and microbial populations (Beylich et al., 2010), whereas they rarely reported the effect of compaction on microbial community structure (Hartmann et al., 2014; Longepierre et al., 2021). Understanding the evolution of microbial community structures in SCM that undergo compaction will help improve the design to ensure the desirable microbial communities strive in SCM. Compaction changes the aeration status, root growth, microbial community, and rhizosphere chemistry which could potentially impact the biodegradation of pollutants. Although numerous studies have examined the effect of these factors on pollutant removal, they did not examine directly as a function of compaction (LeFevre et al., 2015; Mehmood et al., 2021). Compaction could also slow down infiltration and increase contact time, hence the removal of pollutants (Ghavanloughajar et al., 2020). Further studies should isolate the direct and indirect effect of compaction on pollutant removals by physical, chemical, and biological processes.

3.5. Nutrient uptake

Compaction could negatively influence nutrient removal by affecting root health (Wang et al., 2019) and rhizosphere microorganisms

(Ahmad et al., 2009a). The analysis of available data (Fig. 6) showed that compaction significantly reduced plant N concentrations by 22.2 % and P concentrations by 35.1 % (Ahmad et al., 2009a, 2009b). As SCM typically uses sand to increase infiltration rate, compaction could increase the water retention in sandy or sandy loam through pore structure reorganization (Le et al., 2020). Increased water availability for vegetation positively affects plant growth and nutrient uptakes (Zhang et al., 2017).

In SCM, nutrient removal is sensitive to hydraulic retention time, redox conditions, plant health, and soil microorganisms (Valenca et al., 2021). Compaction can affect all these factors for nutrient removal to various degrees. For instance, compaction can increase water retention time and help develop anaerobic patches in SCM (Fassman-Beck et al., 2015; Schnurr-Putz et al., 2006), which are beneficial for denitrification (Payne et al., 2017). On the other hand, compaction can negatively affect plant roots and root microbiomes, thereby lowering nutrient uptake (Hartmann et al., 2014; Lucas and Greenway, 2008; Mariotti et al., 2020). Therefore, moderate compaction could positively affect plant growth and nutrient uptakes, whereas high compaction could inhibit plant growth and nutrient uptake (Botta et al., 2007; Wang et al., 2019; Zhang et al., 2017).

Opportunities: Compaction alters soil pore size distribution, root architecture, and root microbiome, which could affect nutrient uptakes. Future studies should systematically investigate changes in these factors with different degrees of compaction and examine the relative importance of these compaction-induced changes on nutrient uptake. Compaction can change redox conditions in the filter layer from aerobic to anaerobic conditions. To what extent the resulting changes affect the soil microbiome, and nutrient cycles requires a more detailed investigation. One way to alleviate compaction is to introduce plant species that could survive in compacted soil at low oxygen concentrations. Yet, compaction-tolerant plant species are rarely identified for SCM (Ampoorter et al., 2011; Colombi and Walter, 2017). For instance, mycorrhizae inoculation to the root could alleviate the negative impact of the compaction (Miransari, 2014) and facilitate pollutant removal, especially nutrient and organics contaminant (Palacios et al., 2021). However, fungal studies in SCM under compaction are rare. Future studies should examine the performance of mycorrhizal-associated biofilter plants in pollutant and nutrient removal under compaction.

3.6. Greenhouse gas emission

Subsurface soil can act both as a source and sink for greenhouse gas emissions (Kavehei et al., 2021; Vantellingen and Thomas, 2021a). N_2O can be produced in soil by nitrification and denitrification, whereas CH_4 can be produced by methanogenesis under anaerobic conditions (Payne et al., 2017). Compaction could disrupt oxygen diffusion, redox condition, nutrient cycling, and microbial health, which in turn affect these greenhouse gas emissions (Vantellingen and Thomas, 2021b). In particular, compaction can enhance anaerobic conditions (Bessou et al., 2010), which is necessary for greenhouse gas production in soil (Beare et al., 2009). However, a quantitative estimate of the compaction effect on greenhouse gas emissions in the subsurface is lacking. Analysis of limited available data reveals that compaction could significantly ($P < 0.05$) influence both fluxes of N_2O and CH_4 (Fig. 7). Mean N_2O emission fluxes increased two-fold as a result of compaction, potentially because compaction created favorable conditions for denitrification pathways. Compaction could increase water retention and restrict oxygen diffusion (Nawaz et al., 2013; Richard et al., 2001). Reduced aeration and low oxygen diffusion create anaerobic conditions that promote denitrification by reduction of NO_3^- to N_2O and N_2 and increasing net N_2O emissions. Compaction could also restrict carbon mineralization and plant root activities, leading to lower plant uptake of nutrients (Shah et al., 2017). Therefore, a temporary accumulation of mineral nitrogen in SCM is expected, which can increase net N_2O production and emission potential (Wang et al., 2019). The anaerobic soil conditions caused by compaction also create favorable conditions for methane production by methanogens. The data also show that mean CH_4 consumption decreased from −2.1 g CH_4-C $ha^{-1}.d^{-1}$ to −0.75 g CH_4-C $ha^{-1}.d^{-1}$ (64.3 %) due to compaction. For example, cultivable methanogens in compacted soil were found to increase nearly 100-fold compared to uncompacted soils (Schnurr-Putz et al., 2006).

Opportunities: SCM are implemented to improve resilience to the negative impacts of climate changes such as flooding, contamination, water scarcity, and heatwaves. However, they are rarely examined for their contribution to greenhouse gas emission. The analysis indicates that the compaction of SCM filter media could increase N_2O and CH_4 emission. However, limited studies have examined greenhouse gas emission from SCM (Elberling et al., 2011; Kavehei et al., 2021; Payne et al., 2017, 2014). A comprehensive account of compaction effects on greenhouse gas emission in SCM will give insights into the designs that could make them a net sink for greenhouse gases. Systematic studies are needed to understand the long-term greenhouse gas emission in SCM due to compaction. In particular, the effects of compaction on community structure and functions of methanogens and denitrifying microorganisms need further investigation.

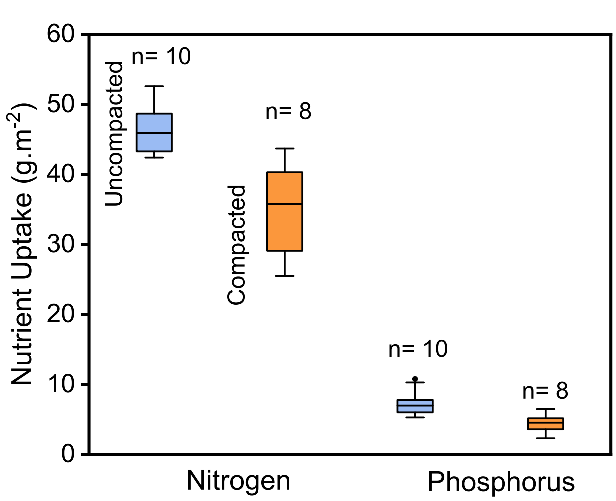

Fig. 6. Effects of compaction on nitrogen and phosphorus uptake by plants. n is the number of data points reviewed.

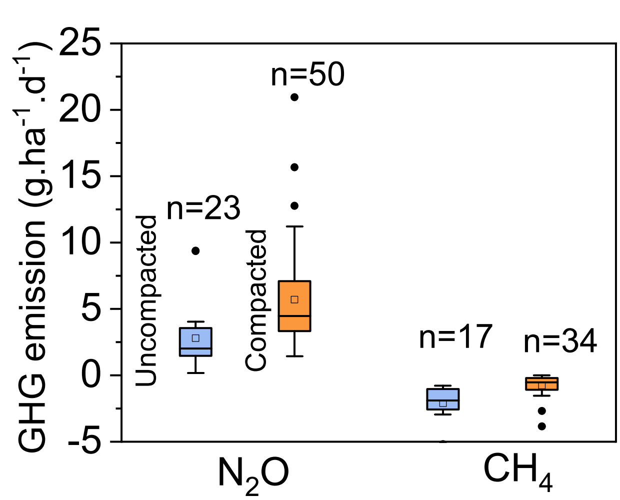

Fig. 7. Effect of compaction on mean N_2O emission fluxes and mean CH_4 emission fluxes. Both emissions are significantly affected by compaction ($p < 0.05$). Data were collected from five studies (Hargreaves et al., 2021; Hynšt et al., 2007; Teepe et al., 2004; Tullberg et al., 2018; Yamulki and Jarvis, 2002). n is the number of data points for each category.

4. SCM design implications to alleviate the impacts of compaction

4.1. Controlled anthropogenic activity

Compaction can be minimized by limiting traffic or human activities after and during biofilter construction. For regular maintenance, foot traffic can be directed by installing stepping stones or narrow paths, without disturbing the entire area. The vehicle, equipment, and foot traffic paths should be restricted in the construction traffic area (Gasso et al., 2013).

4.2. Designs to enhance natural regenerative processes

Natural processes such as earthworm activities through burrow creation, freeze-thaw, and tap-rooted plant growth can create preferential flow paths and reduce the negative impact of compaction on the infiltration rate (Jabro et al., 2014; Yvan et al., 2012; Colombi and Keller, 2019). Colonization of earthworms in compacted soil enhanced the macropores and infiltration rate through extensive burrowing activities of earthworms (Yvan et al., 2012). Repeated freeze-thaw cycles could alter soil structure, increase porosity, improve plant root health in soil ecosystems and thus reduce the negative impact of compaction (Jabro et al., 2014). However, freezing can expand the pore only if the pores are large enough to freeze the water against negative capillary force (Watanabe and Flury, 2008). For instance, water trapped in clay is less susceptible to freezing due to high negative pressures. Thus, adding more sand or sandy loam soil could increase the freezing depth and alleviate the compaction effect. Future studies should examine the effect of freezing on restoring the hydraulic conductivity of different soil types to link freezing with soil structure or texture. Improving soil structure and reducing compaction with the help of extensive taproot systems is a prolonged process and is restricted to a few feet of the surface (Bartens et al., 2008). Bio-drilling can accelerate this process. In the bio-drilling process, the root system grows within the compacted biofilter layer, and once the plant dies, the root leaves a channel in the soil for water to drain away (Williams and Weil, 2004). Deep tap-rooted plants create vertical drainage channels, whereas fine-rooted species like grass make horizontal channels in compacted soil. For instance, bio-drilling using Dakinson Radish (*Raphanus sativus* L. var. *oleiferus*) alleviated 40 % of overall compaction with a 44 % increase in soil porosity (Raut and Dick, 2020). Growing annual or biennial plants with a long taproot system and rapid growth is recommended for bio-drilling.

4.3. Amendments to resist compaction

Soils are susceptible to compaction, but an addition of amendments such as compost, straw mulch, fly ash, biochar, and sand could alleviate the media compaction by improving the hydraulic conductivities (Jourgholami and Etehadi Abari, 2017; Schwartz and Smith, 2021; Tirpak et al., 2021). The addition of amendments with large aggregate or grain sizes, such as sand and biochar, could increase porosity and infiltration capacity. Many other amendments were used in SCM, including coconut coir, manure, straw, zeolite, Expanded Shale Clay Slate, vermiculite, peat, hydro-absorbent polymer, and sphagnum moss (Borthakur et al., 2022; Jourgholami et al., 2021; Pitt et al., 2021; Tirpak et al., 2021). However, they are rarely tested for their capacity to alleviate compaction. Recently, biochar was tested for its ability to resist compaction and found that its moisture content and particle size are critical in preventing the breakage of biochar during compaction (Ghavanloughajar et al., 2020; Le et al., 2020). Despite its positive impact on plant growth and compaction alleviation, compost is not recommended in the biofilter system as it could leach pollutants, including nutrients (Tirpak et al., 2021).

5. Conclusions

The data analysis reveals the extent to which compaction can affect subsurface processes and informs potential implications of compaction on SCM to infiltrate stormwater, remove pollutants by biochemical processes, and provide other ecosystem functions. Compaction could reduce infiltration capacity in SCM, but the addition of sand could alleviate the negative impact of compaction. A comparison of infiltration data with and without sand confirmed that the addition of sand could increase the infiltration capacity by 22 folds. A reduction in infiltration rate or stagnant pore water alters the pore water composition, thereby affecting biochemical processes. A comparison of data with and without compaction confirmed that compaction decreased the oxygen diffusion rate and uptake of nutrients such as N and P and increased the emission of greenhouse gases such as N_2O and CH_4, but it has no significant effect on the carbon mineralization rate or root biomass. Compaction could reduce the oxygen diffusion rate by one-third of the original value, thereby affecting biological processes that rely on dissolved oxygen. The detrimental effect of compaction can be minimized by adding soil amendments, natural attenuation, and reducing unintentional compaction. While natural attenuation could take a longer time to alleviate compaction, soil amendment could provide some immediate improvement. The result will inform the design of roadside stormwater control measures and predict their long-term performance in urban areas where soils are compacted to a greater extent.

CRediT authorship contribution statement

Tonoy Das: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Visualization, Writing – original draft. **Alija Kabir**: Data curation, Investigation, Writing, **Weiyang Zhao**: Data curation, Investigation, Writing. **Michael K. Stenstrom**: Writing-review and editing, Funding acquisition. **Timothy M. Dittrich**: Writing-review and editing. **Sanjay K. Mohanty**: Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

Data availability

all data is available for free here: https://doi.org/10.6084/m9.figshare.18129395.v1

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.160121.

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