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Review

Impacts of climate change on the fate of contaminants through extreme weather events

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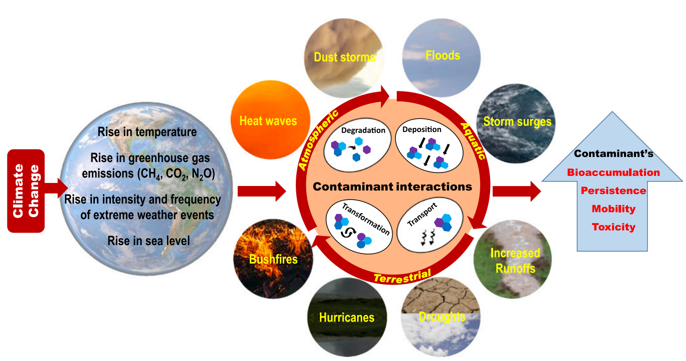
HIGHLIGHTS

- Climate change leads to extreme weather events, floods, droughts, and wildfires
- Extreme weather events impact the emission and transformation of contaminants
- Climate change impacts the contaminant risk assessment and remediation processes
- Practices adaptive to climate change are needed to manage contaminated environments

GRAPHICAL ABSTRACT



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A B S T R A C T

The direct impacts of climate change involve a multitude of phenomena, including rising sea levels, intensified severe weather events such as droughts and flooding, increased temperatures leading to wildfires, and unpredictable fluctuations in rainfall. This comprehensive review intends to examine firstly the probable consequences of climate change on extreme weather events such as drought, flood and wildfire. This review subsequently examines the release and transformation of contaminants in terrestrial, aquatic, and atmospheric environments in response to extreme weather events driven by climate change. While drought and flood influence the dynamics of inorganic and organic contaminants in terrestrial and aquatic environments, thereby influencing their mobility and transport, wildfire results in the release and spread of organic contaminants in the atmosphere. There is a nascent awareness of climate change's influence of climate change-induced extreme weather events on the dynamics of environmental contaminants in the scientific community and decision-making processes. The remediation industry, in particular, lags behind in adopting adaptive measures for managing contaminated environments affected by climate change-induced extreme weather events. However, recognizing the need for assessment measures represents a pivotal first step towards fostering more adaptive practices in the management of contaminated environments. We highlight the urgency of collaboration between environmental chemists and climate change experts, emphasizing the importance of jointly assessing the fate of contaminants and rigorous action to augment risk assessment and remediation strategies to safeguard the health of our environment.

1. Introduction

Climate forcing refers to alterations in the Earth's net energy balance, leading to unforeseen variations in atmospheric temperature that can either cause warming or cooling effects over time (Baede et al., 2001). Elevated concentrations of greenhouse gases in the environment are frequently linked to positive climate forcing, which results in global warming, while changes in atmospheric aerosol concentration can lead to negative climate forcing, which results in global cooling (Foster et al., 2017). Most countries are at risk from the impact of anthropogenic climate change, both now and in the future. Some of the direct consequences of climate change include sea-level rise, extreme weather events, including drought and flooding, increases in temperature leading to wildfires, and greater rainfall variability (Clarke et al., 2022; Seneviratne et al., 2012). Recent reports on climate change indicate that there will be rapid and extensive changes to global ecosystems with unknown and unpredicted impacts on human and ecosystem health (IPCC, 2022). The warming climate can amplify the severity of heat waves by raising the probability of extremely hot days and nights. The rise in surface temperature caused by global warming will lead to an overall increase in potential evapotranspiration (Oelbermann et al., 2022; Peng et al., 2023; Trenberth et al., 2014). Additionally, increased land evaporation due to a warming climate can exacerbate drought conditions, creating an environment more prone to wildfires and extending wildfire seasons (Abram et al., 2021). The changing temperature of the atmosphere is linked with more substantial precipitation episodes, such as rain and snowstorms, due to the augmented capacity of the air to retain moisture (Trenberth, 2012). While El Niño episodes typically result in drought conditions in various tropical and subtropical regions, La Niña events tend to cause increased rainfall in many areas. The intensity of these localized and temporary variations in extreme weather events is anticipated to rise in a progressively changing climate (IPCC, 2022; Martel et al., 2021).

In the early 2000s, a nascent field of climate-science research emerged to investigate the human influence on extreme weather events, including floods, heatwaves, droughts, and storms (Stott et al., 2004; Min et al., 2011; Trenberth et al., 2003; Diffenbaugh and Field, 2013). These studies have substantiated a robust link between human activity-induced climate change and the escalation in intensity and occurrence of extreme weather incidents. To monitor the progression of evidence on this rapidly evolving subject, Carbon Brief has documented extreme weather attribution studies from various sources, which reveals (Carbon Brief, 2022): (i) human-induced climate change was observed to have intensified the likelihood or severity of 71 % of the 504 extreme weather events and trends examined; (ii) among the 152 extreme heat events assessed, 93 % were found to be made more severe due to human activity; and (iii) out of the 126 rainfall or flooding events investigated, 56 % were found to have been made more likely or severe due to human activity; for the 81 drought events studied, this figure stands at 68 %.

Despite an increasing number of reports on the influences of climate change-driven extreme weather events on environmental contamination (Fig. 1), there is limited literature about how these events specifically influence the emission and transformation of contaminants in terrestrial, aquatic, and atmospheric environments. Previous reviews (Grifoni et al., 2022; Kumar and Reddy, 2020; Inyinbor Adejumoke et al., 2018; Biswas et al., 2018) have focused on the connection between climate change and contamination within individual environmental components. In contrast, this current review aims to offer an integrated perspective, examining the link between climate change-driven extreme weather events and contamination across terrestrial, aquatic, and atmospheric environmental components. The overarching objective of this review is to examine the potential consequences of climate change-induced extreme weather events on environmental contamination in terrestrial, aquatic, and atmospheric settings. The discussion will explore how these extreme weather events influence the level of contamination risk in both managed environments (e.g., landfills) and natural environments (e.g., bushland).

The specific objectives of this critical review include: (i) To investigate the release and redistribution of contaminants in terrestrial, aquatic, and atmospheric environments in response to extreme weather events, including flooding, droughts, and wildfires, initiated by climate change. (ii) To analyze the transport and mobility of pollutants during extreme weather events, considering their potential movement across different environmental components. (iii) To assess the bioavailability and toxicity of contaminants in various environmental settings, taking into account the influence of extreme weather events driven by climate change. (iv) To predict the risk assessment of contaminants in terrestrial, aquatic, and atmospheric environments, considering the influences of extreme weather events due to climate change. These objectives aim to provide a comprehensive knowledge of the relationship between extreme weather events influenced by climate change and the contamination of terrestrial, aquatic, and atmospheric environments, with a focus on the release, movement, and potential risks associated with various contaminants.

Although the awareness of the consequences of climate change on contaminants is emerging in scientific and decision-making strategies, the implementation of adaptive measures in the risk assessment and sustainable management of contaminated environments is still in its early stages in the remediation industry (Hurlbert et al., 2019). However, the recognition of the need for assessment measures covered in this review represents a crucial initial step towards more adaptive practices in managing contaminated environments impacted by climate change.

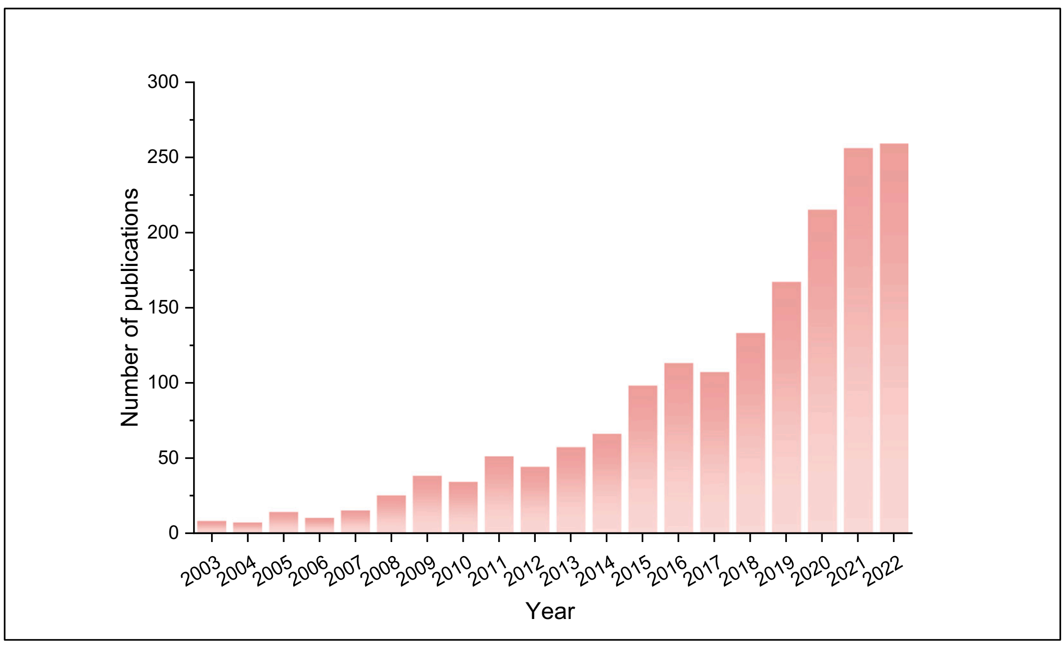
The outcomes from this review will encourage environmental chemists and climate change scientists to collaborate on the likely influences of climate change for risk assessment and remediation processes in contaminated environments.

A literature search was carried out in Web of Science Core Collections with the following searching terminologies: Topic Field (TS) = ("climate change" OR "global warming" OR "climate crisis" OR "temperature rise" OR "climate disruption") AND TS = ("extreme weather" OR "flooding" OR "drought" OR "wildfire" OR "heatwave" OR "hurricane" OR "storm" OR "cyclone") AND TS = ("contamination" OR "pollution" OR "contaminant" OR "toxin" OR "pollutant" OR "toxic" OR "hazardous waste") on 27 Apr. 2023. A total of 1834 results were retrieved, and the data were visualized using the VOSviewer software (version 1.6.19) (Fig. 1).

2. Climate change and extreme weather events

Climate change and global warming have caused a rise in the frequency and severity of extreme meteorological events worldwide. These events are considered 'extreme' when they significantly differ from 90 % to 95 % of previously recorded weather events in the same area (Coumou and Rahmstorf, 2012). These extreme weather events, such as droughts, flooding, and wildfires, resulting from climate change can directly and indirectly, impact the contamination of various environments.

A



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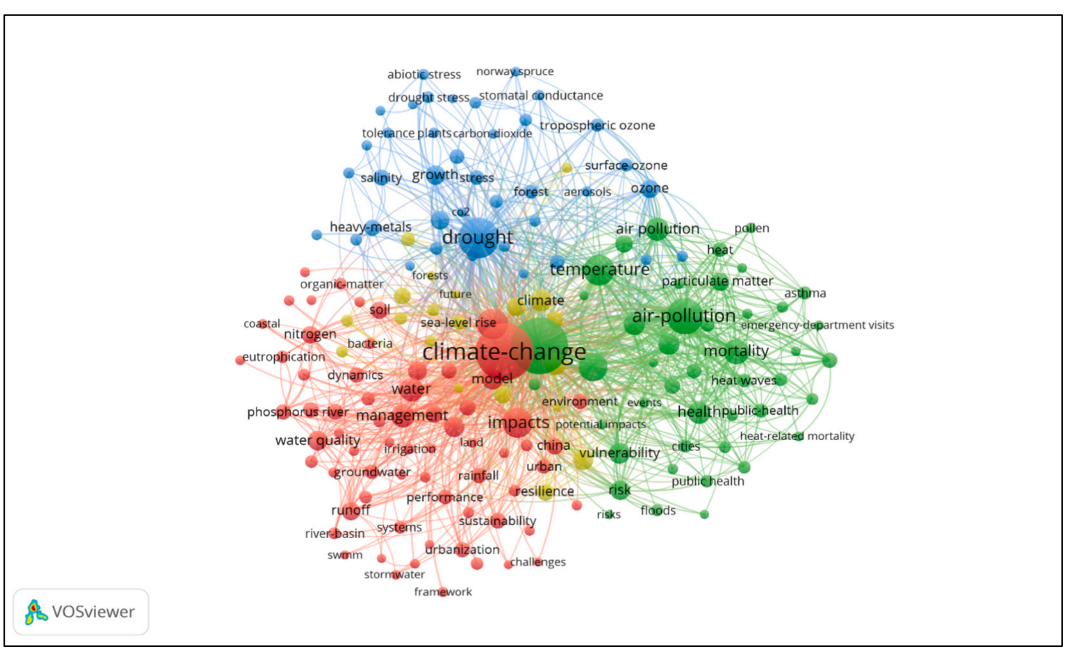

Fig. 1. A. The number of publications on the topic of climate change and soil contamination over the last 20 years. B. Keyword co-occurrence map in this field showing the most frequently investigated topics.

2.1. Drought

Despite the Paris Agreement's goal of limiting the rise in global temperature to below pre-industrial levels of 2 °C or even 1.5 °C (Rhodes, 2016), projections show that global temperatures are expected to exceed pre-industrial levels by >2 °C by 2100 (Raftery et al., 2017). Recent research indicates that, although global climate change may not directly cause droughts, it can increase their risk, making them more frequent, severe, and longer-lasting (Chiang et al., 2021; Samaniego et al., 2018). Indeed, a trend analysis of drought frequency in places such as the Haihe River Basin in China (Liu et al., 2017) confirms this observation (SI Fig. 1). Anthropogenic-induced greenhouse gas emissions triggering climate change are leading to an increase in global average temperatures that impact water availability timing, frequency, and quantity (Pokhrel et al., 2021; Wang et al., 2023b). Droughts often start with decreased precipitation caused by climate change, referred to as meteorological droughts, and are followed by higher temperatures and rapid water evaporation, leading to impacts on streams, lakes, groundwater (hydrologic drought), agricultural topsoil moisture (agricultural drought), and water resources for human use (socio-economic drought) (Mishra and Singh, 2010; Mukherjee et al., 2018; Nyagumbo et al., 2022). Drought has become the most expensive natural disaster in the United States, causing over $250 billion in damages (Ault, 2020).

Climate change is likely to promote the risk of drought in several ways. Elevated CO_2 levels can increase water loss through increased plant photosynthesis, raising soil temperature (Abagandura et al., 2022; Chen et al., 2022; Luo and Keenan, 2022). However, some scholars argue that the increase in atmospheric CO_2 concentration could enhance plant water use efficiency (Ferrara et al., 2022; Matysek et al., 2022; Swann et al., 2016). Although a "CO_2 fertilization effect" may partially offset forecasted drought, increased temperatures result in a decreased trend of soil moisture (Mankin et al., 2017; Swann et al., 2016). In addition, the significant correlation between warm and dry conditions increases the probability of simultaneous heat and drought events (Zscheischler and Seneviratne, 2017), and the coupling impact of soil moisture and temperature may also trigger droughts and wildfires (Bowman et al., 2020). Overall, climate change is likely to accelerate the reduction of soil surface moisture and reduce soil water retention.

Winter snowfall and snowpack are also impacted by climate change, which are important water resources for the 1.9 billion inhabitants of the Northern Hemisphere (Immerzeel et al., 2020). Adequate snowfall needs to be stored during the cold season and melted during the warm season for water supply. However, more extreme climate conditions make snow resources less available and for shorter storage periods (Livneh and Badger, 2020). For example, in April 2015, the snowpack in the Sierra Nevada in the U.S.A. was only 5 % of the historical average, which was the lowest in 500 years (Margulis et al., 2016). The low amount of Sierra Nevada snowmelt, needed to fill 30 % of California's reservoirs, contributed to the state's massive drought then (Madani et al., 2014). Moreover, climate change-induced droughts and wildfires can also accelerate snowmelt, as seen in the extreme wildfires of 2020 that caused the snowpack to melt approximately 18 days earlier than usual in the western United States (You and Xu, 2023). Since snow is considered highly reflective, a substantial quantity of sunlight hitting the snow is reflected back into space instead of having a warming effect on the planet. Thus, rapid reductions in snowpack areas can also cause surface temperatures to increase, creating a chain reaction that exacerbates drought (Perovich, 2007).

Another way atmospheric warming affects precipitation is by changing storm tracks (Shaw et al., 2016). Temperate- and subtropical-cyclone-travel tracks, collectively known as storm tracks, form between 30 and 60° latitude north and south of the equator (Hoskins and Hodges, 2002). Significant changes have been observed in the southern storm track during the summer as CO_2 concentrations rise and ozone depletion occurs (Thompson et al., 2011). Storm tracks are poleward shifting to reduce the energy imbalance between the equator and the poles (Bony et al., 2015). As most rainfall extremes at mid-latitudes happen in cyclones and their concomitant fronts and warm conveyor belts, the two-stage shift (i.e., nonlinear horizontal advection and diabatic heating linked with latent heat release) in storm tracks could lead to reduced rainfall in parts of the world that require moisture (Dacre et al., 2015). However, extra-tropical cyclones can also have extremely large volumes of rainfall linked with them which can lead to flooding in some parts of the same region (Sinclair and Catto, 2023). A vivid example is the significant decrease in cool season rainfall in southern Australia and the rise in warm season precipitation and thunderstorms in northern Australia (Abram et al., 2021; Dowdy, 2020).

Furthermore, the El Niño–Southern Oscillation events may be enhanced by climate change, disrupting hydroclimates more frequently and randomly over wide spatial scales (Lopez et al., 2022) and causing more severe droughts (Cai et al., 2015). Every coin has two sides; climate change may also lead to more precipitation in already wet areas, increasing the likelihood of flooding (Donat et al., 2016; Hou, 2022).

2.2. Flooding

Flooding is one of the most ravaging consequences of extreme weather events that are exacerbated by climate change (Hou et al., 2023; Mallakpour and Villarini, 2015; Wang et al., 2023a). The increased risk of flooding is caused primarily by the warming of the atmosphere and consequent raised atmospheric moisture content, thus increasing the intensity of rainfall (Davenport et al., 2021). Furthermore, increased atmospheric temperatures also lead to a higher frequency of tropical cyclones and hurricanes (Hou, 2021; Smiley et al., 2022). Although limited data on historical flooding creates difficulties in comparison to man-made climate-driven trends in flooding, the Intergovernmental Panel on Climate Change (IPCC) special statement on extreme weather events confirms that current climate change has impacted a number of water-related variables including rainfall and snowmelt that contribute to floods (IPCC, 2012). Meanwhile, Lehmann et al. (2015) highlight that, throughout the preceding 30 years, there has been a significant increase in the frequency of unprecedented precipitation events. This trend resulted in a 12 % rise in rainfall occurrences between 1981 and 2010, conveying a 26 % possibility that the newly established novel rainfall peak was tied to climate change caused by humans.

The increase in atmospheric moisture content with increasing temperature resulting from climate change is a significant factor in flooding. For every degree of warming, the atmosphere can hold around 7 % more moisture (NASA, 2022). The mean global temperature since 1880 increased by approximately 1° Celsius as a result of human activities (NASA, 2023), and atmospheric water vapour content has increased by 17 % (Van Brunt, 2020). Najibi and Devineni (2018) presented the frequency of flood incidents at the global and latitudinal scales (SI Fig. 2) and their correlation with climate change. Furthermore, many studies have found a direct correlation between increased atmospheric water content and increased intensity, duration, and intensity of extreme weather events (Coumou and Rahmstorf, 2012; Jain et al., 2022; Trnka et al., 2014). Climate change has also changed the planetary water cycle, increasing the intensity of current climate patterns. The change in climate patterns has resulted in more concentrated precipitation with intense downpours, creating an increased risk of flooding in flood-prone areas and even areas previously devoid of flooding (Haddeland et al., 2014; Pokhrel et al., 2021). Studies have shown that future heavy rainfall events are anticipated to increase by up to threefold the historical average throughout the 21st century, bringing with them up to 50 % more rainfall (USGCRP, 2017).

Regions of seasonal snowmelt receiving heavier and warmer precipitation as rain are at higher risk of rain-on-snow events (Beniston and Stoffel, 2016; Surfleet and Tullos, 2013). This occurrence is playing out in the western United States, where snowmelt-fed rivers have reached peak flow earlier in springtime since at least 1950 (McCabe et al., 2007; Musselman et al., 2018). In addition, even relatively marginal precipitation levels can lead to substantial damage, predominately in regions where the susceptibility to urban flooding is increased. An analytical study conducted by the National Oceanic and Atmospheric Administration (NOAA), examining extraordinary rainfall in Louisiana in 2016 that triggered catastrophic flooding, concluded that the probability of such phenomena was 40 % more likely, and its intensity was augmented by 10 %, as a consequence of anthropogenic climate change (NOAA, 2016). Hence, the increased risk of flooding caused by climate change is a major concern. In addition to the direct impacts of flooding, Floodwaters can carry pollutants and contaminants, like sewage, chemicals, and waste, which can contaminate waterways and potentially harm wildlife and human health (Song et al., 2019; Wang et al., 2023a; Wang et al., 2022).

2.3. Wildfires

Climate change and the rise in temperature resulting from anthropogenic activities have influenced the prevalence of wildfires and forest fires globally. Wildfires and forest fires occur worldwide (Mansoor et al., 2022), including in the U.S.A. (USEPA, 2022) and Canada (Hanes et al., 2018). In 2004, the total occurrence of worldwide wildfires was 5.09 million, while it slightly decreased to 4.51 million in 2019. A similar decrease in wildfire frequency was observed in the U.S.A. and Canada. The decrease in wildfire frequency could be related to an increase in public awareness, the introduction of tighter fire control regulations, and the development of novel fire control technologies.

Wildfires represent a prominent concern for environmental and public health matters across Asia, Australia, Europe, North America, and South America, as documented by Fujioka et al. (2008), Ganteaume et al. (2013), He et al. (2021), Holz et al. (2012), and Stephenson et al. (2013). Multiple controlled experiments, field studies, and modeling endeavors have been conducted to comprehend various aspects of wildfires, including ignition sources, the impact of climatic and anthropogenic elements, and spatiotemporal fluctuations of air pollutants, as evidenced by Clarke et al. (2019), Lovreglio et al. (2010), Pastor et al. (2003), Shi et al. (2021), and Sulova and Jokar Arsanjani (2021) (Table 1). The occurrence, behavior, and environmental and climate implications of wildfires are intricate and controlled by factors including vegetation fuel, topography, and weather conditions (Fujioka et al., 2008). Climate change and the ongoing expansion of fire-prone landscapes have intensified the frequency, intensity, and impact of wildfires (Jones et al., 2019; Moritz et al., 2014). The socio-economic consequences of extreme wildfires are also noteworthy (Bowman et al., 2017). Notably, the California wildfires led to significant loss of human lives and structural damage (Syphard and Keeley, 2019).

Molina-Terrén et al. (2019) reported a total of 865 human fatalities due to wildfires in four southern European regions from 1945 to 2016, with Spain (346), Portugal (232), Greece (211), and Sardinia (Italy) (76)

Table 1
Key information related to the occurrence of wildfires in various countries.

Country/region of fire	Type of ignition	Analysis method	Key information	Reference
Missouri, USA	Anthropogenic (human-caused)	Akaike information criterion method	Natural factors (moderate slopes and higher elevations) impact fire occurrence	(Yang et al., 2007)
California, USA	Anthropogenic (human-caused)	Logistic regression analysis	Ignitions are highly likely to happen close to roads and residential development, and is also associated with vegetation type	(Syphard et al., 2008)
Wisconsin, USA	Anthropogenic (human-caused)	Classification tree analyses	Significant interactions between human and biophysical variables have been noticed for most fire types	(Sturtevant and Cleland, 2007)
Florida, USA	Anthropogenic (arson)	Poisson autoregressive model	Model estimates show strongly significant arson-induced fire ignition autocorrelation lasting up to 11 days	(Prestemon and Butry, 2005)
Alberta, Canada	Lightning	Logistic regression analysis	Biotic (forest composition) and abiotic (weather) factors impacts lightning-based fire	(Krawchuk et al., 2006)
Ontario, Canada	Lightning	Kernel estimation	Lightning is likely to strike on days once the dryness of the forest area surpassed a specific threshold	(Podur et al., 2003)
Vancouver Island, Canada	Anthropogenic (human-caused)	Logistic regression analysis	Human-caused wildfires are a noteworthy part of the temperate rainforest ecosystem	(Pew and Larsen, 2001)
Madrid, Spain	Anthropogenic (human-caused)	Bayesian statistics (the weights of evidence model)	Spatial patterns of bushfire ignition were correlated with human access to the natural landscape	(Romero-Calcerrada et al., 2008)
Portugal	Anthropogenic (human-caused)	Logistic regression analysis	Human accessibility, population density, land cover and elevation were the major factors of spatial distribution of fire ignitions	(Catry et al., 2009)
England, UK	Anthropogenic (human-caused)	Probit model	An increase in incidence of wildfires observed in summer as well as the possibility of wildfires increases with decrease of rainfall	(Albertson et al., 2010)
Canton Ticino, Switzerland	Lightning and human-caused fires	Logistic regression analysis	Lightning-initiated fires took place in a small range of weather conditions, while human-caused fires happened in a broader range of weather conditions	(Reineking et al., 2010)
Lesvos Island, Greece	Mainly anthropogenic	Back-propagation neural network	Rainfall occurrence, 10 h fuel moisture level, and month of the year parameter were the key indicators of the fire weather, fire hazard, and fire risk indices, respectively	(Vasilakos et al., 2009)
Tasmania, Australia	Lightning	Data from the Global Position and Tracking System	Only 70 % of lightning ignitions were tallied with the lightning records. The lightning ignition efficiency is maximum during the summer season.	(Nampak et al., 2021)
Australia	Lightning	Geographic Information System	Of the 120,829 flashes recorded, only 23 flashes could be categorized as lightning-induced wildfire events (i.e., lightning ignition frequency = 0.00023 fires/stroke)	(Safronov, 2022)
Western Siberia	Lightning	WWLLN-FIRMS	Higher number of lightnings occurs for the whole territory of Western Siberia in July.	(Kharyutkina et al., 2022)
South Asia (SA) and Southeast Asia (SEA)	Anthropogenic (human-caused)	MODIS	Crop residue burning events in SA increased by 844 spots/yr. Wildfires in SEA decreased at a rate of −209 spots/yr, while bushfires equally raised at a rate of 803 spots/yr.	(Yin, 2020)
Southeast Asia	Anthropogenic (human-caused)	MODIS	Correlations between fire burning and the levels of average aerosol optical depth (AOD) within the hotspot zones were identified. Considerable high AOD observed between August and October	(Chang et al., 2015)

Note:
WWLLN - FIRMS: World Wide Lightning Location Network (WWLLN) and The Fire Information for Resource Management System (FIRMS); MODIS: Moderate Resolution Imaging Spectroradiometer (MODIS) fire products

experiencing the highest casualties. Australia frequently experiences wildfires, particularly during the summer months of January and February, driven by an exceedingly dry climate (Pickrell, 2019). An Australian wildfire in New South Wales resulted in the burning of 1.65 million hectares, claimed six lives, and damaged over 500 homes (Pickrell, 2019). The escalation of Australian wildfires can be attributed to rising temperatures (heatwaves) and declining rainfall (Yu et al., 2020). Recent research work has emphasised the recurrent incidence of wildfires, notably uncontrolled forest and peat fires, in South Asia and Southeast Asia, significantly impacting regional air quality and weather patterns (Adam et al., 2021; Yin, 2020).

Various factors, including rising ambient temperatures, prolonged fire seasons, heightened drought conditions, inadequate fire suppression methods, and shifts in land use, contribute to frequent, expansive, and significant fire occurrences worldwide (Cassell et al., 2019). Fire activity hinges on four primary determinants: fuel characteristics, climate and weather conditions, ignition sources, and human activities (Flannigan et al., 2005). Fuel amount, type, supply, and structure and moisture levels influence fire incidence and spread (Flannigan et al., 2016). Pyrocumulonimbus clouds occur above a source of heat, such as wildfires. Extreme fire events result from a combination of extreme atmospheric conditions and surface fire weather conditions (Di Virgilio et al., 2019).

Fire timing is associated with the origins of the fire. Human-caused fires peak in the afternoon, while lightning-induced fires align with weather patterns and seasons, primarily occurring during summer (Ganteaume et al., 2013). Socio-economic elements such as unemployment rates and agricultural activities are linked to intentional and unintentional fire ignition (Ganteaume et al., 2013). Wildfire occurrences in eastern Kentucky, U.S.A., were correlated with factors like elevation, slope, and proximity to traffic and habitations (Maingi and Henry, 2007). Canadian wildfire patterns from 1990 to 2016 were mainly influenced by human activity (49 %), followed by lightning (47 %) and other unidentified causes (3 %) (Tymstra et al., 2020).

Extreme weather conditions, encompassing elevated temperatures, low humidity, and fierce winds, were found to be linked to major wildfires in the eastern United States and southeastern Australia (Brotak, 1980). Over 57 years in Canada (1959–2015), lightning-caused fires increased, while human-induced fires remained stable or decreased across different regions (Hanes et al., 2018). A modeling study for New South Wales projected an almost 25 % rise in extreme fire risk by 2050 under two high-emission scenarios (i.e., greenhouse gas and aerosol emissions), and an additional 20 % increase under a low-emission scenario by 2100 (Pitman et al., 2007). Spatial distributions of fire ignitions in Portugal were influenced by factors like human accessibility, population density, land cover, and elevation (Catry et al., 2009).

Development and promotion of appropriate risk management strategies and mitigation measures could prevent the occurrence of wildfires or minimize the frequency and severity of associated risks, including reduction of the loss of human lives, properties, and resources (Calkin et al., 2014). Understanding fire behavior and its danger at different spatial scales (i.e., from regional to global levels) and temporal scales (i.e., from daily to seasons) could help fire managers develop effective fire management and control strategies (Fujioka et al., 2008). Additionally, comprehending how ignitions occur is crucial for efficiently extenuating built environment damages during wildfires (Cohen, 1999). Wildfire risk management includes the four integrated components of emergency measures, namely (1) planned prevention and mitigation, (2) advance preparedness, (3) prompt response, and (4) post fire disaster recovery (Tymstra et al., 2020).

3. Extreme weather events and contamination transformation

3.1. Terrestrial environment

Climate change is triggered by land use changes that occur in the terrestrial environment (Dandotiya and Sharma, 2022). And, vice versa, the influence of climate change on vegetation can lead to the degradation of ecosystems, ecosystem services, and biodiversity (Cardinale et al., 2012). Climate change can transform extensive land masses from one biome to another, expand wildfires, and lead to the extinction of several floral and faunal species (Thomas et al., 2004). The loss of biodiversity due to climate change can lead to both direct and indirect changes in energy flow and material circulation in several ecosystems, including the terrestrial one (Wang et al., 2017). Spatial and temporal alterations in rainfall and temperature affect ecosystem services, carbon service, and the value of terrestrial ecosystems (Xiang et al., 2019). Terrestrial ecosystems are important because they are responsible for the exchange of water, aerosols (i.e., dust, fume, smoke) and energy between the land and atmosphere. Terrestrial ecosystems function as a source and sink for greenhouse gases, and similarly, physiological and ecological processes in vegetation and soil have a strong influence on the exchange of climatically significant gases, including CO_2, water vapour, nitrous oxide, methane, and isoprene (Meir et al., 2006).

Wildfires cause modification of land cover due to changes in the radiative, dynamic, hydrological, vegetative, and thermal characteristics of land (Littell et al., 2016). The water cycle from the land surface to the atmosphere through evapotranspiration by the vegetated landscapes and evaporation by the non-vegetated landscapes is suppressed during extensive wildfires (Littell et al., 2016). Wildfires contribute to the modification of forest composition and ecosystems, as a modeling-based study, which applied the forest landscape model, LANDIS-II, reported. There was a decrease in sub-alpine species (*Abies lasiocarpa, Pinus albicaulis,* and *Picea engelmannii*) and an increase in lower-elevation species (*Abies grandis* and *Pinus ponderosa*) (Cassell et al., 2019). Modification of the geochemical cycling (e.g., N-cycling) and microbial dynamics and enzyme activities was observed in the soil ecosystem due to wildfires (Fultz et al., 2016).

Temperature change is directly linked with climate change and is known to affect all ecosystem types. High temperatures can cause an increase in the toxicities of several chemical pollutants, together with uptake by organisms in the natural environment (Schiedek et al., 2007). This occurs mainly due to the accelerated metabolic rate caused by the high level of temperature. Similarly, changing temperature and moisture conditions can influence the rate of release of volatile substances (i.e., trichloroethylene, vinyl chloride) into the atmosphere from land and alter persistent chemicals (i.e. polychlorinated dibenzo-p-dioxins [PCDD], dibenzofurans [PCDF]) in the environment (Boxall et al., 2009).

Increasing temperatures are usually integrated with high solar intensities and greatly affect persistent organic pollutants (POPs), including such as polycyclic aromatic hydrocarbons (PAHs). The concentration of PAHs in the environment is projected to increase by events such as forest fires. When temperature and light intensity rise to an unusual level (350° - >1200 °C), PAHs with low molecular weight volatilize easily. Regardless, the photodegradation of PAHs (i.e., naphthalene, anthracene, phenanthrene, and pyrene) occurs partially under high solar intensity conditions and could lead to the emergence of intermediate products. These intermediate products are assumed to be more toxic compared to the original molecules (Srogi, 2007; Kumar et al., 2021).

Climate changes exacerbate the severity and frequency of wildfires, modifying soil properties and impacting biological, chemical, and physical aspects. These fires also affect soil organic matter and structure, influencing soil erosion and metal transport. Elevated temperatures alter organic matter composition, potentially leading to organic matter destruction around 600° - 700 °C. Frequent erosion, spurred by climate change, enhances metal transportation and migration (Frogner-Kockum et al., 2020), along with the loss of metals bonded with humic materials through soil loss and landslides. Climate change can remobilize legacy metals like mercury, altering their release and conversion, such as changing mercury to methyl mercury, which affects uptake by organisms (Balbus et al., 2013; Downs et al., 1998). Alterations of the mobility of various metals resulting from redox reactions due to flooding could impact the transport and accumulation of potentially toxic elements (PTEs) in the groundwater. For example, while under unsaturated conditions, As and Cr remain as less mobile As(V) species and more mobile Cr(VI) species, respectively, they are reduced to more mobile As(III) and less mobile Cr(III) species under flooded conditions, respectively, thereby impacting their bioavailability, toxicity and transport in soil and aquatic environments (Fig. 2). This is considered one of the main sources of environmental contamination (Ayotte et al., 2011). In addition, altered rainfall intensities affect net carbon release from the soil. Low rainfall leads to droughts thereby causing excess N_2O release from natural soil and inorganic carbon (i.e., carbonates, bicarbonates) and CH_4 and CO release from acidic soil (IPCC, 2019).

Climate change, including rising temperatures and heavy precipitation, impacts POPs, a significant contaminant category (Nadal et al., 2015). Elevated precipitation rates lead to runoff of POPs and pesticides. The transportation, transformation, and partitioning of POPs are governed by temperature-dependent chemical-physical properties (Hung et al., 2022). As demonstrated by Lamon et al. (2009), a 1 °C temperature rise resulting from climate change is projected to increase the volatility and mobility POPs, like polychlorinated biphenyls (PCBs). Consequently, these contaminants are transported to uncontaminated environments. Conversely, reduced rainfall extends these contaminants' persistence in soil (Casas et al., 2021). Table 2 shows the potential consequences of climate change on selected pollutants in terrestrial environments.

Global climate changes, influenced by natural and anthropogenic factors, impact toxicant transportation and transformation (Gouin et al., 2013). Extreme weather events, including heavy rainfall-induced floods, facilitate the movement of metals, dioxins, and hydrocarbons from contaminated to non-contaminated areas (Lake et al., 2005). Wind erosion also leads to off-site heavy metal contamination (Fig. 3). Enhancing strategies, like green technologies, necessitates precise remediation steps for contaminated lands. Phytoremediation, for example, benefits from elevated atmospheric CO_2 levels, improving plant growth and metal detoxification, thus contributing to CO_2 fixation and emission reduction (Luo et al., 2019; Tan et al., 2023).

However, interactions with various environmental factors must be considered. For example, Cd phytoremediation was found to be efficient at elevated CO_2 (550 ppm) in monocultures of *Festuca arundinacea* but not in intercropped scenarios with *Echinochloa caudata* (Yang et al., 2020). Novel phytoremediation technologies addressing climate change impacts have emerged. These approaches require consideration of environmental factors, site conditions, and design specifics. Table 3 summarizes terrestrial contaminant responses to climate change.

The terrestrial environmental pollutants possess the potential to result in adverse impacts on the sustainability of natural ecosystems including the health of human beings. The heavy metal contaminants circulate in the terrestrial environment are distinctly possible to induce many physical and neurological abnormalities (Anetor et al., 2022). Exposure to As, Cd, Pb and Hg in large quantities lead to amendment of homeostasis and apoptotic cell death (Goldhaber, 2003), alteration of synaptic transmission and neurotransmitter balance (Garza-Lombó et al., 2019), renal failure, renal tubular acidosis, and hypercalciuria (Friberg et al., 2019), interstitial fibrosis, glomerulonephritis,

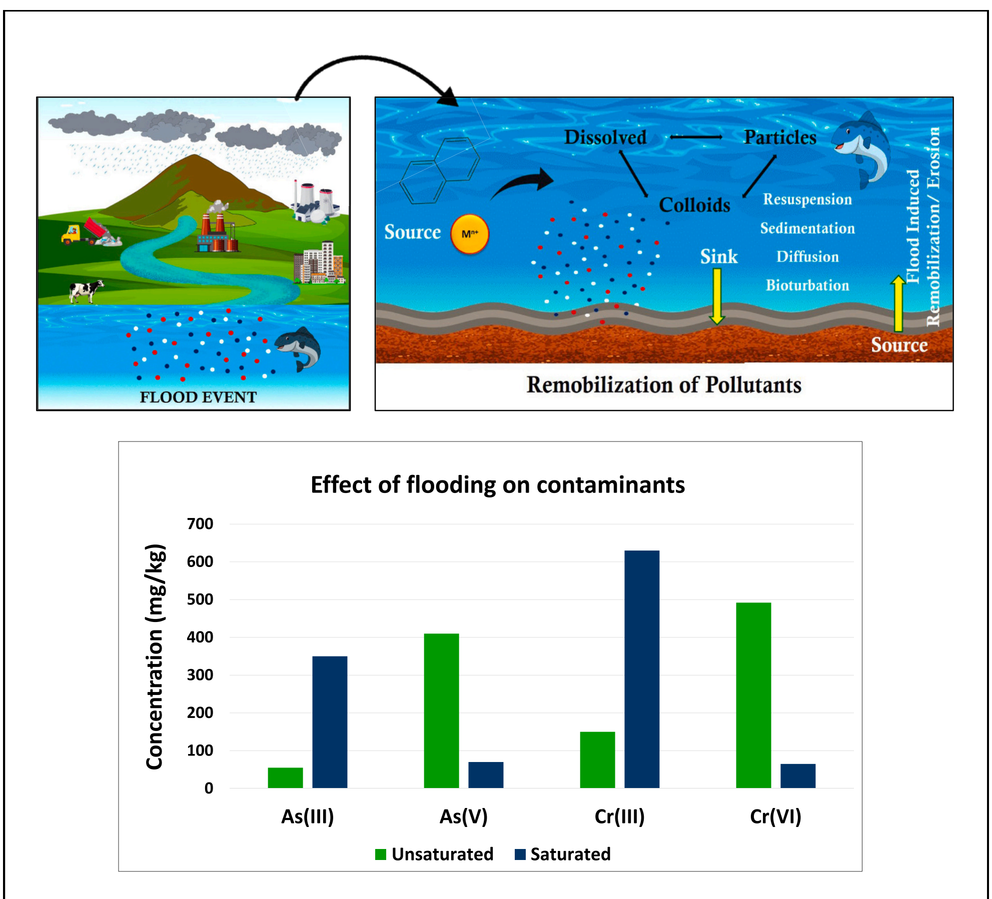

Fig. 2. Remobilization of contaminants during extreme flood events. While arsenic is *more mobile* and bioavailable under reduced conditions, chromium beomes *less mobile* and bioavailable.
(Schematic figure - Crawford et al., 2022)

Table 2
Potential impacts of climate change on selected contaminants in terrestrial environment (Balbus et al., 2013).

Contaminants	Effect of climate change on the source of contaminants	Effect of climate change on the fate and transport of contaminants	Impact nature
Dioxins, PCBs, DDT	Increased release of POPs from the sources of the production sector, product utilization, thermal processes, waste management	Increased release of POPs; remobilization of soil and sediments associated with POPs; transferral into uncontaminated areas	High
Mercury	Microbial transformation of divalent mercury species into more biologically available organic species	Increased uptake and mobility Conversion of mercury Species→Vapour Mercury→Methyl Mercury	High
Arsenic	Changes of microbial communities and water dynamics of freshwater aquatic systems impact distribution of As in surface water	Increased contamination	High
Pesticides Glyphosate Neonicotinoids	Increased use of pesticides and changes of type of pesticides used	Decreased degradation due to alteration of temperature and moisture	Medium

High and Medium stand for severity level of impact, PCBs - Polychlorinated biphenyls, DDT: Dichlorodiphenyltrichloroethane, POPs - Persistent organic pollutant.

hyperplasia and mercury-induced chronic kidney damage (Lentini et al., 2017). The PAHs in terrestrial environments stimulate health concerns such as behavioral changes, neurodevelopment impairment, hemolysis, cataracts and decreased immune function with liver and kidney damage (Rodriguez et al., 2012). Alternatively, PCBs and other dioxin-like compounds result in porphyria, cardiovascular diseases, chloracne, endometriosis, cancer, dermal hyperpigmentation and altered metabolism when overexposed (Egendorf et al., 2020; White and Birnbaum, 2009).

3.2. Aquatic environment

Water is a valuable natural resource, and its protection from contamination is critical for economic growth, nature sustainability, and human well-being. Climate change can have significant impacts on aquatic environments. It results in water scarcity, unpredictable precipitation, and an increased frequency of floods and droughts (Anawar, 2013). Climate change and drought conditions are decreasing the quality of water sources in semi-arid and arid zones by increasing temperature and evaporation, reducing rainfall, and decreasing freshwater inputs to reservoirs, particularly during the summer and autumn (Anawar, 2013; MarcÉ et al., 2010). For example, increased water temperatures induce eutrophication and excessive algae blooms in many regions, reducing drinking water quality. Water eutrophication poses challenges for water resource management and has become a growing concern in light of the consequences of climate change (Nazari-Sharabian et al., 2018). Usually, eutrophication occurs more readily in small and stagnant water sources, including lakes and reservoirs. However, research shows that recently, there have been increasing risks of water pollution leading to eutrophication in large water bodies, such as rivers and marine systems, due to a shift in climate and increased pollution (Xia et al., 2016).

Climate change significantly influences contaminants' occurrence and fate in aquatic ecosystems (Abdelhak et al., 2023). For example, microplastic (MPs) abundance in local environments is influenced by the interplay of local plastic sources and environmental conditions, leading to a highly heterogeneous distribution. Current circulation models used for predicting plastic distribution do not take into consideration the future changes in circulation patterns and weather systems due to

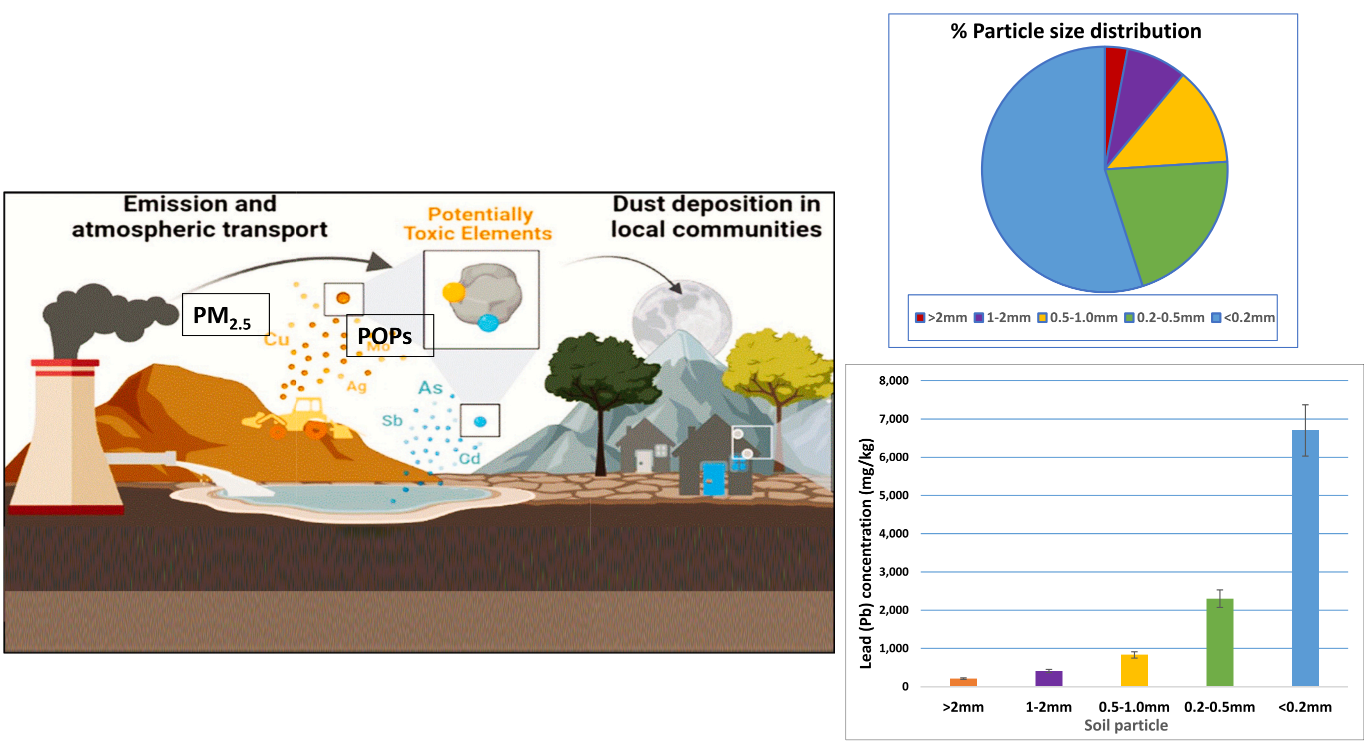

Fig. 3. Dust dispersion of contaminants. Wind erosion carries finer particles (<0.2 mm) with enriched concentration of contaminants including lead (Pb), resulting in off-site contamination.
(Schematic figure - Zanetta-Colombo et al., 2022)

Table 3
Climate change and behavior of terrestrial contaminants.

Country/region	Climate event	Type of contaminant	Potential effect	References
China	Increased temperature and precipitation pattern	Pesticides	Increase by 1.1 to 2.5 times by 2040 Increase by 2.4 to 9.1 times by 2070	(Zhang, 2018)
Arctic and Pacific	1 °C temperature rise	POPs PCBs	10 % - 15 % increase in the volatility of contaminant	(Lamon et al., 2009)
Lindane/ HCH producing countries	Temperature rise	Hg	Increased rate of volatilization	(Vijgen et al., 2018)
		PFOS PFAS	Increased mobility of the contaminant	(UNEP, 2011)
		POPs	Increased degradation of the contaminant	(UNEP, 2011)
Global glacier regions	Melting of polar and alpine glaciers, permafrost and ocean ice	POPs Hg	Increased exchange between air and soil	(Noyes et al., 2009)
Ontario, Canada	High rates of precipitation	Hg	Increased release from the ground	(Chen and Driscoll, 2018)
Global	High intensity and frequency of droughts and floods	Hazardous chemicals	Accelerated redistribution Increased rate of transport and translocation	(IPCC, 2019) (Innocenti et al., 2015)
Canada	Forest and peat fires	POPs PCB PCN (Polychlorinated naphthalene) PBDE (Polybrominated diphenyl ether) CH_4	Increased release of the contaminants	(Wang et al., 2017)
Global	Increased CO_2 level in atmosphere	Metals	Increased chemical weathering leading to the increased release from Earth crust and soil	(Prathumratana et al., 2008)

climate change. Factors including changes in water density, increased runoffs, increased floods, and strong winds can significantly impact the fate of aqueous plastics (Fig. 4). Hence, climate-induced alterations in ocean salinity, volume, air, and water movement are expected to reshape plastic distribution patterns, exacerbating the threat of MPs in the coming decades. Welden and Lusher (2017) proposed four main impacts on MPs in water: 1. Increase in terrestrial MPs input due to increased runoff; 2. Increase in MPs input through the air due to stronger winds; 3. Increased resuspension of MPs; and 4. Higher persistence of MPs due to higher evaporation and increased water density. Indirectly, climate change is also driving more use of recycled wastewater, thus exposing a larger population to MPs and other pollutants through direct or indirect potable reuse (Lenka et al., 2021). More wastewater-impacted drinking water sources would also translate to more micro-pollutants in drinking water as emerging and more toxic disinfection byproducts, such as nitrosamines, are formed through the exposure of certain nitrogenous constituents to disinfectants (Jasemizad et al., 2021a, 2021b).

Although the effect of climate change on the dynamics and fate of pesticides and other organic contaminants is likely to be extremely

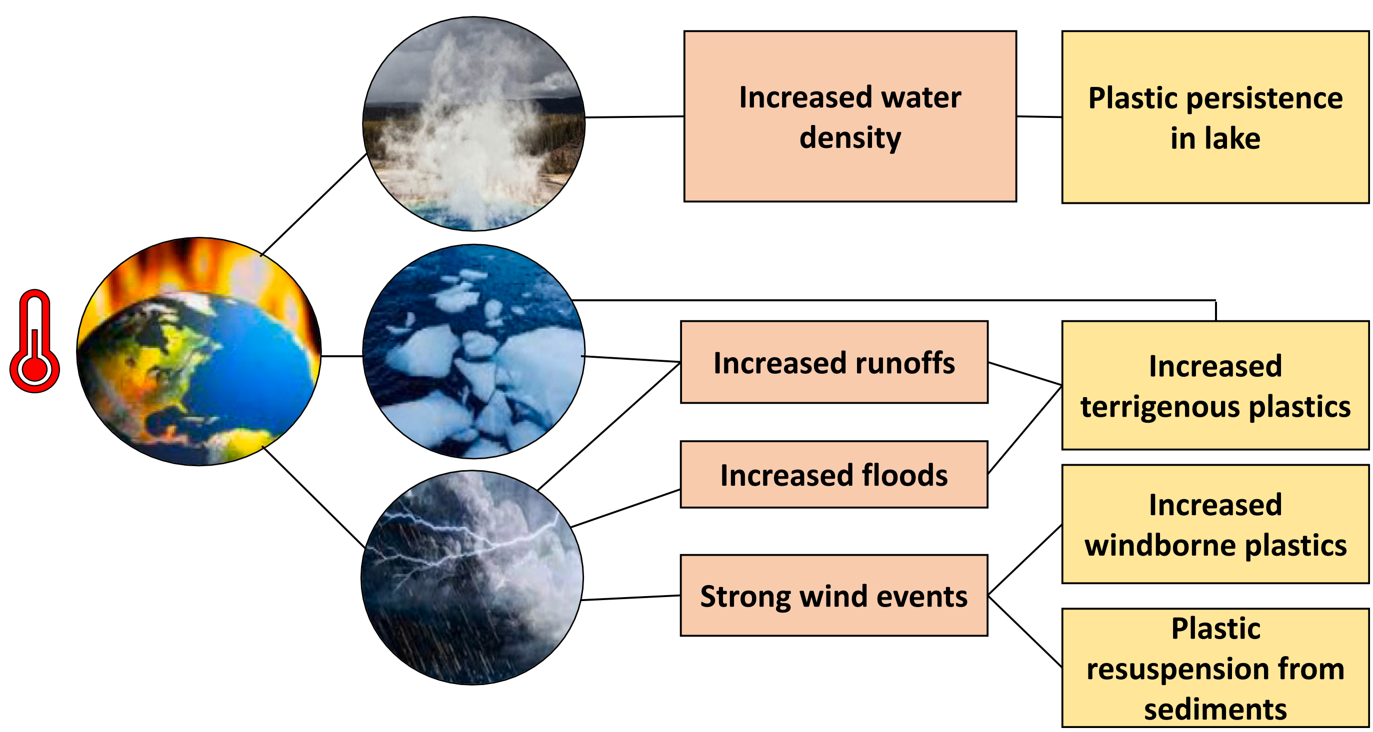

Fig. 4. Climate change- extreme weather events' impact on aquatic plastic distribution.
(Kakar et al., 2023 – modified)

unpredictable and challenging to forecast, the changes in their fate and behavior due to climate change can be through variations in precipitation seasonality, rainfall intensity, and rising temperatures. The levels of pharmaceuticals, pesticides, and *per*- and polyfluoroalkyl substances (PFAS) in surface and groundwaters may be influenced by indirect impacts, including increased water stress, increased sewage overflows, and land-use changes driven by climate change rather than direct influences of climate change on their dynamics and fate (Bloomfield et al., 2006; Lenka et al., 2022). One of the major pathways that these organic contaminants move within different aquatic environmental compartments is surface runoff (Otieno et al., 2013). Farmers can control drift by checking wind speed when applying pesticides, but managing runoff is more challenging due to factors such as slope and precipitation. Increased precipitation has been shown to enhance runoff contaminated with many organic pollutants (Probst et al., 2005).

Higher temperatures can also impact the distribution of contaminants in water and reduce agricultural runoff loads. However, the effect of increasing CO_2 levels on pesticides is contradictory (Carere et al., 2011; Delcour et al., 2015). Although higher temperatures can promote the volatilization of pollutants and the degradation of their residues, low summer flows may result in a major loss in dilution capacity and higher pesticide content if runoff or spray events occur (Bloomfield et al., 2006). Leaching is the movement of chemicals through the soil, which can lead to groundwater contamination. Climate and soil-pesticide interactions affect the transfer of pesticides to both surface and groundwater. Temperature also plays a role in leaching, as it affects soil mineralogy and geochemistry (Delcour et al., 2015).

Freshwater environments may be subject to increased physical and chemical stress due to higher water temperatures, desiccation events, and land use changes. Recalcitrant compounds, such as pesticides and PFAS, can be immobilized or degraded by microhabitats like stream biofilms. However, alterations in water temperature and light input can impact the ability of biofilms to degrade pesticides. For instance, the transformation of glyphosate to AMPA (aminomethylphosphonic acid) by microbes is expected to be increased by an increase in light availability and water temperature in streams subjected to global change (Abdelhak et al., 2023).

In addition, climate change influences the fate of inorganic pollutants, including nutrients and heavy metals, due to direct and indirect effects on water resources. Although strong winds can prevent algal blooms by dispersing and reducing their formation and aggregation, they can lead to increased sediment and nutrient inputs, further

Table 4
Selected literature on the effect of different climate change conditions on aquatic environments.

Source of aquatic environment	Climate change condition(s)	Findings	Reference
Mediterranean watersheds	Drought and post-drought conditions	• More than five pesticides were found in 83 % of samples from three catchments. • The detections of pesticides in water were associated with rainfall events and pesticide application. • After the drought was over, approximately half the number of pesticides were found.	(Chow et al., 2023)
Agricultural runoff	Rising levels of CO_2, temperature, and precipitation	• Compared to variations in temperature or CO_2 concentration, precipitation showed a bigger effect on agricultural runoff. • An increase in CO_2 levels led to an increase in phosphorus, nitrate, and chlorpyrifos but a decrease in sediment and diazinon. • The only factor that decreased the yields of all agricultural runoff components was temperature.	(Ficklin et al., 2010)
Rainwater	Precipitation	• Small amounts of atrazine were detected in precipitation despite its prohibition in Germany. This could be due to its transportation from neighbouring countries where atrazine is used. • Desethylterbuthylazine, a degradation product of terbuthylazine, was detected in precipitation with a similar level as terbuthylazine.	(Jager et al., 1998)
Mediterranean wetland	A decrease in annual rainfall and an increase in temperature	• Temperature rise is less significant than local precipitation for pesticide exposure.	(Martínez-Megías et al., 2023)
Lake	Precipitation	• Chlorpyrifos residues levels were affected by climate-induced rainfall patterns. Higher concentrations were found during heavy rainfall, and significantly low concentrations were found during low precipitation. • Average chlorpyrifos concentration in water varied from 8.6 to 22.4 μg/L during the rainy season while it ranged from <detection limit (DL) to 13.6 μg/L during the dry season.	(Otieno et al., 2013)
Urban lakes	Precipitation, temperature, sunshine duration, and wind speed	• Fluoride and arsenic levels in the majority of urban lakes showed a notable positive relationship with temperature and rainfall. This correlation is primarily attributed to diffuse pollution caused by rainfall. • The correlation between volatile phenols and precipitation or temperature was negative, which was attributed to their increased rates of volatilization and biodegradation due to higher temperatures. • The variations in climatic factors did not affect selenium, attributed to its low content in the lakes.	(Wu et al., 2014)
Different water bodies like plain and alpine lakes, rivers, estuaries, and costal lagoons	Climate change	• The consequences of climate change on the water quality of plain lakes are likely to include salinization, eutrophication, and nutrient discharge. • Heavy metal transport from soil to aquatic habitats is an issue in alpine lakes. • Under climate change, nutrient loads could increase in estuaries and rivers. • Under climate change, oceans are facing issues such as a decrease in biodiversity and some salinity changes.	(Xia et al., 2015)
River basin	Temperature and precipitation changes	• Temperature changes have no effect on total nitrogen (TN) concentrations and loading. • Precipitation changes are affecting TN loading significantly but TN concentrations moderately. • The large variations of TN concentrations and loadings under distinct climate change scenarios highlighted the importance of climatic variability in influencing water quality parameters.	(Yang et al., 2017)

compromising the quality of drinking water sources (Nazari-Sharabian et al., 2018; Stanichny et al., 2010). For example, in an experiment by Wu et al. (2014), fluoride and arsenic levels in the majority of urban lakes displayed a notable positive relationship with temperature and rainfall. This correlation is primarily attributed to diffuse pollution caused by increased rainfall.

Anawar (2013) reviewed the effect of climate change on the formation of acid rock drainage and the transport of pollutants in water ecosystems in arid and semi-arid mining areas. They reported that climate change-related flooding and heavy rainfall might destroy hydraulic structures such as dams at mine sites, resulting in an increase in the risk of pollutant runoff or the closure of mining activities. Moreover, vegetation covers and mining waste phytoremediation could be influenced by higher temperatures, evapotranspiration, and changes in precipitation. Hence, climate change can impact mining sites with poor design and management (Anawar, 2013). Table 4 shows the impacts of various climate change conditions on different water sources.

Unsafe and contaminated water presents a significant risk to human health, with acute and chronic health consequences linked to exposure levels and duration (Babuji et al., 2023). Waterborne contaminants, including pharmaceuticals, pesticides, and MPs, can transform into hazardous by-products during treatment processes (Jasemizad et al., 2021a, 2021b; Jasemizad and Padhye, 2022), leading to the production of carcinogenic, mutagenic, and teratogenic substances like nitrosamines and disinfection by-products (Ghanadi et al., 2023; Jasemizad et al., 2020). Inorganic contaminants in water, such as heavy metals, can accumulate in the food chain and animal tissues, causing health issues, including kidney, bladder, and skin cancer from arsenic ingestion (Marmot et al., 2007), cytotoxicity and genotoxicity from high silver exposure (Padhye et al., 2023), and respiratory cancer from high cadmium levels (Zhitkovich, 2011). Legacy POPs like PCBs, PAHs, dibenzofuranes, and polychlorinated dioxins in groundwater sources disrupt immune, reproductive, and endocrine systems, leading to cancers, thyroid problems, diabetes, and behavioral concerns, with a higher risk due to bioaccumulation and biomagnification in the food chain (Prevedouros et al., 2006; Kelly et al., 2007). Emerging POPs like PBDEs exhibit exponential concentration growth within human tissues in North America, Europe, and Japan, doubling approximately every five years (Hites, 2004). Nitrate concentrations in drinking water above the 10 mg/L standard increase the risk of colorectal cancer (Schullehner et al., 2018).

3.3. Atmospheric environment

Climate change and air quality are strongly coupled with each other (Hassan et al., 2016) (Fig. 1). Climate change could directly or indirectly impact the atmospheric environment, specifically the distribution, dynamics, and transport of air pollutants (Hassan et al., 2016; Jacob and Winner, 2009; Kallenborn et al., 2012). Air quality primarily depends on prevailing weather conditions and, hence, is highly sensitive to climate change (Jacob and Winner, 2009). Many studies have indicated that climate change considerably influences the surface concentrations of atmospheric pollutants such as $PM_{2.5}$ and tropospheric ozone (O_3) (Dawson et al., 2009; Jacob and Winner, 2009) (Table 5). With the application of the Global-Regional Coupled Air Pollution modeling system for the prediction of changes in the levels of $PM_{2.5}$ and O_3 due to climate change in the eastern part of the United States over a 50-year period (2000–2050), a decrease of $PM_{2.5}$ concentration was noticed in January with a mean level of 0.3 $\mu g/m^3$, while an increase in the level of $PM_{2.5}$ was found in July with average concentration: 2.5 $\mu g/m^3$ (Dawson et al., 2009). The reduction of $PM_{2.5}$ levels in January was linked to the increase in precipitation, whereas the increase in air temperature and lower ventilation rate (i.e., mixing depth) due to the decrease of wind speed and mixing height caused the higher level of $PM_{2.5}$ in July (Dawson et al., 2009). A similar observation was also noticed for O_3, with an increase of the O_3 level by 1.70 ppb as recorded in the summer season (July) (Dawson et al., 2009). Another study also observed a similar trend using a general circulation model plus chemical transport model, which projected an increase of O_3 concentration by 1–10 ppb and a rise of $PM_{2.5}$ level by 0.1–1.0 $\mu g/m^3$ in the upcoming decades (Jacob and Winner, 2009). In a study carried out for central and southeastern Europe over a three-decade time span, data analysis using regional climate-chemistry models revealed the exceedance of concentration of various atmospheric pollutants (PM_{10} (PM with diameter $\leq$ 10 μm), SO_2 and O_3) in most areas of the studied regions (Huszar et al., 2011). Notably, the increase of SO_2 and PM_{10} was mainly found in the winter and autumn seasons, which was partly ascribed to dissimilar vertical and horizontal mixing that was demonstrated by the changes in the ventilation coefficient (Huszar et al., 2011). A dynamic multimedia model predicted that climate change could cause an increase in annual or monthly average concentration of polycyclic aromatic hydrocarbons (PAHs) by a factor of two in diverse environments (air, water, and soil) (Cai et al., 2014). Climate change can also induce modification in atmospheric deposition. The alteration in advective flux due to wind speed differences influences the variation of the PAHs levels in the atmosphere (Cai et al., 2014).

Analysis of changes in urban air quality over 20 years in Stockholm, Sweden, using a nested system of global and regional climate models, indicated insignificant changes in air quality resulting from climate change, which was due to a low emission rate of pollutants (e.g., NOx) (Gidhagen et al., 2012). Simulations of atmospheric-pollutant data over the U.S.A. for nearly 50 years (2001–2050), by taking into consideration the impacts of climate change, increase in human activities, and application of emission controls, projected a considerable reduction of the level of various air contaminants (NO_x: 51 %, SO_2: 51 %, O_3: 20 %, and $PM_{2.5}$: 23 %) (Tagaris et al., 2007). The attenuation of atmospheric-pollutant concentrations was mainly attributed to the application of effective control strategies (Tagaris et al., 2007). However, most studies in the literature have reported that climate change has caused in an elevation in the level of atmospheric pollutants.

Wildfires cause the disturbance of many ecosystems (Fultz et al., 2016). Wildfires increase environmental pollution due to the emission of smoke particles (organic carbon derived from plant tissues and black carbon due to incomplete combustion) and greenhouse gases (mainly CO_2) (Littell et al., 2016). Black carbon emissions account for 5–10 % of the total fire smoke particles, while CO_2 emission accounts for 87–92 % of the total carbon burned (Littell et al., 2016). The smoke particles can impact the atmospheric radiative budgets by their ability to scatter and absorb solar radiation, which can further influence the precipitation and cloud cover in the local area (Littell et al., 2016). Sapkota et al. (2005) assessed the impact of the 2002 Quebec, Canadian forest fires on $PM_{2.5}$ (particulate matter with diameter $\leq$ 2.5 μm) levels in the atmosphere of Baltimore, U.S.A. The 24-hour $PM_{2.5}$ level reached up to 86 $\mu g/m^3$, which was above the 24-hour national ambient air quality standard (65 $\mu g/m^3$). Analysis of 5 years (2004–2009) of wildfire data in 561 western US counties showed that bushfires contributed to an average of 12 % of total daily $PM_{2.5}$ (Liu et al., 2016). Additionally, on days in which in $PM_{2.5}$ level in the atmosphere exceeded the regulatory standard, wildfires contributed a major fraction (71.3 %) of the total $PM_{2.5}$ level (Liu et al., 2016). Particulate matter (e.g., $PM_{2.5}$) and gaseous compounds that are released into the atmosphere from wildfires can adversely impact human health (Jaffe et al., 2020). Fig. 5 shows the detrimental effects of climate change-air quality interactions on local climate and human health.

Smoke-haze incidents caused by uncontrolled biomass burning, such as forests and peat-fires, frequently occur in Southeast Asian countries during dry seasons (Adam et al., 2021; Betha et al., 2014; Engling et al., 2014). Smoke haze episodes impact the regional air quality, atmospheric radiative balance, atmospheric chemistry, visibility, hydrologic cycle, climate, ecosystems, and human health (Adam et al., 2021; Keywood et al., 2015). A study on the Southeast Asian smoke haze in June 2013 reported that the level of $PM_{2.5}$ in the atmosphere was higher (up to 329

Table 5
Studies on the effects of climate change on air quality.

Study region	Air pollutant	Analysis method	Effects on air quality	Reference
USA	$PM_{2.5}$ and ozone	GCM-CTM	Increase summer time surface ozone level in polluted areas by 1–10 ppb. $PM_{2.5}$ concentrations by ±0.1–1 μg/m^3.	(Jacob and Winner, 2009)
Eastern USA	$PM_{2.5}$ and ozone	GRE-CAPS	Decrease in average $PM_{2.5}$ concentrations of 0.3 μg/m^3 in January and an increase in July, 2.5 μg/m^3. The average change in July ozone concentration was +1.70 ppb.	(Dawson et al., 2009)
Stockholm, Sweden	NO_2 and ozone	NSGRCM	Climate change slightly impacts air quality over the 20-year period assessed. Residents are expected to have lower exposure to NO_2 and ozone.	(Gidhagen et al., 2012)
Indonesia	NOx and $PM_{2.5}$	–	NOx and $PM_{2.5}$ concentrations increased up to 51 % and 26 %, respectively (2015–2030)	(Haryanto, 2018)
Central and southeastern Europe	PM_{10}, SO_2 and ozone	Regional climate models (RegCM3 and ALADIN-CLIMATE/CAMQ)	Increase in concentration of PM_{10}, SO_2 and ozone was observed. Moreover, the concentration of SO_2 and PM_{10} mostly increased in winter and autumn.	(Huszar et al., 2011)
USA	NOx, SO_2, $PM_{2.5}$ and ozone	CMAQ-GISS GCM	Decrease of concentration observed: NOx (51 %), SO_2 (51 %), $PM_{2.5}$ (23 %) and ozone (20 %). The reduction is attributed to the application of control strategies to reduce anthropogenic emissions.	(Tagaris et al., 2007)
California, USA	$PM_{2.5}$	Multiple models	Annual-average population-weighted $PM_{2.5}$ mass levels due to climate change was not statistically significant (2000–2050).	(Mahmud et al., 2012)
USA	$PM_{2.5}$ and ozone	CMAQ-GISS GCM	Increase of annual average $PM_{2.5}$ concentration in the northeastern USA, but average ozone concentrations slightly decreased across the northern sections of the USA, and increased across the southern USA.	(Tagaris et al., 2009)
Portugal and Porto metropolitan area	NO_2, PM_{10} and ozone	CAMx	NO_2 and PM_{10} concentrations are likely to increase in both regions, and ozone levels are likely to increase in Porto suburban areas (nearly 5 %), but be reduced in urban area (nearly 2 %).	(Sá et al., 2016)
Zanjan region, Iran	PM_{10}	Artificial neural network	Maximum amount of PM_{10} predicted for the year 2043 was 74.26 μg/m3. Additionally, highest rise of PM_{10} concentration was noticed in May and July (84.85 μg/m^3), and the lowest level was found in December (50.54 μg/m3).	(Moghanlo et al., 2021)
California, USA	$PM_{2.5}$	Parallel Climate Model	Considerable reduction of the predicted $PM_{2.5}$ mass concentrations of nearly 0.6–1.1 μg/m^3	(Mahmud et al., 2010)

Notes: GRE-CAPS: Global-Regional Coupled Air Pollution Modeling System
GCM-CTM: General circulation model plus chemical transport models
NSGRCM: Nested system of global and regional climate model
CMAQ-GISS GCM: Community Multiscale Air Quality (CMAQ) Modeling System and meteorological measurements downscaled from the Goddard Institute of Space Studies (GISS) Global Climate Model
Multiple models: Parallel Climate Model (PCM), the Weather Research and Forecasting (WRF) model and the UCD/CIT 3-D photochemical air quality model.
CAMx: Comprehensive Air quality Model with Extensions (version 6.0)

μg/m^3) during the smoke haze episode than that of the non-smoke haze period (11–21 μg/m^3) (Betha et al., 2014). Pavagadhi et al. (2013) examined the changes in physicochemical characteristics of aerosols ($PM_{2.5}$) in Singapore due to bushfires in Indonesia during 21–23 October 2010. The concentration of $PM_{2.5}$ in urban aerosols increased by nearly four-fold during the smoke haze activity period (107.2 μg/m^3) compared to the non-smoke haze period (27.0 μg/m^3). According to Popovicheva et al. (2017), during agricultural biomass burning in Hanoi, Vietnam, during May–June 2015, the mass of PM_{10} was elevated up to 167 μg/m^3, which surpassed the World Health Organization (WHO) 24-h standard guideline value of 50 μg/m^3.

Global climate change factors, namely the increase of air temperature, atmospheric CO_2, and O_3 concentrations, cause an increased emission of plant-based biogenic volatile organic compounds (VOCs) (Yuan et al., 2009) to the atmospheric environment. A field-scale experiment using various plant species (deciduous dwarf shrubs, graminoids, and forbs) showed that with an increase of ambient temperature by 2 °C, the concentration of VOCs (monoterpene and sesquiterpene) released by the plants was increased by 2–5 fold (Valolahti et al., 2015). Another study also found that changes in air temperature positively influenced the VOC emission rate from the plants, because the exposure of Norway spruce (*Picea abies*) plants to various temperatures (23–35 °C) induced an increase of emission rate of acetaldehyde and acetic acid with a maximum emission rate of ~1.5 μg/g/h and 0.16 μg/g/h, respectively at 30 °C (Filella et al., 2007). Assessment of VOC emissions using a global dynamic vegetation model under various time-scale scenarios indicated that the concentration of isoprene and monoterpenes would increase by 27 % and 51 %, respectively, by the end of the century (2100) (Lathière et al., 2005).

Recent reports have assessed the impact of climate change on urban air pollution and its health consequences (D'Amato, 2011; Haryanto, 2018). The growth of urbanization exacerbates climate change due to increased release of vehicle-derived air pollutants (D'Amato, 2011). In urban areas, transportation activities contribute significantly (80 %) to air pollution, surpassing emissions from other sources like forest fires and industrial or domestic activities (Haryanto, 2018). Indonesian research predicts a 6–8 % rise in energy consumption between 2015 and 2020, leading to a 51 % NOx concentration increase and 26 % $PM_{2.5}$ rise, raising the prevalence of airborne diseases (Haryanto, 2018). Exposure to gaseous pollutants (NOx, SOx) and particulate matter ($PM_{2.5}$, PM_{10}) leads to various human diseases (lung cancer, respiratory infections, asthma, bronchitis, skin and eye irritation, and cardiovascular diseases) (D'Amato, 2011; Haryanto, 2018).

Fang et al. (2013) showed that chronic $PM_{2.5}$ exposure increases global annual premature mortality by nearly 100,000 deaths, with chronic ozone exposure increasing respiratory disease-related mortality by 6300 deaths. $PM_{2.5}$ has a more severe health impact than O_3; $PM_{2.5}$-induced premature mortality is 15 times higher than that for O_3 (Tagaris et al., 2009). Strategies to mitigate climate change, air pollution, and airborne diseases include reducing greenhouse gas emissions from anthropogenic sources, efficient energy use, and adopting non-fossil fuel (Haryanto, 2018). Fig. 6 summarizes the effect of climate change and associated extreme weather events on the fate of contaminants in the environment.

4. Extreme weather events and contamination risk management

4.1. Terrestrial environment

When the land's capacity to provide benefits from a certain land use under a given kind of land management has decreased, the land has degraded. One of the key causes of land degradation that threatens sustainable development is climate change (Wan Mahari et al., 2020). Degradation of land includes changes to the soil's chemical, physical, and biological composition. Climate change is a danger to food security, because it alters soil properties, making it more difficult to grow food. Soil microorganisms respond to higher atmospheric CO_2 levels by boosting their rate of decomposition of organic materials (Raza et al., 2023), which might result in even more CO_2 being released into the atmosphere. Climate change has the potential to render barren soil that has degraded as a result of inadequate land management. Large-scale deforestation and a subsequent increase in methane (CH_4) emissions directly result from climate change (Chaddad et al., 2022). Soil erosion and rainfall patterns are two areas where climate change is expected to induce a major impact on the planet's soils. Erosion rates can be impacted by changes in climate that affect soil surface characteristics such as sealing, surface roughness, and crusting. The state of agricultural land, natural resources, and water quality might be seriously affected by changes in erosion. Unless precautions are taken, increased erosion rates will occur due to increased rainfall volumes and intensities. Erosion by wind and water, depletion of soil carbon, mass movement of nutrients, deterioration of soil structure, formation of acid sulphate soils, and acidity of soil are all threats to the quality of land (Lindgren et al., 2022). The transition from snow to rain, as a result of climate change, might have far-reaching consequences for soil erosion and sediment production (Marcinkowski et al., 2022). The biogeochemical cycle is also negatively affected by erosional processes (Steinmuller et al., 2020).

One major problem with using groundwater is groundwater depletion, which is the gradual lowering of water tables due to repeated pumping. The availability of groundwater is crucial to the maintenance of terrestrial and aquatic ecosystems and to the capacity of humans to adapt to climatic unpredictability and change. Groundwater availability and reliance are both directly impacted by the increased unpredictability of precipitation and more severe weather events brought on by climate change (Martin-Kerry et al., 2023). Much of the world's agriculturally cultivated food supply is at risk due to groundwater depletion and pollution. The quality of groundwater and potential drinking water supplies might be negatively impacted by climate change-related sea level rise if salt water begins to seep into coastal aquifers. Rising sea levels due to climate change pose a danger to the quality and utility of groundwater resources in coastal regions by causing widespread flooding (Sangsefidi et al., 2023). Heat-related illnesses and water-borne infections will cause more illness and death due to climate change. Because floods provide ideal conditions for mosquito reproduction, the malaria transmission window will be extended. Heat waves throughout the planet might become more often and more severe. The anticipated changes in hydrological cycles in East, South, and Southeast Asia are connected with an increase in endemic morbidity and death owing to diarrheal illness (Tulchinsky et al., 2023). In heavily-polluted countries and in certain regions of East Asia, dengue disease has already shown up

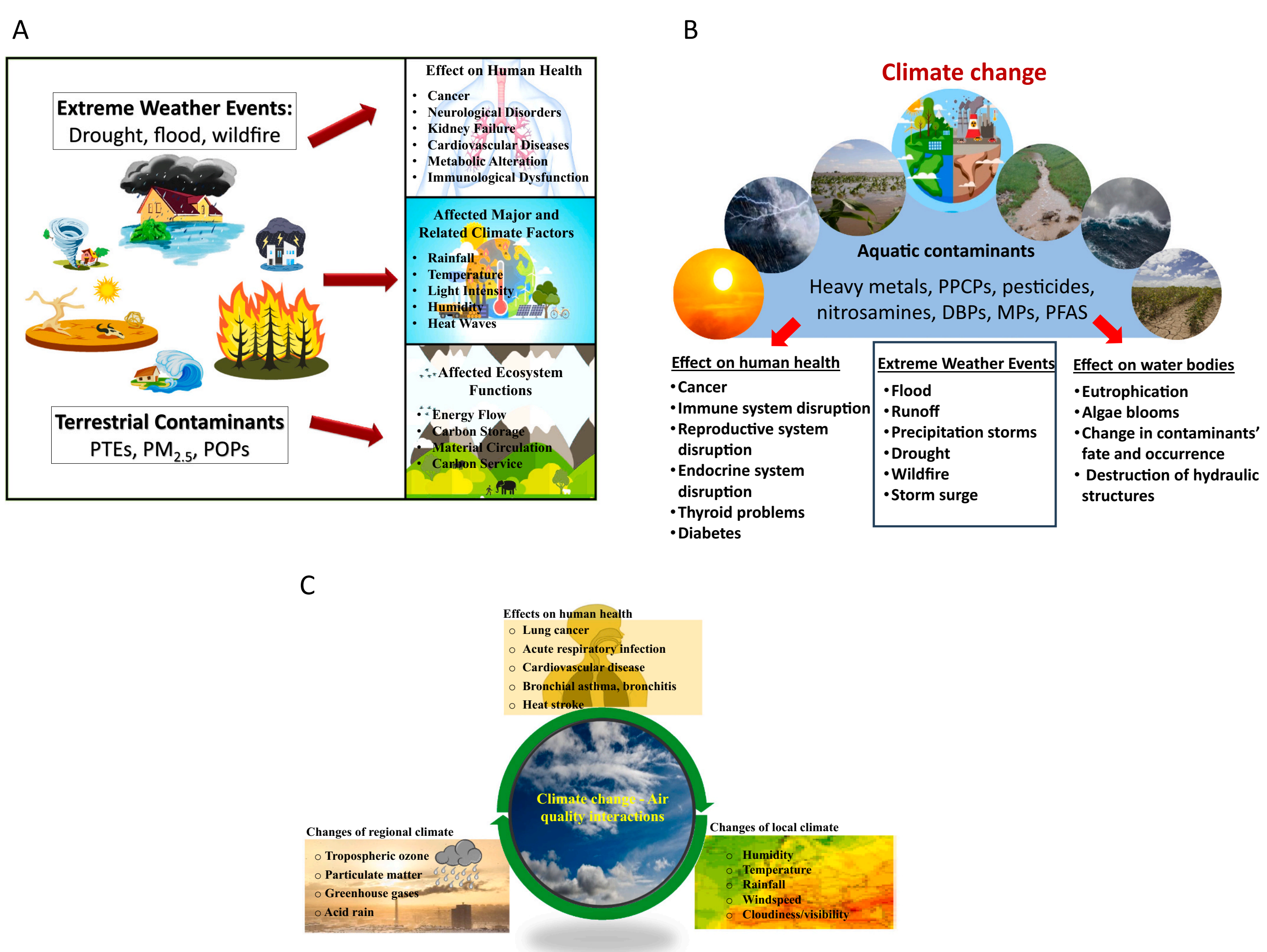

Fig. 5. Effects of climate change and terrestrial (A), aquatic (B) and atmospheric (C) contaminants interactions on local and regional climates as well as on the human health effects.

at high rates (Parker et al., 2022).

4.2. Aquatic environment

All species, including humans, require water. Water resource managers rely on wastewater treatment to maintain water quality for best usage. By 2025, 5 billion of 8 billion people will live in water-stressed regions (Wang et al., 2023a). Micro-pollutants from industrial and chemical compounds dumped into freshwater systems are a serious environmental hazard. Although most of these pollutants are detected at very low levels, some pose serious toxicological issues, especially when included in composite mixes. Many micro-pollutants resistant to conventional treatment have been found and are subsequently transmitted to the aquatic environment (Junaid et al., 2023). Hormones, steroids, pesticides, industrial chemicals, medications, and a plethora of other novel substances fall under this category. As a result, they are a threat to aquatic and human life. Thus, freshwater contamination is a serious public threat that calls for international attention.

Climate change is the consequence of long-term shifts in atmospheric temperatures and weather patterns. Currently, it may be resulting in the gradual increase of Earth's average surface temperature. It is generally accepted that people are responsible for this increase because their burning of fossil fuels emits CO_2 and other greenhouse gases into the environment (Baz et al., 2022). In addition to contributing to increasing sea levels and extreme weather, these gases also contribute to the overall warming of the Earth's atmosphere. Researchers who study global climate change consider natural and human impacts on the terrestrial climate and hydrologic cycle. The United States government has several different agencies, some of which include the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the Environmental Protection Agency (EPA), that have affirmed that climate change is a threat to humanity caused by human actions (Bray et al., 2017).

Ecology, climate, and the weather are all influenced by human actions. Although certain human actions do not impact the environment, there are many others that do. While the environment can tolerate

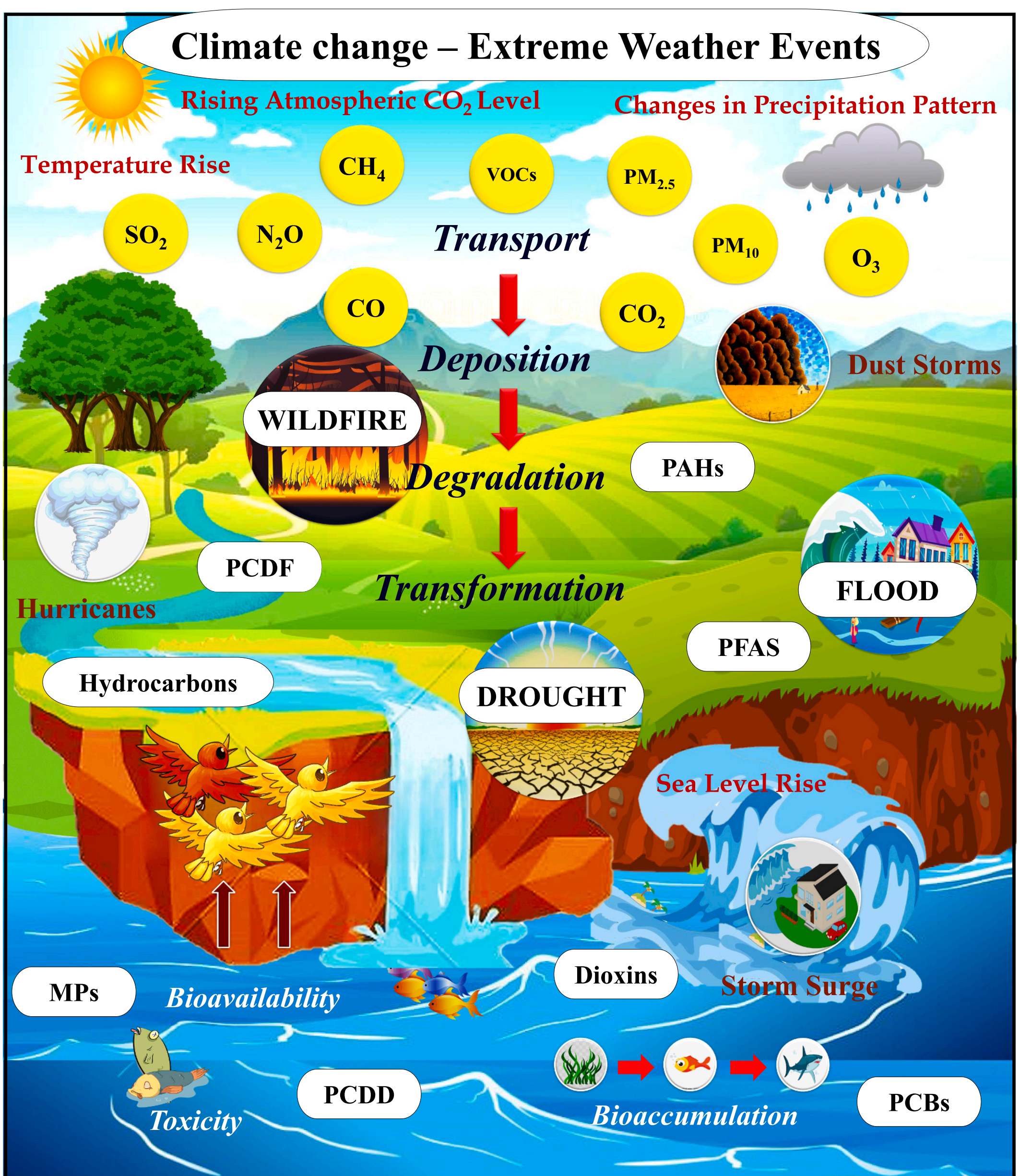

Fig. 6. Climate change-induced extreme weather events and contaminant dynamics.

certain forms of human interference without suffering permanent damage, the extent to which it can withstand such interference is often much exceeded. One of the unavoidable consequences of human-caused climate change is water contamination, which has prompted immediate action to address the problem (Anik et al., 2023). Micro-pollutants and physiochemical and biological characteristics that determine water quality will be affected or altered by the presence of pollution. River flows, chemical reaction kinetics, and freshwater ecological quality are susceptible to unpredictable and persistent shifts in precipitation and air temperature. These processes dilute toxins and wash sediment loads into lakes, which change the lakes' physical characteristics and threaten the lives of their inhabitants. Some toxic and greenhouse gases may be produced due to this kind of water pollution or by adding manmade harmful chemicals or/and byproducts, potentially contributing to global warming activities or even more serious environmental hazards (Li et al., 2023).

Remediation efforts can be made to lessen the impacts of climate change on water contamination. One example is capturing and storing CO_2. Others include managing croplands with decreased tillage, planting bio-energy crops; properly disposing of solid waste; afforestation; and reforestation (Qi et al., 2023). When studying water contamination, scientists should go beyond simple empirical comparisons and instead focus on identifying the underlying physical and molecular processes. If the underlying processes are understood, it will be much easier to put solutions to water contamination in their correct context. Researchers have suggested that this goal may be attained by establishing a framework for evaluating the most effective tools for controlling water pollution. It should be one that considers the problem's sources and impacts as well as the long-term nature of the issue. Particularly in emerging and poor nations, where the threat of water pollution has not been adequately addressed, a sustainable working strategy on water contamination should be created, adopted, and strictly enforced. Researchers have provided a categorization system for controlling water pollution. Economic tools, such as a product or substance charge (a fee), can be imposed on items that contain hazardous chemicals in order to restrict the use of these substances (Tan et al., 2024). Regulations, such as a ban on a substance or a restriction on its authorized use, can be established. Information about a substance, such as disposal requirements, which can be disseminated to the public, would also be useful. Procedures used at the end of the wastewater treatment process, known as "end-of-pipe" measures, focus on filtering contaminants after input into the system, as opposed to those taken at the source, which prevents pollution before hazardous and harmful chemical elements reach waterways (Jurowski, 2023). Procedures should focus on preventing a contaminant from getting into waterways.

4.3. Atmospheric environment

Synergistic and dynamic linkages between human, and urban and regional environmental systems are rooted in a continuously changing global environment (Miyahara et al., 2022). Anthropogenic activities are driving increasing temperatures and other climate changes, impacting health and quality of life. Predominantly in economically advanced or high GDP (gross domestic product) nations, urban-zone centres are substantial producers of transportation and CO_2 emissions from industrial and home fossil fuel usage (Qureshi et al., 2022). In the 21st century, the impact of urban heat islands causes cities to warm quicker than rural regions. The chief anthropogenic cause of urban climate change worldwide stems from the change of original native terrains into compact, dense, urban settlements. These areas are characterized by heat-trapping impermeable surfaces and construction materials, which limit nocturnal temperature reduction (Lian et al., 2021). The dissemination and dynamics of a broad array of pollutants that impact respiratory, cardiovascular, and allergic diseases compound the complexity of air quality on urban and regional health outcomes, going beyond the singular effects of temperature. In 50–55 US metropolitan locations, the boost in life expectancy between the 1960s and 2005 may be partly ascribed to a reduction in air pollutants (Mueller et al., 2023). Air quality in low and middle-income cities continues to deteriorate, imposing increased health expenses on rising populations who depend on high energy consumption for household and industrial needs.

Hot weather occurrences and heat waves are expected to increase in frequency and intensity in the 21st century. Climate affects air quality; therefore, summer heat may add to air pollution that worsens the health effects of heat (Sziroczak et al., 2022). Coupled global and regional model simulations reveal that global warming would likely worsen surface ozone. Ozone and particle matter concentrations are both on the rise in metropolitan areas, as smoke from wildfires and certain pollens increase in some locations of the globe. Climate change will most affect Northern mid-latitude cities during high pollution events. The exposure of cities to the dangers of high temperatures and air pollution varies according to location, economic status, climate, and other variables. Robust historical research on air pollution and racial and environmental justice and advancements in the socio-spatial testing of fine-scale social, ecological, and weather data are allowing improved insight into the various health risks among urban sub-populations within specific cities (Qiu et al., 2022). The goal of adaptations is to decrease susceptibility to the impacts of climate change, whereas the goal of mitigation methods is to minimize emissions of greenhouse gases and increase carbon sequestration (da Silva et al., 2022). Policies that cut energy consumption in the transport sector, industry, and homes, enhance the built environment, or promote carbon sequestration via the maintenance or construction of urban trees may all help cities contribute to long-term mitigation of increasing temperature and atmospheric contamination. Modifications include better weather forecasting, air quality alerts, heat warning systems, and emergency readiness to cope with elderly people during severe occurrences. It is crucial to have climate policies that are locally integrated and can adapt to different socio-ecological settings.

A wide range of strategies have been used in urban and regional environments, but all have the underlying objective of minimising the negative effects of human activities on the natural world. Urban areas have adopted or are contemplating a number of approaches to climate change adaptation and mitigation (Mosca et al., 2023). The mitigation methods provided in this overview are not all possible ways to deal with climate change in urban and regional areas, but they do offer a good representation of the range of options. In order to make communities more resilient to climate change, every action plan must include metrics and goals. Weather advisory standards, warning systems for air quality (dust management and carbon emissions), and construction rules are all being established mostly in urban setups. New land-use techniques that make parks, open areas, and urban forests more easily accessible are a major priority, as are targets for increasing the utilization of renewable energy (Zhu et al., 2022). Plans of action need a coordinated system of both centralized and decentralized strategies to be effective. They also must stress the need for local government, community organizations, public interest groups, and private citizens to work together. Although more research is required to determine the efficacy of programmes, implementing climate adaptation and mitigation techniques may have a range of co-benefits to health, both direct and indirect, and positive environmental implications. Direct advantages from encouraging these techniques may be predicted, as can an indirect reduction in fatalities and diseases caused by heat and air pollution. Urban populations, in particular, who are physiologically fragile, socioeconomically disadvantaged, and dwell in the most degraded surroundings, bear a disproportionate share of health costs (Zhu et al., 2022). Thus, doing research that identifies these groups and areas is vital. Strategies for mitigating and addressing climate change in urban and regional areas may include modifying the built environment, land use, or transportation in order to lessen the city's exposure to heat-trapping greenhouse gases and to make the area more comfortable for residents. Health co-benefits, such as reduced rates of heat-related and respiratory ailments and so-called "lifestyle" diseases, may result from the implementation of these strategies. Numerous municipalities have implemented monitoring systems for alerts and warnings in preparation for hazardous air quality days. Few studies assess the use of alternative methods or health co-benefits. Costly components of municipal mitigation and adaption strategies are difficult to execute in the present economic context, and further study is required to examine the extent to which health benefits lessen the price tag of climate policies (Mosca et al., 2023). Furthermore, it is important to assess the influences of atmospheric pollution on natural ecosystems and biodiversity so as to adopt mitigation strategies.

Although all studies acknowledge the presence of scenario-based uncertainties, the only method chosen to mitigate these uncertainties is to employ a number of different scenarios. The most common methods for dealing with model uncertainty include using a collection of models, sometimes known as a "ensemble," and the downscaling methodology. However, much research has relied on a single General Circulation Model (GCM) paired with a dynamic downscaling technique, because doing so did not require a huge amount of computer resources. This might be because just one GCM is available and powerful enough to represent the local climate. For instance, the United States government uses a GCM created at the Goddard Institute for Space Studies (GISS) to make predictions. The U.K.'s Hadley Centre Coupled Model, version 3 (HadCM3), was used to predict European forecasts. Due to the extensive processing requirements, most research has relied on a single Active Queue Management to foretell future air pollution levels. However, predictions based on a single model might cause bias owing to the uncertainty associated with each model's different simulation methods and functions.

Plants, animals and other organisms are certainly facing challenges due to climate change. For instance, the atmospheric temperature and humidity are strongly related to the net primary productivity of tropical moist deciduous forests (Behera et al., 2023). Climate change is anticipated to hinder the regeneration of trees, with detrimental impacts on the health, diversity, and ecosystem services of regional forests due to regeneration shortfalls in currently dominant southern boreal species (Reich et al., 2022). It has already been reported that there is a danger of critical temperature thresholds approaching tropical forests (Doughty et al., 2023). In dry grasslands, phenology might be directly influenced by urban heat islands, but in varying directions and magnitudes, and these may impact ecosystem services, biogeochemical cycles, and ecological interactions (Christmann et al., 2023). Similarly, the faunal diversity is also affected significantly by air pollution. A meta-analysis study revealed that an increase in herbivory and a decreased abundance of decomposers are the most prominent impacts of air contamination on arthropod communities (Zvereva and Kozlov, 2010). Across the tropics, climate change impacts on demographic rates must be integrated into conservation planning, as demonstrated in this study for six of 21 focal species, accounting for 29 % (Neate-Clegg et al., 2021). Researchers continually update the impact of air and temperature changes on various animal groups worldwide, with a particular emphasis on the pronounced effects observed in microorganisms (Ibáñez et al., 2023). However, the mitigation strategies for all these effects on global biodiversity are still inconclusive.

5. Summary and conclusions

Climate change is intricately associated with sea-level rise and the emergence of extreme weather events like droughts, floods, and wildfires. Recent times have witnessed an escalation in the frequency and intensity of these events, linked to intensified greenhouse gas emissions driving climate change. This comprehensive assessment explores the potential consequences of climate change on extreme weather events, focusing on their impact on contamination in terrestrial, aquatic, and atmospheric domains. The interactions between extreme weather events—droughts, floods, and wildfires—and contaminants are multifaceted, with both direct release into the environment and indirect influence on contaminant speciation, mobilization, transportation, and dispersion. For instance, wildfires contribute to the emission of diverse contaminants, including PAHs, VOCs, and particulate matter. Both droughts and floods affect contaminant dynamics across various phases.

Given the well-established connection between greenhouse gas-driven climate change and extreme weather events like droughts, floods, and wildfires, coupled with the existing knowledge gaps regarding the direct and indirect ramifications of these events on contaminants across terrestrial, aquatic, and atmospheric realms, the following research directions are recommended:

5.1. *The nexus between climate change and extreme weather events*

Providing scientific evidence linking climate change to extreme weather events is crucial. Extreme event attribution or attribution science examines extreme weather phenomena from the perspective of climate change and quantifies their direct impact. An anthropogenic climate change scenario is compared with the natural variability of the climate to determine which of these recent events can be attributed to climate change. Attribution analysis generally encompasses four steps (Wehner and Reed, 2022): (1) analysing observed data and quantifying an event's magnitude and frequency, (2) utilizing computational modeling for corroboration with observed data, (3) executing identical models on a baseline climate change absent "earth" model, and (4) applying statistical analysis to quantify the difference between outcomes from the second and third steps, thus measuring the explicit impact of climate change on the examined event.

5.2. *Direct and indirect effects of extreme weather events on contaminants*

The direct contribution of extreme weather events including wildfires on the release and spread of contaminants, including VOCs, PAHs and particulate matter, needs to be examined using advanced technologies including the Light Detection and Ranging (LIDAR) remote sensing method. The impact of these contaminants on environmental, human, and ecosystem health need to be examined during extreme weather events. The indirect effects of extreme weather events on contaminants need to be studied. Their effects on the mobilization, transport and bioavailability of contaminants need to be examined using advanced spectroscopic and analytical techniques to explore the human fingerprint on extreme weather and how it is related to environmental contamination.

5.3. *Awareness of climate change impacts on contaminants*

The awareness of the impacts of climate change in the science and decision-making process of contaminants is only just emerging, and the remediation industry is a long way from implementing adaptive measures in mainstream assessment and management of contaminated environments. Contaminants released by humans from land-based sources or the atmosphere also adversely affect many ecosystems. This paper examined how current and future climate change might influence risks from contaminants based on examples from different ecosystems. However, recognizing the need for assessment measures is the first step towards more adaptive practices in managing contaminated environments impacted by climate change. Formulating policies and strategies for assessing and remediating contamination likely to result from climate change-induced extreme weather events caused by greenhouse gas emissions requires the collaboration of environmental and climate change scientists with close engagement with environmental regulatory agencies. There is a critical need to pay attention to the interplay between climate change and extreme weather events on contaminant mobilization, toxicity, and bioaccumulation in different ecosystems.

CRediT authorship contribution statement

Shiv Bolan, Lokesh P. Padhye, Tahereh Jasemizad, Nanthi Bolan -

Conceptualization, Writing – original skeleton of the entire draft, contributed to Section 1, 3 and 5.

Muthusamy Govarthanan, N. Karmegam, Hasintha Wijesekara, Dhulmy Amarasiri – Covered Section 4.

Deyi Hou, Pingfan Zhou, Basanta Kumar Biswal, Rajasekhar Balasubramanian – Covered Section 2.

Hailong Wang, Kadambot H.M. Siddique, Jörg Rinklebe, M.B. Kirkham - contributed to the interpretation of the discussion of various sections and provided critical revision and editing of the article.

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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