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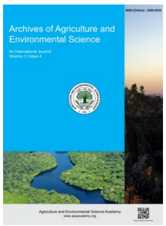

REVIEW ARTICLE

CrossMark

A review on the impact of wildfires on ecosystems, water quality, and health risks to humans

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ABSTRACT

Due to global warming, climatic changes, and enhanced anthropogenic activities (due to population growth) over the past 20 years, the number and intensity of wildfires have increased manifold around the world. Although forest fire is integral to shaping the forest's flora and fauna and maintaining the environment's health, frequent fires and their severity are causing several adverse impacts on the environment, aquatic organisms, wild animals, and humans. Wildfire releases the volatile organic pollutants in the environment (in the form of smoke), inducing changes in soil physicochemical properties and affecting the hydrological cycle. The pH values of soil and surface water are altered due to ash, which adversely impacts the aquatic organisms and soil microbes. The soil's water retention capacity significantly reduced (35-45%). The smoke generated during wildfires adversely affects the health of wild animals and humans. Trends that are predicted to continue are not only a natural disturber of forests and ecosystems but also significantly affect human and wild animals' health adversely. Wildfires not only damage forests and have a negative impact on human and animal health but also threaten water security, increase the probability of flooding, and increase economic losses. In-depth research and understanding on this topic are urgently needed for the better management of forest ecosystems. In this review research information publish after 2019 was considered and we have discussed the recent update in wildfire and forest fire, their causes, impacts on the soil quality, water resources, biodiversity and human health, and this article will serve as the basis for future wildfire research.

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INTRODUCTION

The oldest agricultural practice is to develop the forest (growing plants and trees), which meets the basic needs, i.e., shelter, food, clothing, and heat (Singh, 2022). Forests not only stabilize the environment but also provide a habitat for numerous living species. Forests also regulate the environmental carbon cycle (Li *et al.*, 2021; Balla *et al.*, 2021). A wildfire is defined as a fire on forestland that is not planned for forest protection and management. For a healthy environment, shaping the forest's flora and fauna is essential, and that is maintained by natural wildfires. For some species, forest fires are beneficial, but wildfires do have disadvantages to the ecosystem and citizens. Over the past 20 years, due to population growth, climate change, global warming, increasing aridity, and human activities, the severity and frequency of wildfires at the interface of wildland-urban areas have increased several times (Lan *et al.*, 2021; Vilar *et al.*, 2021). The literature denotes that approximately 400 million hectares of earth (4 million km²) were impacted by the wildfires in 2023. In Africa, roughly 8% of the total earth's land is affected by wildfires. The annual tree loss area globally is approximately 9 million hectares. Depending upon their geographic distribution, magnitude, and timing, climate changes disturb the aquatic ecosystem globally. Greenhouse gas emissions, loss of biodiversity, soil erosion, reduction in forest cover, alteration of soil structure, and soil hydrological changes are the factors caused

by wildfires for global climate change. Forest fires also impair the livelihoods of forest-dependent communities. In developing countries, the adverse socio-economic impacts of wildfires are more significant. According to the FSI (Forest State of India) report, more than 36% of forest cover is susceptible to wildfires. The forests of Andhra Pradesh, Assam, Chhattisgarh, Odisha, Maharashtra, Madhya Pradesh, Manipur, Mizoram, Nagaland, and Uttarakhand that together make up about 10.66% of total forest area in India are classified as highly fire-prone areas. In the event of wildfires, the primary focus is to protect lives and property. Smoke produced by wildfires contains both primary and secondary pollutants, including particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs) (Palm *et al*., 2020), polycyclic aromatic hydrocarbons (PAHs), and ozone (Grulke & Heath, 2020), as well as terpenoids and organic acids (Permar *et al*., 2021). This smoke can travel thousands of kilometers and has a negative impact on human health, air quality, and climate (Haque *et al*., 2021; Scordo *et al*., 2022).
The impact of wildfires is influenced by local and regional factors. Smoke from wildfires alters plant physiology, assimilation of carbon dioxide (CO_2), and the emission of volatile organic compounds. It is estimated that 65 million tons of CO_2 will enter the environment in the year 2050 against 48 million tons in the year 2024 due to wildfires. Brando *et al*. (2020) reported that wildfires in the Amazon region of the United States would release approximately 17 petagrams (Pg) of CO_2 into the environment by the year 2050. The European Commission documented that in 2022, wildfires released approximately 1,455 megatons of carbon worldwide. The smoke from wildfires inhibits photosynthesis and stomatal conductance by interacting with leaf surfaces and stomata. Furthermore, as forest fires deteriorate vegetation, water infiltration into the groundwater system decreases which in turn reduces soil water retention capacity. In 2023, the global economic losses from wildfires are estimated to be US $6.8 billion (Salas, 2024). In India, the loss in the year 2023 due to wildfires was around US $110 million, while the global loss in 2018 was US $22 billion.

CAUSES OF FOREST FIRES

The forest fires can be attributed to natural and human anthropogenic activities.

Natural causes

Temperature, wind speed, wind direction, soil moisture, and humidity are the key factors that influence wildfires. Dry leaves serve as fuel for these fires, while plants, shrubs, and trees that contain oils or resins further promote tree combustion and fire. Wind accelerates the spread of wildfire by flames toward highly flammable leaf litter and dry wood on the forest floor. Mangiameli *et al*. (2021) reported that wildfires can spread at speeds up to 23 km/h. Other natural causes of forest fires are lightning and volcanoes.

Anthropogenic Causes

The research literature survey (Farid *et al*., 2024; Zhuang *et al*., 2021) shows that approximately 90% of forest fires are caused by human activities. Carelessness during campfires, debris burning, and improperly discarded cigarettes are among the primary contributors to human-made wildfires. Furthermore, global warming resulting from human actions exacerbates the intensity, duration, and spread of these fires. Village residents who live near forests often use fire to protect themselves from wild animals and for cooking, which also contributes to the incidence of man-made wildfires.

IMPACT OF FOREST FIRES ON FOREST BIODIVERSITY

Undoubtedly, forest fires have several disadvantages; however, they are essential for significantly promoting diversity in forests. Forest fires change the composition of species present in the ecosystem, and their effects can be either beneficial or harmful, depending on the context. Plant species such as *Terminalia chebula, T. bellirica, and T. tomentosa*, with commercial applications, are impacted by fires. In contrast, the forest fires have little impact on plant species like *Lantana camara*, *L. indica*, *Eupatorium glandulosum*, *Parthenium hysterophorus*, *Cassia tora*, *and C.* occidentalis.

Impact of forest fires on air quality

When trees, organic compounds, and litter are burned, harmful organic and inorganic pollutants are released into the atmosphere, leading to air pollution that not only contributes to climate change but also significantly adversely impacts the lives of both humans and animals. Air quality in areas far from the fire is also impacted; the extent of this effect depends on wind direction and speed of the wind. During forest fires, harmful chemical compounds, including carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and volatile organic compounds (such as benzene, toluene, ethylbenzene, o-, m-, and p-xylene, and naphthalene), as well as nitrogen oxides and polycyclic aromatic hydrocarbons (PAHs), are released into the atmosphere. The volatile organic compounds and nitrogen oxides emitted during wildfires react with sunlight to form secondary pollutants, such as ground-level ozone.

Impact of wildfires on water resources

Around the world, the availability of drinking water for citizens depends heavily on groundwater and surface waters of rivers and lakes. Climate change and extreme events, such as wildfires, are not only depleting these important resources but also negatively impacting water quality. Pollutants present in smoke include carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (such as benzene, toluene, ethyl benzene, o-, m-, and p-xylene, and naphthalene), nitrogen oxides, polycyclic aromatic hydrocarbons (PAHs), and potentially toxic metals (Cu, Cd, Pb, Cr, Fe, Co), arsenic along with anions such as nitrite, nitrate, phosphate, and sulfate, which are deposited on the surrounding surfaces, contaminating surface water (Ma *et al*., 2022; Leveque *et al*., 2021). Rao & Parsai (2025) reported that the concentrations of Fe, Al, and vanadium increased by 740%, 510%, and 530% respectively in surface water after wildfires. Additionally, fire retardants that are used to suppress fires also adversely affect water quality. The concentration of V, Cr, Mn, Cu, As, Cd, Sb, Ba, Tl, and Pb in drinking water increased 4-2880 times due to fire retardants, was the finding of Schammel *et al.* (2024). The contamination of water by these pollutants alters the total nitrogen content, concentrations of dissolved organic carbon, dissolved organic nitrogen, and concentration of total soluble solids in surface water samples (Raoelison *et al.*, 2023). Toxic compounds that are released from the burning cars, homes, and other infrastructures built by people in the forested areas during wildfires also contaminate the water. In most of the research articles on wildfires included in this review article, the concentration of these pollutants in water was higher (in 42-88% of reviewed articles) than pre-wildfire parameters. Few studies also have reported a decrease in the concentration of these pollutants (Table 1).

Wildfires have a major impact on soil quality. During the fire, the temperatures rise, altering the soil structure and increasing its hydrophobicity. This means that the soil becomes water-repellent and absorbs less water. Collar *et al.* (2023a,b) and Ackley *et al.* (2021) reported a 35-45% reduction in the soil's water retention capacity. On the soil surface, sediments and ash containing potentially toxic metals, anions, nitrogen, phosphorus, and organic pollutants are accumulated (Ozgeldinova *et al.*, 2025), which can leach into surface water, river water, streams, and groundwater. Lopez *et al.* (2023) reported that ash produced during wildfires contains 327-13100 ug/kg of Cr. After wildfires, rainfall can cause water containing sediments and ash to flow more rapidly into rivers and streams. Due to wildfires, freshwater species and ecosystems are significantly impacted as the fires alter the physicochemical properties of the water. When potentially toxic metals, nitrogen, phosphorus, polycyclic aromatic hydrocarbons (Li *et al.*, 2022; Wang *et al.*, 2022), and other nutrient-containing ash contaminate surface water, the oxygen content and light regimes are disrupted, resulting in mass mortality of aquatic species (Gomez Isaza *et al.*, 2022). Ferrer *et al.* (2021) and Ferrer & Thurman (2023), in their studies of ash and surface water samples from four wildfire-affected locations in the USA, found that the ash leachates and surface water samples from the studied regions contain aromatic polycarboxylic acids, including benzene polycarboxylic acid (with two or three –COOH groups attached to a benzene ring), 3, 5-pyridine dicarboxylic acid, naphthalene carboxylic acid, quinolone carboxylic acid, and benzofuran carboxylic acid.

Table 1. Impact of wildfires on pollutants status and their reported maximum concentration in water.

S. No.	Parameter	Increase (%)	Decrease (%)	No change (%)	Concentration
1.	Temperature	80		20	
2.	Suspended sediments	91.5		8.5	
3.	Nitrogen	78	5	17	0.044-0.12ug/L
4.	Calcium	81	8	11	0.5-4.5mg/L
5.	Sodium	73	11	16	5.0-10.1 mg/L
6.	Potassium	63	10	27	0.4-1.0mg/L
7.	Magnesium	72	16	12	0.4-1.3mg/L
8.	pH	40	50	10	5.5-6.7 mg/L
9.	Bicarbonate	16	78	06	4.4-28.4 mg/L
10.	Nitrate	83	17		14-180 mg/L
11.	Sulphate	54	24	22	1.5mg/L
12.	Organic carbon	52	26	22	0.26-0.45 mg/L
13.	Total Phosphorous	48	36	16	0.03-0.29mg/L
14.	NH_4^+	64	24	12	0.0-0.006mg/L
15.	Arsenic	84		16	0.92ug/L
16.	Chromium	84		16	0.0-2.65mg/L
17.	Cadmium	100			0.1ug/l
18.	Copper	66	15	19	0.85-4.42 ug/L
19.	Iron	80	10	10	100 ug/L
20.	Lead	71	14	14	1.0 ug/L
21.	Zinc	73		27	1.0 ug/L
22.	Benzene	100			1.25 ug/L
23.	Naphthalene	75		25	0.05ug/L
24.	Toluene				0.017-25 ppbv
25.	Camphor				0-0.915 ppbv
26.	Isoprene				0.021-4 ppbv
27.	Methylene chloride				0.48-9.2 ug/L
28.	Chloroform				0.14-67 ug/L
29.	Xylene				0.6 ug/L
30.	∑PAH				0.02-29.24ug/L

When water becomes contaminated by the ash and sediments produced during a wildfire, its pH values are altered. An increase in temperature and pH levels converts approximately 37% un-ionized ammonia into ionized ammonia, leading to the mortality of aquatic organisms (Gomez Isaza *et al.*, 2022; Gorshkov *et al.*, 2020). When such water is used for irrigation, the soil microbiology and cation exchange capacity are significantly affected. Uzun *et al.* (2020) and Robinne *et al.* (2021) during their studies found that wildfires change the quality of dissolved organic carbon. The ash produced by the combustion of burning plants and vegetation during forest fires contains a large amount of organic matter and nitrogen compounds that contribute to the formation of more disinfection byproducts. The concentration of anions such as iodide, bromide, and nitrite in surface water is also changed due to wildfires, which improves the production of inorganic disinfection byproducts. The ash generated during wildfires contaminates soil and surface water; the soil microbial communities and the microbes present in water are negatively affected (Wan *et al.*, 2021; Valenca *et al.*, 2020). Concentrations of Al, Fe, Mn, As, Cd, Pb, and Hg in stream water were higher after wildfires than before the wildfires (Pennino *et al.*, 2022). Moazeni & Cerda (2024), during their studies, found that the arsenic concentration increased by 97%, and the strontium (Sr) concentration increased by 105%. It was reported that the concentration of bicarbonate (HCO_3-) was decreased, while 317% increase in nitrate (NO_3-) and a 155% increase in sulfate concentration. The concentrations of cations such as sodium (Na^-), calcium (Ca^{2-}), potassium (K^-), and magnesium (Mg^{2-}) were also higher (by 38-200%) in post-fire stream water, possibly due to the leaching and infiltration of ash (Moazeni & Cerda, 2024). Water contamination by these ions increases water hardness and changes the chemical composition of the habitat, which has a negative effect on aquatic organisms (Emmerton *et al.*, 2020). When such water is used for agricultural purposes, it negatively affects the taste, growth, and yield of crops (Ortiz-Partida *et al.*, 2020). Paul *et al.* (2022) and Beyene *et al.* (2021) during their studies found that stream flow after wildfire was 10,000% higher than pre-wildfire.

Impact of forest fires on humans

Pollutants such as polycyclic aromatic hydrocarbons (including biphenyls, diphenyl ethers, dioxins, and furans) and toxic metals are found in the forest vegetation and waste of forests. During combustion, these pollutants are released into the air as smoke, either as particulate matter (PM) or in gaseous form. The composition of the gases and chemicals in the smoke varies based on forest regions, weather conditions, and the type(s) of fuel burned (Wang *et al.*, 2024). Wildfire smoke primarily affects the lungs, followed by the liver, kidneys, and central nervous system, leading to cardiovascular disease, respiratory issues, inflammation, oxidative stress, and neuronal death (USEPA, 2022; Jiang *et al.*, 2022; Baudet *et al.*, 2022; Neumann *et al.*, 2021; Rajasekhar *et al.*, 2020; Orr *et al.*, 2020). Some of the gaseous pollutants in smoke are carcinogenic (Shala *et al.*, 2023; O'Dell *et al.*, 2020). The adverse effects of wildfire smoke on human health depend on factors such as age, pre-existing health conditions, and occupation. Wildfire smoke increases the risk of cardiac arrest and heart arrhythmias, particularly in individuals already suffering from respiratory and cardiovascular diseases. In older adults, immune function is also negatively impacted. The wildfires also impact the mental health of the young ones who reside near the affected area for many years (Rosenthal *et al.*, 2021). Studies have shown that short-term exposure to wildfires leads to 240 deaths each year and 2500 for long-term exposure in Canada only. The estimated cost of Canada's short-term health effects from wildfires is about US $410 million to $1.8 billion, with long-term health impacts ranging from $4.3 billion to $19 billion.

Particulate Matter (PM)

When wildfires occur, pollutants such as black carbon (resulting from the incomplete combustion of fossil fuels), organic matter particles (produced by vegetation and human activities), and inorganic substances like sea salts, nitrates, sulfates, and ammonium are emitted in the form of particles with a diameter of 2.5 microns or less (referred to as PM 2.5 particles). These particles can easily penetrate the bloodstream, lungs, and respiratory tract of humans (Grant & Runkle, 2022; Xu *et al.*, 2020). Research by Cristaldi *et al.* (2021) and Kyung & Jeong (2020) has shown that exposure to particulate matter can lead to asthma, impaired lung function, airway irritation, coughing, and difficulty breathing, as well as adversely affecting human neurological (including neurodegenerative diseases) and cardiovascular systems (such as irregular heartbeat and non-fatal heart attacks). Longer exposure increases the risk of developing cancer. The World Health Organization reported in 2021 that particulate matter is responsible for approximately 6.7 million deaths worldwide each year. Particulate matter also has a negative effect on the quality of the agricultural product and agricultural harvest. Studies have shown that as the particulate matter reduces the amount of sunlight reaching the leaf surfaces, it decreases crop yield by 15% (WMO, 2024).

Sulfur Dioxide (SO_2)

Sulfur dioxide is a colorless gas with a very unpleasant, choking odor that affects the respiratory and pulmonary systems in humans. Prolonged exposure to SO_2 can cause severe asthma, excessive mucus production, recurrent bronchitis, and damage to the skin and eyes. In moist air, sulfur dioxide is converted into a strong acid (sulfuric acid, H_2SO_2), which adversely impacts species in soil and water, disrupting freshwater and marine food chains. Additionally, the plant growth and crop yields are negatively affected.

Nitrogen Dioxide (NO_2)

Nitrogen dioxide is a reddish-brown, toxic gas that has negative effects on lung health. Exposure to nitrogen dioxide, even at low concentrations, can lead to coughing or wheezing, which may trigger asthma in humans. Longer exposures can lead to inflammation of the airways. When nitrogen dioxide reacts with sunlight and moist air, it forms not only acids but also contributes to the formation of tropospheric ozone.

Carbon Monoxide (CO)

Carbon monoxide, a colorless and odorless gas, poses significant health risks. Exposure even to a very low concentration of carbon monoxide can lead to symptoms such as fatigue and headaches. This impairs the transport of oxygen to the heart, and prolonged exposure can result in more severe effects, including drowsiness, headache, confusion, loss of consciousness, convulsions, chest pain, shortness of breath, low blood pressure, and permanent damage to the brain (Otgonbyamba *et al.*, 2023; Oyun-Erdene *et al.*, 2021; Chaiklieng *et al.*, 2021). In cases where the concentration is very high, it may lead to causing a coma. Additionally, carbon monoxide contributes to environmental degradation by increasing levels of methane and nitrous oxide, which affects ecosystems and causes global warming.

Volatile Organic Compounds (VOCs)

During wildfires, the biomass burning releases volatile organic compounds (VOCs), biogenic oxygenated compounds such as isoprene, pinene, benzene, toluene, xylene, and ethylbenzene into the environment. Wang *et al.* (2024) reported that in wildfire smoke benzene concentration was 1.03 µg/m^3, while in the Nethker and Williams fires Dickinson *et al*. (2022) found benzene levels ranging from 0.42 to 25 parts per billion by volume (ppbv). The amount of benzene in the California wildfire smoke was up to 4.7 µg/m^3 (Simms *et al.*, 2021). Benzene not only increases the risk of leukemia but is also classified as a carcinogen (USEPA, 2021). The concentration of toluene, which can lead to neurological disorders in humans, was in between 0.017 to 25 ppbv in forest fires (Dickinson *et al.*, 2022); 2.15 to 15.1 µg/m^3 (Wang *et al.*, 2024; Simms *et al.*, 2021). The concentration of ethylbenzene in wildfire smoke ranged from 0.006 to 4.0 ppbv. Inhalation of these compounds not only increases the risk of liver, kidney, and lung cancer but also causes eye and throat irritation (NCBI, 2021). Hexane has not been consistently reported in all wildfire smoke, but its inhalation can lead to neuropathy.

Polycyclic Aromatic Hydrocarbons (PAHs)

Several polycyclic aromatic hydrocarbons (PAHs) are released into water and the environment during wildfires. These persistent aromatic pollutants are highly toxic, and some are known as carcinogenic (Wang *et al.*, 2022; Li *et al.*, 2024). The total concentration of PAHs in water ranged from 0.02-29.24ug/L.

Potentially toxic metals

Potentially toxic metals are transferred from plants and vegetation to soil and surface/groundwater during wildfires. Consumption of water contaminated with these metals can lead to various developmental disorders and health issues, including cancer (Gavhane *et al.*, 2021).

Gaps in the knowledge

- Impacts of different pollutants (other than particulate matter) on the health of humans.
- Long-term studies on the effects of wildfire on groundwater and receiving surface water quality.
- Long-term research studies/monitoring of water pollution with organic pollutants.
- A deep study of the geochemical and soil properties of the affected area will help in identifying areas that are more contaminating the streams.
- Long-term studies on the frequency of combustion and their impacts on humans.
- Impact of wildfires on soil nutrients and metal content.
- Effect of particulate matter 2.5 from wildfire smoke and their comparison with PM 2.5 from all other sources
- Mental and behavioral changes in the young ones residing near the wildfire areas.

Conclusion

As the frequency and duration of wildfires increase, the smoke they produce (particulate matter as well as volatile and semi-volatile gases) negatively impacts the environment and communities. Wildfire smoke includes harmful substances such as benzene (which poses a cancer risk), toluene, xylene, ethyl benzene, and hexane. Wildfires have a detrimental effect on both ground and surface water. The leaching of organic acids produced by the incomplete oxidation of vegetation biomass and soil leads to a change in water pH value. Additionally, polycyclic aromatic hydrocarbons, semi-volatile gases, potentially toxic metals, and anions enter the water through debris, vegetation, and ash. As a result, the concentrations of anions such as nitrate (NO_3^-), sulfate (SO_4^{2-}), phosphorus, arsenic (As), calcium, magnesium, potassium, and sodium in the water increase, while the concentration of bicarbonate decreases. These pollutants not only degrade water quality, creating further challenges for drinking water supply and public health, but they also have adverse effects on aquatic organisms. The physicochemical properties of soil are also affected by an increase in electrical conductivity, soil hydrophobicity, and changes in soil pH values.

DECLARATIONS

Author contribution statement

Conceptualization, Methodology, Software and validation, Formal analysis and investigation, Resources, Data curation, Writing—original draft preparation, Writing—review and editing, Visualization, Supervision, Project administration, Funding acquisition: O.P.B.

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