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Abstract

Surface and sub-surface fire in municipal solid waste landfills (including dumpsites) is a complex and intricate phenomenon, whose frequency is expected to increase due to climate change. Partial or incomplete combustion of landfill waste at low temperatures during fires leads to generation of toxic compounds, including hydrocarbons, particulate matter and hazardous gases, which contaminate the surrounding geoenvironment and ultimately pose severe health hazards to living entities. Under these circumstances, it is the need of the hour to understand the (i) occurrence mechanisms of landfill fires, (ii) waste properties and operational conditions that may favour landfill fires and (iii) strengths and limitations of the available detection techniques in order to provide recommendations to detect such incidences at an early stage and plan emergency measures. Hence, the present review article critically assimilates the literature on landfill fires and discusses the (a) conditions under which the initiation and sustenance of landfill fires take place, (b) ecotoxicological (geoenvironmental) hazards of landfill fires, both in short- and long-term and (c) detection techniques for an early warning system. Finally, a discussion on the coupled multi-physics interactions undergoing in the waste matrix during landfill fires is presented in this manuscript, which is crucial to mastering this subject.

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Notation

A	parameter for biodegradation
α	thermal diffusivity
C_p	specific heat capacity
D_T	span of degradation time
A_{Ti} and B_{Ti}	Coefficient for the peak heat production rate and its time, respectively
ΔH_R^0	change in enthalpy in reaction
$\Delta H_{f,p}^0$ and $\Delta H_{f,e}^0$	change in enthalpy for products and educts, respectively
M_w	molar mass of the waste
m_x	mass of product or educts x
Q	rate of heat generation
q	conductive heat flux
q_T	heat generated by unit amount of the biodegradable MSW
ρ	density
ρ_0	initial density
T	temperature
t	time
w	moisture content
ω	proportion of a component

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Introduction

Landfilling (including open dumping) is one of the most commonly adopted methods of handling the growing amount of municipal solid waste (MSW) worldwide (Kaza *et al.*, 2018). Unsecure landfill poses severe geoenvironmental issues, including leaching of contaminants and pollution of surface and groundwater (Papapetridis and Paleologos, 2012), environmental degradation of resources and surrounding areas (Chandana *et al.*, 2021; Chembukavu *et al.*, 2019; Goli *et al.*, 2020; Mohammad *et al.*, 2021a). Owing to the list, landfill fires (LFs), whose frequency is predicted to increase due to global warming, poses severe environmental threats, mainly by emitting toxic gases and chemical compounds. LFs can persist for weeks and can (i) engage a number of personnel and equipments for their containment, and (ii) emit hazardous gases, which may aggravate respiratory conditions and even may lead to the evacuation of surrounding communities (US FEMA, 2002). The thermal radiation from a fire in a landfill site can be intense and make it very difficult for firefighters to approach its source to apply extinguishing media. Owing to these reasons their characteristics and mitigation measures have been receiving attention from the recent research fraternity (Chavan *et al.*, 2019; Manjunatha *et al.*, 2020; Mikalsen *et al.*, 2021; Milosevic *et al.*, 2018; Mazzucco *et al.*, 2020; Morales S *et al.*, 2018).

LFs can be categorized primarily into surface fires (located within 1.5 m depth from the top of MSW) (location#1 and #2) and sub-surface fires (location#3) (also known as underground fire), depending on the location of the source, as depicted in Figure 1 (Davis *et al.*, 2021; Frid *et al.*, 2010).

The major ignition sources of the surface landfill fires (SLFs) are intentional or accidental disposal of flammable substances (such as hot ash, active match stick and cigarette butts, etc.) at the site, spontaneous combustion or self-ignition, lightning strikes, sparks from the technical or electrical failure of instruments and vehicles, and arson and thermal runaway of batteries (Davis *et al.*, 2021; Manjunatha *et al.*, 2020; Mikalsen *et al.*, 2021). A particular hazard of landfills is the presence of the highly flammable methane (CH_4) gas generated during anaerobic MSW decomposition, intrusion of oxygen/air due to over-extraction of gas from extraction wells especially located near a slope or through cracks and fissures, leading to the occurrence of sub-surface landfill fires (SSLFs) (Jafari *et al.*, 2017). The release of gas from landfill cover having cracks may lead to combustion at the surface due to the self-ignition capacity of the CH_4 gas at ≥5% (v/v basis) in the atmosphere (Manjunatha *et al.*, 2020).

Biochemical decomposition of MSW (i.e., chemical and biochemical oxidation) is an exothermic process, generating heat and increasing the temperature of the landfill system (Chavan *et al.*, 2019). Consequently, the rate of biochemical decomposition of MSW increases as per the Arrhenius relationship and subsequently, more heat generation takes place (Kiersnowska *et al.*, 2020). Typically, during aerobic decomposition of MSW in landfills, the temperature might reach 60 to 80°C, while under anaerobic conditions it rises to 45-70 °C (Kumar *et al.*, 2021; Yesiller *et al.*, 2005). However, due to the thermal insulation properties (i.e., low thermal conductivity and diffusivity) of the MSW, heat accumulates until the 'ignition temperature' is reached leading to SSLFs (Chavan *et al.*, 2019). The increase in temperature takes place when heat generation becomes higher than its dissipation in the waste matrix

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(Sabrin *et al.*, 2021). Ignition and duration of landfill fires depend on several parameters, such as waste composition and their thermal characteristics, oxygen availability, ambient pressure, moisture content, properties of landfill leachate and climatic conditions (Stearns and Petoyan, 1984). Out of these parameters, thermal properties, especially thermal conductivity and the specific heat capacity, play crucial roles in the heat migration in MSW in landfills (Manjunatha *et al.*, 2020).

Relatively limited research has been conducted to understand the mechanisms and subsequent hazards associated with LFs, which includes alteration of the ambient atmosphere, water bodies and finally, the geological strata due to migration of pollutants (Roots *et al.*, 2004). For instance, SLF can damage final covers, similar to the decomposition induced uneven settlements in landfill, create cracks if the covers are made of clay due to its shrinkage behaviour while drying upon the application of thermal stresses (Jafari *et al.*, 2017). In addition, LFs may emit several toxic compounds, such as polychlorinated dibenzo-p-dioxin, polychlorinated dibenzo-furans, polyaromatic hydrocarbons, polychlorinated biphenyls, chlorophenols, polychlorinated benzenes, particulate matter ($PM_{2.5}$ and PM_{10}) and hazardous gases, such as CO, CO_2, NO_x and SO_x (Ruokojärvi *et al.*, 1995a,b). The harmful health effects of the LFs depend on the distance from the landfill and the physical condition of the concerned person.

Vassiliadou *et al.* (2009) have reported the presence of polychlorinated dibenzo-p-dioxin/furans in food samples, having translocated to animals, including humans, via the food chain. LFs also alter the physico-chemical properties of leachate in MSW landfills.

SSLF can damage the landfill gas and leachate collection system (Mazzucco *et al.*, 2020); even the service life of High-density polyethene geomembrane will reduce due to the high-temperature stress (Chavan *et al.*, 2019; Kumar and Reddy, 2021; Zhang *et al.*, 2022). It must be stressed that high temperature affects the performance of the bottom liner geomembrane, which contains the leachate from subsurface, and at temperature ≈100^{o}C, it is practically destroyed, allowing the unimpeded transport of contaminants to the surrounding geoenvironment. In addition, the heat from LF may lead to the thermal decomposition of waste and the geomechanical instability of a landfill due to softening of MSW or creation of temporary cavities in matrix (Jafari *et al.*, 2017). Therefore, these complicated phenomena, which are known as coupled multi-physics phenomena, should be studied under the realm of Environmental Geotechnics.

Based on the above-mentioned discussion, this article primarily concentrates on three areas related to the: (i) occurrence and parameters that are responsible for the sustenance of LF, (ii) ecotoxicological effects of LF on geoenvironment, animals and human beings and (iii) the coupled multi-physics interactions taking place during a LF, to provide better understanding of this event.

Occurrence of landfill fires and influencing parameters

The U.S. Fire Administration (2001) reported that every year an average of 8,300 LFs took place in the USA, mostly in the spring and summer months, with 40% attributed to arson. Illegal waste burning takes place in European countries as well. In southern Italy, the area around the city of Naples has been given the name of “Land of Fires” for the frequent illegal burning of industrial and hazardous waste set by organized crime (D'Alisa *et al.*, 2017). In the UK, the National Fire Chiefs Council (NFCC, 2021, see https://www.ukfrs.com/guidance/fires-waste-sites) has estimated that about 300 significant LFs occur every year. In India, landfill fires are common and recently, in November 2020 at the Ghazipur landfill in Delhi, and in April 2022 at Bhalswa landfill a fire took place.

The occurrence of LFs is increasing due to global warming, incidence of the heatwave, etc., which are interconnected with climate change. For instance, the most recent statistical data till 2019 on fires at waste disposal sites located in Poland (see: https://stat.gov.pl/download/gfx/portalinformacyjny/pl/defaultaktualnosci/5484/1/21/1/ochrona_srodowiska_2020.pdf (in Polish)) indicates that the number of fire events increased in recent times. Many fires are also likely to have been set up in order to devour illegal waste imported from other countries (Vaverková *et al.*, 2019). As part of the monitoring of interventions undertaken by the entities of the National Headquarters of the State Fire Service of Poland, there has been an increase in the number of fires, both in landfills and in illegal dumps (Vaverková *et al.*, 2019). The number of big (surface area=301-1000 m^2) and very big (surface area> 1000 m^2) fires that occurred in Poland in 2018 were 2.4 and 2.6 higher than the average for 2010-2017, as depicted in Figure 2(a) (Bihałowicz *et al.*, 2021). The analysis of the fire events in Poland shows that the largest number of fires occurred in the spring and summer period (in 2019: March - 25 fires, April - 34, July - 29) due to high atmospheric temperature and prolonged dry periods during this time. Past data on fires of waste gathering sites in Poland exhibited an increasing trend (except for the year 2019 which shows fewer fire events)

(Statistics Poland, GUS, 2020) as depicted in Figure 2(b).

On the contrary, Milosevic *et al.* (2018) have reported that due to improved landfilling, awareness and cooperation from citizens, analysis and learning from previous LFs, the incidence of fires has reduced in Nišava County (Serbia). However, when the reported data by Milosevic *et al.* (2018) were plotted (refer to Figure 2c) no districted trend is observed. Therefore, more datasets must be generated for different countries at the global level to compare data from different nations and accurate and reliable tracking of LF.

Occurrence of landfill fires

The combustion of MSW takes place in three phases: (i) ignition and propagation, (ii) compression stage and (iii) equilibrium and pyrolysis (the production of volatile products, condensable liquids or tar and char) stage. Depending on the waste material characteristics, the duration of each phase varies. For instance, the duration of the ignition and propagation phase of rubber tires is approximately 30 minutes where the flame front develops, and constant radiant heat flow occurs. After the inception of fire, until 60 minutes, a compression phase occurs where the fire penetrates deep in the tire pile, leading to the collapse of top layers (FEMA-USFA, 1998). The compression phase of fire is followed by pyrolysis, which can last approximately 48 minutes and is followed by an increase in liquid run-off (Nadal *et al.*, 2016). The smouldering time (Ts) (=23 to 34 min) and the ignition time (Ti) (=27 to 48 min) are directly proportional to the age of MSW, which is due to presence of higher moisture content in fresh MSW that consumes more heat for evaporation as compare to old MSW having less moisture and more combustible content (Chavan *et al.*, 2019). Most often, partial combustion in the MSW in landfills occurred at temperatures between 100 and 120°C (Ettala *et al.*, 1996). In some cases, the temperature during smouldering combustion has been specified in the range of 200-300°C, and even 700°C (Lönnermark *et al.*, 2008). The generated heat would try to migrate through the MSW matrix.

The heat migration phenomena in porous media are very complex and primarily occur due to conduction, convection and radiation. However, for the sake of simplicity, Kumar *et al.* (2021) reported that a dominant mode of heat transfer in MSW occurs due to conduction, which can be expressed as shown in Equation 1, where convection due to migration of leachate is insignificant. Further, *q* indicates the conductive heat flux (refer to Equation 2), whereas *Q*, is the rate of heat generation during exothermic reaction that occurs due to microbial activities and can be computed based on the rate of generation of the CH_4 gas (Hao *et al.*, 2017). Alternatively, *Q* can be generated from the oxidation of waste.

$$(c_p)_{eff} \frac{\partial T}{\partial t} + \nabla \cdot \mathrm{q} = Q \qquad (1)$$

$$\mathrm{Q} = - k_{\mathrm{eff}} \nabla \mathrm{T} \qquad (2)$$

where, $(c_p)_{eff}$, k_{eff}, T and t represent the effective heat capacity, effective thermal conductivity, temperature and time, respectively.

However, it should be understood that the thermal conductivity (*k*) of the MSW would depend on the porosity apart from waste characteristics which can decide the heat migration phenomenon. It should be worth mentioning that the porosity is being guided by density of the matrix. Hence, the values mentioned in Equation. 1 and 2 will depend on density of the matrix. Thermal diffusivity (α) is the parameter which is being influenced density along with *k* and

Specific heat capacity (C_P) (refer to Equation 3) which can be more prudent to use to model Q.

$$\alpha = \frac{k}{\rho . C_p} \tag{3}$$

Recently, Zhang *et al.* (2022) have used Equation 4 to calculate the total heat generated from per unit volume of waste per unit time due to biodegradation of three categories of biodegradable wastes, i.e., easily-, moderately- and slowly (difficultly) degradable wastes fractions.

$$Q = \Sigma_{i=1}^{3} \omega_i \frac{A_{Ti}}{B_{Ti}} \left(t + D_{Ti} \right) e^{-\left(\frac{t + D_{Ti}}{B_{Ti}} \right)} \tag{4}$$

In Equation 4, i =1, 2 and 3 represent easily degraded, moderately degraded, and difficultly degraded components in the MSW, respectively; ω_i represents the proportion of a component; D_{Ti} is the span of degradation time that produces heat; A_{Ti} and B_{Ti} are the parameters related to the peak heat production rate and its time, respectively. Further, A_{Ti} can be estimated by:

$$A_{Ti} = \rho_0 q_T A / M_w \tag{5}$$

Where, ρ_0, A and M_w are the initial density of the waste, the parameter related to the biodegradation and the molar mass of the waste, respectively; q_T is the amount of heat generated by unit amount of the biodegradable MSW.

In addition, Lu and Feng (2020) have determined the heat generation based on the concept of reaction enthalpy as mentioned. Under standard condition, change in enthalpy (ΔH_R^0) can be estimated as

$$\Delta H_R^0 = \sum \Delta H_{f,p}^0 - \Delta H_{f,e}^0 \tag{6}$$

Where, R, p and e represent reaction, products and educts;

Once, the ΔH_R^0 known, the heat generation can be estimated by multiplying it with reaction rate as shown in Equation 7.

$$Q = \sum_x \frac{\partial m}{\partial t} \Delta H_R^{0x} \quad (7)$$

where, m_x is mass of product or educts x.

The thermal properties of waste play an important role in the SSLF due to their insulation nature and accumulation of heat generated during biochemical processes of decomposition of MSW. In this context, density, *k* and C_P of MSW and its different components are major guiding parameters. Furthermore, the thermal properties of waste change during a fire, which impacts heat migration, moisture and gas distribution, and leaching through a landfill.

Thermal properties of MSW: guiding factor of landfill fires

Biochemical decomposition of MSW in the landfills affects the temperature rise during the LFs and vice versa. The heat generated during these processes (i) accumulates, which subsequently results in smouldering (the slow, flameless form of combustion), or spontaneous landfill fires when the rise in temperature reaches the ignition point (Chavan *et al.*, 2019), (ii) dissipate into the surrounding environment and (iii) can be extracted (depending on the amount) for direct heating of nearby residential and industrial facilities (Nocko *et al.*, 2021). In all these cases, the heat accumulated in the landfills cannot be dissipated naturally through their covers and slopes, and heat exchangers can be used to extract the thermal energy from the landfills (Coccia *et al.*, 2013; Shi *et al.*, 2018). This will not only help in the dissipation of heat that controls landfill fires but can also work as a source of geothermal energy. In this context, Nocko *et al.* (2021) performed a field-scale heat extraction study at Santee, California, using horizontal heat exchangers installed at 6 m height above the liner, which started working at a stable temperature of 52°C. However, it should be noted that heat extraction from landfills should be performed carefully because heat is required to maintain the decomposition rate of microbes. The assemblies for heat extraction can be installed easily in new landfills during their filling operation as compared to the matured (i.e., old) or operational landfills, which are already closed.

The thermal properties such as k, C_P and α of the bulk MSW would be of utmost importance, which will be influenced by the physical properties such as moisture content, density and porosity apart from the intrinsic waste composition as presented in Table 1. From this table, it can be observed that a wide range of these properties has been reported based on the composition of waste. Yeşiller *et al.* (2015) have reviewed the MSW thermal properties and found that k=0.44 to 1.5 W/m·K, C_P= 378 to 4000 kJ/m^3·K and α =1.5× 10^{-7} to 9.4×10^{-8} m^2/s. Food waste, garden and plastic wastes have different k values and the overall thermal properties of MSW will change with the region and decomposition time depending on the relative percentage of these constituents. For instance, in developed countries, wherein plastic waste content is high in MSW will tend to possess lower k. On the other hand, in developing countries like India, where MSW is dominated by food waste and other organic-rich waste which tend to hold higher moisture content, k values will be higher. The C_P is directly proportional to w and organic matter, and inversely proportional to density of MSW, whereas, k

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is inversely proportional to moisture content and organic matter and directly proportional to density of MSW. The k value decreases with temperatures above 75°C, and at 130 to 140°C its value is 0.007 W/(m·K), which hinders the dissipation of heat leading to temperature rise and subsequent occurrence of LF (Manjunatha *et al.*, 2020). Further, density of MSW depends on the composition of its individual components and compaction levels (Cline *et al.*, 2020). This indicates that with the same compaction efforts MSW with various density can be obtained due to variation in the composition, influencing the thermal properties. Therefore, suitable parameter such as porosity, which is devoid of the variation in composition can be used to establish the dependency of thermal properties of MSW. Furthermore, these properties of MSW in landfills would change consistently due to the decomposition and subsequent settlement of the waste. Hence, efforts should be made to measure the in-situ properties of the MSW in landfills. More recently, due to the global COVID-19 pandemic, the composition of MSW in developing countries has changed significantly, and a more combustible fraction has been accumulated from the disposal of personal protection equipment kits along with MSW (Vaverková *et al.*, 2021; Mohammad *et al.*, 2021c).

Further, from Table 1, it can be observed that the k of the MSW varies between 0.01 and 1.50 W/(m K) (Bonany *et al.*, 2013; Hanson *et al.*, 2008; Yeşiller *et al.*, 2015; Manjunatha *et al.*, 2020; Nocko *et al.*, 2021), which is, in general, higher than that of dry inorganic soils (k=0.27-0.38 W/m K) (Mondal *et al.*, 2016, 2017). Such a higher value can be due to the higher moisture content and electrical conductivity of the leachate (Grellier *et al.*, 2006), which is proportional to k (Schwarz and Bertermann, 2020). The C_P of the MSW also has been reported to vary between 1000 and 3080 J/kg K, which is much higher as compared to that of dry soils (280-335 J/kg K) (Mondal *et al.*, 2017).

Many studies have adopted the transient line source method for measuring the thermal properties of the MSW. These methods only measure the heat migration through conduction (Mondal *et al.*, 2016), whereas heat migration in MSW landfills, where the MSW may be partially or completely saturated with leachates and gas, takes place through convection and radiation as well (Bonany *et al.*, 2013). Hence, in-situ studies should be conducted to understand the influence of convection and radiation mechanisms on the thermal properties of the MSW.

On the other hand, the moisture content of the MSW has been conventionally measured by resorting to the gravimetric oven drying method. However, sample for measurement requires to be retrieved from landfills (Mohammad *et al.*, 2021a) in the disturbed state which cannot be representative of field conditions due to releasing of the in-situ moisture present in the pore spaces of the MSW matrix, apart from being an expensive and time-consuming task. Hence, in-situ determination of moisture content of MSW is a must to understand its influence on thermal properties. Further, degree of saturation, which influences thermal properties, of MSW varies spatially and is directly proportional to volumetric moisture content that can be determined by dielectric property measuring sensors, such as frequency domain reflectometry and time domain reflectometry probes (Patil *et al.*, 2017). This would also facilitate real-time in situ monitoring of the spatial and temporal variations in the volumetric moisture content and would assist in the estimation of the changes in thermal properties of the MSW. Finally, the

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density of MSW in landfills varies spatially and temporally due to overburden pressure and decomposition-driven settlements (Cline *et al.*, 2020). Such conditions had not been considered by the studies presented in Table 1 and makes the report of thermal properties there questionable with regards to real field conditions.

Other influencing parameters

The ignition temperature of the MSW is directly proportional to its moisture content in the range of 5 to 55% (Chavan *et al.*, 2019). It has been established based on the investigation performed by Chavan *et al.* (2019) on MSW collected from Bhandewadi Dumpsite, Nagpur, India, that MSW with moisture content > 55-60% required an ignition temperature of 270 °C. Further, old MSW required lower ignition temperatures due to lower moisture content and organic matter and the high percentage of plastics waste (which is combustible in nature) as estimated by Chavan *et al.* (2019), whereas five years old MSW required 98°C temperature. The moisture and temperature of waste in the landfill can be regulated when a leachate re-circulation system is installed and operated based on in-situ measurements (Patil *et al.*, 2017).

Operational parameters also influence the LF. For instance, overdrawing of landfill gas through extraction wells leads to intrusion of air, especially through the wells placed near the slope, cracks and fissure leads to fire. Sterans and Petoyan (1984) reported that convection created due to the high temperature of the air during LFs also led to the entry of air due to chimney effects.

Ecotoxicological effect of landfill fire

MSW landfills are a storage of heterogeneous materials, including hydrocarbons, chlorinated compounds and pesticides, which are the primary source of toxic compounds emanating during LFs (Morales S *et al.*, 2018). Landfill fires lead to the emission of toxic gases and several carcinogenic and mutagenic compounds including polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-furans (PCDFs), polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), fine particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NO_x) along with trace elements, such as As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Sn and V and toxic gases, as summarized in Table 2. They are responsible for elevated hazards to surrounding human beings, animals and soils (Rovira *et al.*, 2018).

Vassiliadou *et al.* (2009) reported that food samples exhibited a higher concentration of PCDDs/Fs and PCB than the limits prescribed by the European Union (regulation 1881/2006/EC). Also, in soil and olive samples, the PCB concentration is normal, and with increase in the distance from the source, the concentration of dioxin is reported to reduce. It should be noted that these contaminants can migrate/translocate to animals, including humans, via the food chain. Ruokojärvi *et al.* (1995b) noticed the concentrations of PAH, PCB, chlorophenols (CP), and polychlorinated benzenes (PCBzs) in air and waste samples during the fire from two investigated locations, where one was an intentionally created fire while the other was a spontaneous fire. The PAH and PCB concentrations were found to be below the threshold for both the sites, and PCB, PAH, CP, PCBz were low in the burnt sample. Recently, fire at the Ghazipur landfill in Delhi (India), led to the air quality index (AQI) of the capital city

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attained the value of 445 (Sharma, 2020), which can be categorized as hazardous as per Table S1 (developed by authors). The U.S. EPA uses the AQI to summarize the effects of five air pollutants, ground-level ozone, particulate matter (both PM_{10} and $PM_{2.5}$), CO, sulfur dioxide, and nitrogen dioxide. An additional difficulty arises from the fact that industrial facilities are often placed in the same broad area where landfills existed, and hence a LF could expand to threaten more hazardous substances stored at these industrial facilities.

The ecotoxicological threats from LFs are more pronounced in vulnerable groups, especially elderly citizens, children, pregnant women and patients suffering from chronic conditions. In terms of $PM_{2.5}$, employers in direct waste-management systems and people living in the near vicinity of landfills are more vulnerable (Kodros *et al.*, 2016; Mazzucco *et al.*, 2020). Furthermore, Kodros *et al.* (2016) have reported that annual premature death due to LF is 0.27 million globally; though the predicted results depend on the characteristics of concentration-response-function, chemical transport model and emission inventories considered in the modelling. Morales S *et al.* (2018) reported a case study of Santa Marta landfill fire on January 2016, in the area of Santiago, which was initiated after the collapse of landfill's slope. This study also suggested that the concentration of $PM_{2.5}$ was at higher levels than recommended for the protection of the health of the vulnerable person. In another study by Adetona *et al.* (2020) on LF in Lagos Landfill, Nigeria, concluded that persons of age> 11 years old were more vulnerable with symptoms including the daily occurrence of tingling (numbness), whitener of fingers, headache, memory problem, tremor/cramps and confusion. Adetona *et al.* (2020) reported that LFs contain about 29% of PM. The adverse impact of PM as reported by Bihałowicz *et al.* (2021) suggested that with every 10 $\mu g/m^3$ increase in PM_{10} concentration increasing human mortality rate by 1.47±0.31% and the relative risk of croup syndrome increases by 0.1. Recently, Abayalath *et al.* (2022) estimated the impact of PAH, PM_{10} and heavy metals in the air and stated that the air is polluted with these potential carcinogenic and mutagenic compounds and they can pose severe health threats and respiratory track-related ailments. Dioxin and dioxin-like substances, such as PCDDs, PCDFs and PCBs are known carcinogens and have been associated with several toxic effects, which include immunotoxicity, developmental and neurodevelopmental effects, as well as changes in thyroid and steroid hormones and the reproductive function (WHO, 2010). On the other hand, Øygard *et al.* (2005) measured the leachate characteristics before and after a fire event and observed that during fire and firefighting operation, the nitrogen, pH, electrical conductivity, chemical oxygen demand and heavy metal values were high. However, these values get reduced to the normal value after one week.

On combustion of rubber tires, several hazardous and toxic compounds are generated, leading to the geoenvironmental pollution. Recent tire fire incidents include the Sulaibiya-Kuwait tire graveyard fire in 2012 and 2020, the Weld County Colorado tire recycling facility fire in 2020, West Odessa-Texas tire fire in 2017 and the Federal Corporation Zhongli Factory-Taoyuan Taiwan fire in 2017, etc. (Page *et al.*, 2020). Also, due to high temperature during the fire under anaerobic condition, pyrolysis oil is produced, which finally ends up contaminating soils, water bodies and underground water when mixed with a fire extinguishing agent. Rubber tire fires, in several cases, even exceed for more than one month

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and subsequently pose a threat to the health and wealth safety of the society by closing nearby services and utilities, voluntary evacuations and even increasing respiratory issues (Singh *et al.*, 2015). For example, the smoke plume from Rhinchart tire fire-Winchester, USA, was high at about 100 m and also spread over almost 80 km, and the fire lasted for about nine months (Stefanov *et al.*, 2013). Nadal *et al.* (2016) and Rovira *et al.* (2018) estimated that a May 2016 LF at Toledo, Spain, where 70,000-90,000 tons of tires were accumulated for over 15 years, and which lasted for more than 20 days, would present a cancer risk to areas close to the landfill at 500 m. Nadal *et al.* (2016) determined the concentrations of PAH, PCB, PCDD/Fs and trace heavy metals in soil, air and plant samples after this fire, and noticed that PAH concentration (134 ng/m^3) in air samples collected near to the location of the fire was six times higher than air samples (PAH concentration=19.5-22.7 ng/m^3) located at 4 km away from the source. Also, PAH concentrations in lettuce were found higher than in the food quality monitoring program. This increased the possibility of cancer to 3 to 5 times for the population located nearby to the landfill due to their exposure to the high concentration level of PAH. At the same area, food sample had PAH concentrations that were relatively higher than those found in typical safe food items. Open tire fire emissions contain both “criteria” pollutants and “non-criteria” hazardous air pollutants, such as PAHs, dioxins, furans, hydrogen chloride, benzene, PCBs, and metals, which can create acute (short-term) and chronic health hazards to firefighters (who should be equipped with respirators and dermal protection) and nearby residents.

A huge variety of pollutants are released during the fires in landfills. Hence, further

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research should be conducted on the migration and degradation of these compounds in soils under saturated and unsaturated conditions. The different attributes of porous media, such as mineralogical composition, particle size, should be incorporated to forecast the ecological impact of these harmful chemical compounds and ensure environmental safety. Studies are not available on the alternation of biodiversity of landfill and surrounding area due to LF, making them a crucial future area of research.

Monitoring of fires

Though SLFs are relatively easily extinguishable, significant issues are created for the firefighters related to the SSLF, whose location identification and detection is a major challenge (Chavan *et al.*, 2019). In this context, the detection techniques employed to find out the location of SSLF primarily consist of occurrence of unusual settlement, smoke formation, presence of CO and rise in temp of landfill gas and residue in gas vent. Jafari *et al.* (2017) have reported that for fire event the following parameters can be used: CO>1500 ppmv, ratio of CO_2 and CH_4 >5, temperature >80 °C and settlement strain>3%/year. It has been also reported that the temperature for smouldering may vary from 200 to 300, even 700 °C, which might be difficult to use as confirmatory indicator (Jafari *et al.*, 2017). Also, if the temperature measurement system is not installed in landfill, this method cannot be employed. Though, Frid *et al.* (2010) employed electrical resistivity tomography, surface temperature measurement and gas composition data to detect fire, the effectiveness and usefulness of the approach are under question due to cost and temporal and spatial resolution limitation. In their study, it has been observed that ratio of CO_2 and CH_4 is higher than 8 in smouldering/combustion zone than normal waste body. This ratio is controlled by the oxygen intrusion (i.e., oxygen concentration) as per the Equation 8 (Frid *et al.*, 2010).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + heat \uparrow \qquad (8)$$

The effective method in early-stage fire detection in landfills are thermovision cameras and pyrometers, which are already being applied in coal waste dump sites (Wasilewski, 2020) and could also be adopted in MSW landfills too (Fjelsted *et al.*, 2019). Mihajlović *et al.* (2016) have employed (i) LandGEM model to estimate the CH_4 emission and (ii) ALOHA software to calculate the fire-vulnerable zone. Evaluation of the effect on the air quality was graphically estimated by employing EPA SCREEN 3 Model. Milosevic *et al.* (2018) have employed thermal sensing cameras to measure gas well temperature and gas concentration to identify the fire at sanitary landfill 'Bubanj', Serbia. Based on the data, a predictive model has been developed by logistic regression. Furthermore, to timely and cost-effective approach to identify the location of SSLF and monitor their migration within landfills, Nazari *et al.* (2020) have investigated the utility of satellite thermal infrared imagery technique at a moderate spatial resolution. It should be prudent to conduct further studies to define indicators (or indices), which would comprise easy to measure properties of waste (i.e., temperature, gas, leachate and settlement characteristics) to predict the places and positions as well as extent of combustion of MSW in landfills to help both the workers and researchers.

Based on a local multi-agency retrospective review of the public health response to the Iowa City fire that occurred in 2012, Singh *et al.* (2015) have provided some recommendations for emergency responses in terms of air quality such as careful evaluation of the higher priority

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in fire data monitoring, adjusting pollutants emission rates using monitoring data in real-time, interpreting obtained data to the public, and issuing public health statements. In a nutshell, once the landfill fires have occurred, the emergency response of the imminent problems is desirable from the various aspects including economy, politics, environment, and human resources, which is systematic engineering by different agencies.

Coupled thermo-hydro-geomechanical phenomena

The coupling behaviour in the landfill before, during and after the occurrence of fire (for SLF and SSLF) is involved in heat, solid mechanics, hydraulic, also chemical and biological fields. On a short-term basis where the biochemical process can be ignored, the three major areas are geomechanical, thermal and hydraulic phenomena, depicted as 'modules' in Figure S1.

The geomechanical module mainly deals with the mechanical behaviour of the MSW, whereas the hydraulic module primarily deals with the multiphase and multicomponent flow of leachate, micro-organisms and gas in the MSW matrix. Finally, the thermal module, which is very crucial during LFs, is dedicated to heat generation and its migration, and alteration of thermal properties of MSW at the ambient and elevated temperatures. It is evident that during the LF, very high temperature can be reached, which leads to thermal decomposition of waste and subsequently drastic collapse of the landfill (Jafari *et al.*, 2017). Additionally, at elevated temperatures, gas pressure would be very high if a proper gas extraction system is not in place, which subsequently leads to a reduction in effective stress and geomechanical stability of the landfill (Jafari *et al.*, 2017). Shu *et al.* (2022) recently studied the effect of gas pressure on landfill slope stability and opined that for landfill slope of height 50 m and slope 1:3 exhibited

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8.8% lower factor of safety when gas pressure is included in analysis. In addition, waste mass will start softening and lose its strength at elevated temperatures. Furthermore, due to high temperature, the thermal properties of waste will change, which impacts the heat migration through porous media of MSW as discussed earlier. It is needless to mention that these complicated phenomena, known as coupled THG phenomena, should be studied.

It is very challenging to experimental study this coupled THG phenomena occurring in a landfill. Hence, researchers have attempted to simulate coupled processes numerically by considering primarily coupled (i) hydro-biological-mechanical (HBM) processes, (ii) thermo-hydro-bio-chemico-mechanical (THBCM) processes (McDougal, 2007, Hubert *et al.*, 2016, Kumar and Reddy, 2021; Kumar *et al.*, 2021). It has been realized that these studies are to model the decomposition processes and its effect on coupled THBCM interactions and these models need to be modified to simulate landfill fire.

In general, combustion of MSW is complex due to significant difference in time-scale for fluid dynamics, combustion and heat transfer process. Combustion is modelled with constant burning (reaction) velocity, eddy break-up and eddy dissipation model, finite rate chemistry model, flamelet model, burning velocity model. Also, computation fluid dynamic is gaining importance to model landfill fires (Sun *et al.*, 2016; Xia *et al.*, 2014). The combustion also acts as additional source term or sink term for other fields. This section is mainly focused on the influence of high temperature on the porous media properties including mechanical deformation and fluid transport. Therefore, a precise description of combustion in the MSW is not mentioned here.

In old landfills where waste is highly compressed, despite the traditional chemical diffusion, chemical osmosis in very low permeability media is very important (Di Maio, 1996; Karnland *et al.*, 2005; Zheng *et al.*, 2021). Landfill fire can influence the chemical osmosis, and change the water flow direction in the pore, which significantly affects the thermal transport and solid deformation. Models that covered research in THGC model were mainly concentrated in geomechanics, geothermal reservoir and backfill engineering (Cui and Fall, 2015; Liu *et al.*, 2015; Seetharam *et al.*, 2007; Taron and Elsworth, 2009).

The above theories are often called mechanics approach models, which are mainly derived from mechanical equilibrium and momentum balance. The governing equations come from different fields, often borrow equations from geochemistry instead of using a unified fully coupled theory framework (Chen *et al.*, 2016). Because of the complex geochemical reaction and decomposition in the waste, Mixture-Coupling Theory (originally named Modified Mixture Theory) (Heidug and Wong, 1996), a theory based on non-equilibrium thermodynamics, is a more suitable approach to build the smooth bridge between geophysics and geochemistry in landfill engineering than mechanics approach models. This theory uses entropy production as the driving force to build a unified multi-field coupled theory which covers both coupling effects between solid deformation, hydraulic field, heat transfer, and chemical reaction, and the phenomenological interaction between fluid flow, chemical flow and heat flow. Mixture Coupling Theory has been used to derive the hydro-geomechanical (Chen, 2013; Chen and Hicks, 2011), hydro-geomechanical-chemical and THGC models (Chen and Hicks, 2013; Ma *et al.*, 2021).

Attempts to model fires in landfill wastes have faced significant difficulties due to the heterogeneous nature of waste, and the interaction of thermal, mechanical, biological, chemical, and hydraulic processes that determine the structural changes in the landfill, biodegradation of waste, moisture distribution and gas generation, and leachate movement, among others, which require the simultaneous solution of the equations that describe each individual process. It is highly unlikely that modelling exercises can predict the conditions for the inception and propagation of a fire in a landfill. It must be remembered that all models rely on simplifying assumptions in order to make them mathematically or numerically tractable, and in the case of LF, the many assumptions that need to be considered will make the results highly dependable on model simplifications, and hence will not represent real field conditions. Therefore, given the heterogeneity of waste, the significant variation of the thermal and other MSW landfill parameters, which depend on waste composition and age, the specific climatic and weather conditions, practice of landfill operation (Mohammad *et al.*, 2022), the time of inception and location of a fire source, and the interdependence of the multiple processes during LF, must be specified in a model.

Concluding remarks and recommendations

Landfill fire is a very complex phenomenon that needs immediate attention from the scientific community. Avoiding LFs should be the prime focus of the urban local bodies to enhance the quality of the surrounding biota and human life. Further, the MSW landfills should be equipped with emergency services, and the site plan should be modified based on geographical and meteorological aspects. Apart from above mentioned precautionary measures, the research on the aspects that trigger and/or prevent LF should be given prior importance to incorporate the engineering aspect in the prevention measures. Based on the critical review conducted on the various aspects of LFs, the following points can be recommended for future research.

- Heat migration mechanisms of the landfill should be established thoroughly to understand the heat dissipation processes and plan modalities to enhance them. In this context establishing the temporal variation of depth-wise thermal profiling of MSW landfill would be a good starting point.
- Thermal properties of the MSW were mostly determined by considering conduction as the primary heat migration path. However, thermal properties such as conductivity, diffusivity and specific heat capacity of the MSW should be established by considering both conduction and convection heat transfer mechanisms.
- If the heat dissipation from the landfills was found to be minimal, engineering systems such as heat exchangers should be installed to extract the heat energy and to maintain the landfill temperature below the ignition temperature of the MSW. This can also open up new research in the area of the utilization of landfill as a geothermal reservoir.
- Non-invasive techniques based on different sensors should be developed for realtime monitoring of moisture content, gas composition, temperature and settlement to avoid landfill fires.
- Coupled thermo-hydro-geomechanical-chemical-biological models to incorporate various processes such as MSW decomposition, leachate transport, microbial activities, and settlement, temperature variations and pore pressure development and dissipation

that occur simultaneously in the landfill should be developed to enhance the present understanding of the landfill fires initiation and their mechanisms.

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Table 1. Summary of the studies conducted on the thermal properties of municipal solid waste

Reference	Study location	Experimental conditions	Method of measurement	Thermal conductivity (*k*) (W/m·K)	Specific heat capacity (C_P) (J/kg·K)	Thermal diffusivity (α) ($m^2/s \times 10^{-7}$)	Remarks
(Hanson *et al.*, 2000)	-	w= 16-38	Needle probe- ***λ;*** Dual probe- C_P	0.01-0.70	-	0.2-0.7	-
(Yoshida and Rowe, 2003)	Tokyo Port, Japan	For unsaturated landfill layer: w= 28.90; ρ= 1157	-	0.35	1939	-	Variation in the ρ of the MSW with an increase in depth of the landfill has not been considered.
		For saturated landfill layer: w= 42.30; ρ= 1424	-	0.96	2363	-	
(Hanson *et al.*, 2008)	Michigan, USA	ρ=999	Transient	1	2000	5.0	-
	New Mexico, USA	ρ=755	Transient	0.6	1200	5.0	
	Alaska, USA	ρ=530	Transient	0.3	1000	3.0	
	British Columbia, Canada	ρ=999	Transient	1.50	2200	7.0	
(Bonany *et al.*, 2013)	Sainte-Sophie, Quebec,	ρ=970	Heat flux	0.67	1400	-	Temperature rise in the landfill up to 10.5

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	Canada						months has been modelled for different λ, C_P, and latent heat of fusion of the liquid fraction of the MSW
(Faitli *et al.*, 2015)	Gyal, Hungary	ρ= 352-725	Heat flux	0.24-1.15	1990-3080	2.07-9.66	A measuring steel box (1.8 × 1.8 × 0.8 m).
(Manjunatha *et al.*, 2020)	Bhandewadi, Nagpur, India	w= 52; ρ= 500-650; *OM*=60; PW= 13	Heating box	0.32-0.42	2180-2340	-	An increase in temperature of the heating plate from 32.25 to 128.29 °C led to a reduction in λ from 3.60 to 0.08 W/m. K. The C_P of the MSW was increased from 2.5 to 6290 J/kg·K with an increase in temperature from 32.25 to 128.29 °C.
	Bellahalli, Bangalore, India	w= 46; ρ= 500-650; *OM*=51; PW= 19		0.53-0.70	2070-2250	-	-
	Synthetic MSW	w= 28-53; ρ= 800;		0.41-1.05	1390-2500	-	The relationship

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		OM=35-60; PW= 8-25					between the λ and C_P with ρ and w has been proposed.
(Nocko *et al.*, 2021)	Santee, San Diego County, USA	Short-term analysis (between 20-100 h) and long-term analysis (20-405 h) have been conducted.	Transient probe	Short term: 0.86-1.28; Long term: 0.89-1.32	-	7.85 to 10.5	17-day heat extraction thermal response tests were performed on geothermal heat exchangers placed at 3 different layers of landfill.

w= moisture content (%); ρ= density (kg/m^3); *OM*=organic matter (%); PW= plastics waste content (%)

Table 2. Summary of the reported studies on landfill fires and their ecotoxicological impacts

Sl. No.	Location	Salient points	Reference
1	Northamptonshire, England	• The smoke from a LF contained dangerous chemical compounds: ○ acenaphthylene (60-90 ng/m^3), ○ fluoranthene (50-100 ng/m^3), ○ phenanthrene (30-520 ng/m^3), ○ anthracene (85-160 ng/m^3), ○ fluorene (120-180 ng/m^3), ○ pyrene (120-170 ng/m^3), ○ benzo(a)anthracene (60 ng/m^3), ○ chrysene (70-80 ng/m^3), ○ benzo(a)pyrene (15-20 ng/m^3), ○ indeno[1,2,3-cd]pyrene (10 ng/m^3), ○ dibenz[a,h]anthracene (10 ng/m^3), ○ benzo[ghi]perylene (10 ng/m^3), ○ PAHs (810-1480ng/m^3), ○ PCBs (15,5-590 ng/m^3).	(Bates, 2004)
2	Niger Delta, Nigeria	• The following compounds have been detected in the air: ○ suspended particular matter (773-801 µg/m^3), ○ CO (133.7-141.6 ppm), ○ CO_2 (401-404.5 ppm), ○ NO_2 (21.0-27.3 ppm), ○ SO_2 (27.7-37.1 ppm), ○ NH_3 (14.7-19.5 ppm), ○ CH_4 (2310-2771 ppm), ○ H_2S (3.4-7.7 ppm). • Levels of suspended particular matter, CO, CO_2, and CH_4 within the vicinity of the dump site fires were above regulatory limits.	(Rim-Rukeh, 2014)
3	Seseña, Toledo, Spain	• Most of the target pollutants (i.e., PAHs, PCBs, PCDD/Fs, trach elements) did not show increased concentrations in the surrounding environment after the fire.	(Nadal *et al.*, 2016)
4	Ravni Kotari in	• The increased concentration of PCDD/Fs has been detected in the air (1940.4 fg/m^3), soils	(Fajkovic *et*

	the Northern Dalmatia, Croatia	(2597.6 ng/kg) and sediments (23.17 ng/kg) nearby the LFs. The concentration of these compounds was increased by 4000 times in air as compared to the condition before fire.	*al.*, 2017)
5	Santiago, Chile	• $PM_{2.5}$ reached concentration levels on the order of 1000 μg/m^3, three days after the start of the fire. • Hourly $PM_{2.5}$ concentrations were recorded at levels above 200 μg/m^3 at a distance of approximately 20 km from the place where the fire occurred.	(Morales S *et al.*, 2018)
6	Western Sicily, Italy	• Heavy metals, dioxins and dioxin-like substances were found in soils (upto depth of 40 cm), food and dairy products and the concentration of these elements were higher than the permissible limit. • The highest concentration (=60 μg/m^3) of PM_{10} was noticed within 24 hours of LF.	(Mazzucco *et al.*, 2020)
7	Poland	• 6.5 and 0.36 million people were exposed to an additional 1-hour average concentration of PM_{10}>10 μg/m^3 and 100 μg/m^3, respectively. This exposure depended on the location of the fire and residential place. • The emission of PM_{10} from waste fires is accounted for >2% of national emission.	(Bihałowicz *et al.*, 2021)

Figure 1. Conceptual depiction of landfill fires and their potential sources and locations

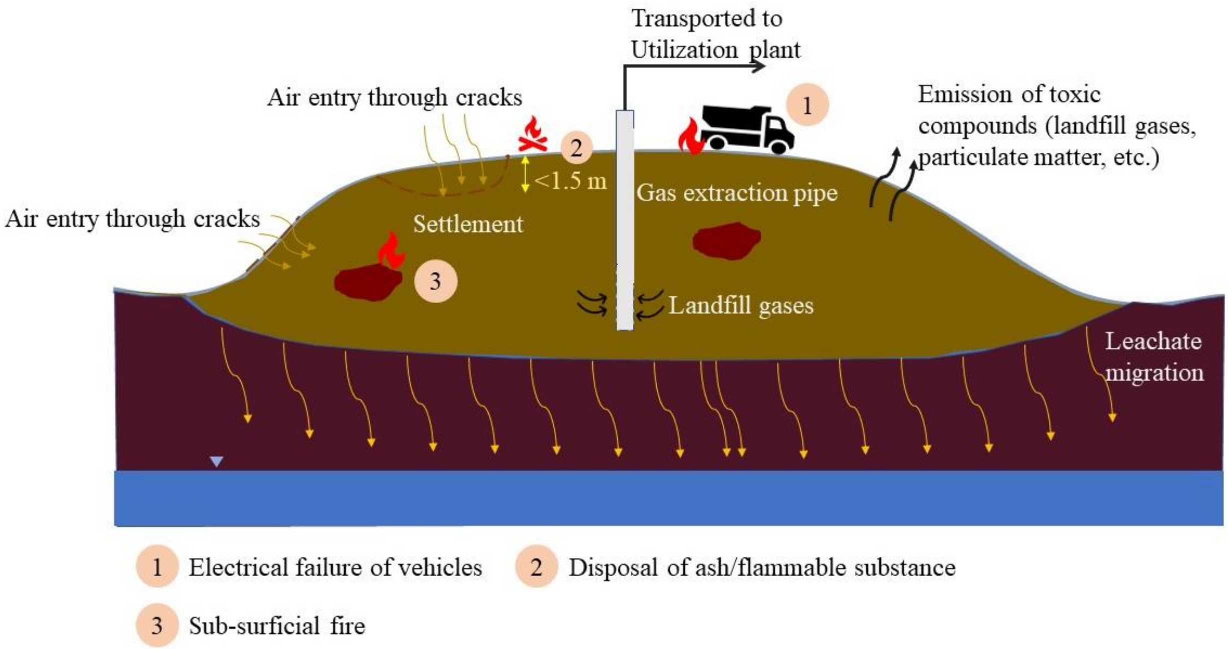

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Figure 2. Number of (a) big and very big landfill fires, (b) total landfill fires and (c) reported by Milosevic *et al*. (2018) with years