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Role of Methanotrophs in Methane Oxidation from Municipal Solid Waste Dumpsites in Tropical Countries

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ABSTRACT

Municipal Solid Waste (MSW) dumpsites are one of the major source of methane (CH_4) emissions due anaerobic degradation of organic matter content in the waste. Control technologies are available to reduce these emissions, but they are costly and their application on existing sites is complex. Moreover, tropical climate is responsible for rapid degradation of organic matter in open dumps leading to substantial CH_4 emissions mainly due to hot and humid conditions amongst other factors. Methanotrophs are bacteria capable of oxidizing CH_4 into carbon dioxide (CO_2) by virtue of methane monooxygenase enzyme. Various cover materials can be utilized to enhance methane oxidation (MO) ability of these organisms by providing favorable conditions thus converting methane from unmanaged dumpsites into CO_2 which has lower global warming potential. Hence their application shows great potential for contributing towards meeting the greenhouse gas (GHG) reduction goals. This review focuses on the attempts to attenuate CH_4 emissions by different biocover systems and the current scenario while giving special emphasis to tropical conditions.

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INTRODUCTION

GHG emissions and climate change are one of the biggest problems that humans as a species are facing in the current time, which in turn and as a whole affects all the biotic and abiotic fractions of the planet. GHGs are the main contributing factors to global warming and climate change that trap heat in the atmosphere. The average rise in land and ocean temperatures globally is about 0.85° C from 1880 (Tuckett, 2018). Among these GHGs, CH_4 is a major contributor not by abundance but due to its Global Warming Potential (GWP) of 28-36 over 100 years (Balcombe et al., 2018). CH_4 is the most widely present organic chemical in the atmosphere of earth and although it is present in trace amounts compared to CO_2, it absorbs infrared radiation per molecule much more strongly (Lashof and Ahuja, 1990; Cicerone and Oremland, 1988). Recent developments show that CH_4 is more potent when its GWP is considered for a shorter period, it can be as high as 96 if we consider a time frame of 20 years (Alvarez et al., 2018). The level of CH_4 in the global atmosphere was 1909 ppb in 2021 as opposed to 722 ppb in pre-industrial times (Dlugokencky, 2021; Singh et al., 2018), which has increased by approximately 250% as compared to CO_2 concentrations, which have doubled during the same time (Chai et al., 2016). The primary sources of atmospheric CH_4 are both natural, including

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wetlands, termites, oceans, wildfires, grasslands, coal beds and lakes, as well as anthropogenic sources including livestock production, oil and gas sector, MSW landfills, paddy fields, biomass burning, etc. (Jackson et al., 2020).

Global MSW sector stands fourth in contributing to GHG emissions (Maria et al., 2020) while landfills contribute about 5% to GHGs globally (Zhang et al., 2019). Landfills are a primary source capable of producing CH_4 over a long time because of the slow decomposition rate of organic matter. Estimations suggest the worldwide CH_4 generation from landfills is about 10% of all the anthropogenic sources (US EPA, 2011). Landfill methane emissions are largely governed by climate and the type of cover applied at the site. However, humid subtropical climates have shown higher emission concentrations regardless of the type of cover (Goldsmith et al., 2012). Moreover, degradation of waste is accelerated four to five times in tropical wet conditions leading to higher LFG emissions, with CH_4 emissions 2 to 3 times higher than dry season (Sutthasil et al., 2019). This may be due to enhanced rate of transportation of nutrients in different layers of waste (Abushammala et al., 2016). Alternatively, higher CH_4 emissions are also observed during dry seasons which can be attributed to the presence of cracks at the surface of landfills (Chiemchaisri et al., 2007). By storing and recirculating excess leachate produced during previous wet season these problems can be mitigated (Lavagnolo et al., 2018). There is also possibility of formation of CH_4 hotspots where semi-aerobic conditions are developed after rainfall (Sutthasil et al., 2019).

Gas collection systems are utilized globally to reduce the escape of this CH_4 into the atmosphere. But, studies have shown that the efficiency of gas collection systems in landfills is about 50% on average resulting in escape of CH_4 into the atmosphere as fugitive emissions even after the installation of proper gas collection and utilization systems (Mohsen et al., 2020; Duan et al., 2022). Hence, microbial CH_4 oxidation by Methanotrophs by application with various cover materials is a beneficial and cost-effective alternative to conventional gas collection systems for biological oxidation of CH_4 emissions from landfills (Scheutz et al., 2009). Utilization of such materials in biocover systems can also help resolve the problems related to management of such waste materials as they can be reduced through such practices (Elkhouly et al., 2021). In tropical climates however, particular attention is to be paid to the condition of the cover soil as absence of optimum moisture content due to evaporation affects the methane oxidation even if aerobic conditions are maintained (Abushammala et al., 2016). Upgrading anaerobic to semi-aerobic open dumps commonly known as Fukuoka method has also shown to reduce GHG emissions by upto 40% (dos Muchangos & Tokai, 2020). Maximum rates of methanotrophic methane oxidation occur at 30°C, with genus *Methylobacter* dominating the methanotrophic community. Rising temperatures lead to a shift towards more thermophilic genus of methanotrophs like *Methylocaldum* (Reddy et al., 2019). Oxygen also plays an important role as a limiting factor in methane oxidation as it can penetrate upto a depth of 60 cm in the cover soil. But, in tropical conditions this can be vastly reduced during heavy rainfalls which lead to water-logging of the soil surface (Kallistova et al., 2005).

Due to above mentioned factors like higher methane emissions due to seasonal variations and humid atmosphere in tropical conditions it is necessary to obtain a comprehensive knowledge on this problem. Also, current global scenario of landfill emission and the different types of cover material that are used to enhance the methane oxidation by methanotrophs along with the environmental factors which influence their capacity to obtain an idea about the conditions required by these bacteria to function at an optimum level all form a part of this review.

Current global trends in methane emissions from MSW dumpsites and management practices

Varying trends have been seen in the past relating to CH_4 levels, in the 1980s the CH_4 levels on average increased by about 12 ± 6 ppb per year, during 1990s, this rate slowed down by 6 ± 8 ppb per year. Steady levels of CH_4 were observed from 1999 to 2006 at 1,773 ± 3 ppb, after

2007 CH_4 levels started to rise again at 1,799 ± 2 ppb in 2010 and are currently measured to be at 1909 ppb (Dlugokencky, 2021). In the year 2020, natural CH_4 emissions from wetlands and agriculture combined with the energy sector comprising of gas, coal and oil were maximum; followed by emissions from wastes; emissions related to biomass and biofuel combustion; etc. (IEA, 2020).

Current global CH_4 levels, according to World Bank show 5.3 GT of CO_2 equivalent (CO_2 e) in 1970 to 8 GT of CO_2 eq in 2018. China, Russia and India are the three biggest emitters of methane (World Bank, 2018). Global data shows developing economies are responsible for maximum emissions of methane, however major amount is exported in the form of exported goods to developed countries (Fernández-Amador et al., 2020). GHG emissions from landfills has been at the center of interest of research community from past two decades and continues to be as landfilling may continue to remain as one of the main methods utilized for disposal of solid waste around the world (Zhang et al., 2019). In the United States of America (USA), MSW landfills account for 15 percent of the total CH_4 emissions. Total of 1123 reporting facilities generated about 94.2 million metric tons of CO_2e methane in the year 2020 (EPA, 2022). In 2018, upwards of 40 percent of the 220 MT of MSW generated was sent to landfills in European countries. 100 million tonnes of CO_2e methane was emitted in the same year which accounted for more than 20 percent of the total CH_4 emissions (ESWET, 2018). There are around 1274 landfills in operation in Australia which receive 27 MT of waste. Waste sector in Australia contributes 2.2 percent to the total net emissions, while landfill emissions amounted to 716 Gg of CH_4 in the year 2020 (DISER, 2022). Similarly in China, landfilling is the primary method of waste disposal dumping upto 107.28 MT of waste in 2014. Total annual LFG production of China is about 13.2 billion m^3 of which 55-60% is CH_4. In a business as usual scenario the landfill CH_4 emissions are expected to reach 37.73 MT of CO_2e by 2030 (Cai et al., 2018; He et al., 2021). Africa has a MSW production of 125 MT per year, with a high organic content of upto 57 percent which has a huge potential for CH_4 emissions. But only about half of this waste is collected which is insufficient and leads to waste being dumped in open areas and side of the roads which can also lead to choked drains (Godfrey et al., 2020).

The landfill gases that arise as a result of the decomposition of waste in dumping sites consist of about 50% of methane and 50% carbon dioxide. Certain technologies of LFG capture are utilized which can trap these gases anywhere between 60 and 90% efficiency (U.S. EPA, 2011a). This collected gas can be utilized in various profitable ways including electricity generation, combined heat and power, as alternate fuels, etc. (EPA, 2012). Different projects have been taken up for capture and use of landfill gas. Landfill methane outreach program (LMOP) of US-EPA is responsible for keeping records of LFG and MSW projects in USA. Most of the LFG which is extracted is used for generation of electricity followed by use in boilers or other thermal applications (EPA, 2020).

Studies conducted to assess the biogas potential of MSW in tropical Ethiopia showed highest biogas production in mixed waste amounting to 0.15 m^3 biogas/kg of volatile solids (VS) when compared with individual biogas potential of organic wastes like fruit, food and yard waste, also paper waste which showed lowest potency (Getahun et al., 2014). When considering methane potential of different MSW components in Malaysia, cooked food waste showed highest methane potential of 328.39 ml CH_4/g VS (Yasim & Buyong, 2023). High methane potential upto 528 CH_4/g VS is observed in fresh waste while 151 CH_4/g VS is observed in 5 year old waste dug out from a Colombian landfill (Sandoval-Cobo et al., 2020). Comparative study between on site and laboratory measurements at a site in Brazil gave similar results close to 70 m^3 CH_4/ ton of MSW, which is lower value than normally observed in other developing tropical countries which may be due to excess moisture content present in the waste which has shown to offset the high organic matter content (Machado et al., 2009).

MSW generation in India is about 1.6 million tons. But, high waste collection rate of around

95% ensures that the waste is collected and treated or dumped at around 1900 designated sites (CPCB, 2021). In India methane emitted from landfills was expected to be 20 MT of CO_2e per year by 2020. Tropical climate in India facilitates rapid decomposition of waste and thus landfills are expected to produce great amounts of LFG in 1 to 3 years. All the potential LFG can be emitted within 20 years, but landfill may continue to produce CH_4 for 50 years or more (Kashyap et al., 2016). India shows huge potential in the utilization of LFG emissions due to high biodegradable content along with the warm and wet climate. In Indian context the LFG utilization scenario seems to be immature and further development in terms of innovative technologies, development of a standard framework for performance evaluation of such technologies and allocation of financial incentives are the major challenges (Siddiqui et al., 2013). Current studies show CH_4 concentrations to be in the range of 19 to 50% v/v in one of the biggest landfill in Okhla with a LFG flow of 8 to 22 m^3/hr which is adequate for a low-grade LFG to energy project (Siddiqui et al., 2022). Another study focused on assessment of methane potential from the waste generated in capital city of Delhi, the LFG generation rate is calculated as 130 m^3/t with CH_4 fraction of around 50 to 55%. The energy potential of CH_4 emission by waste is 5748 terajoule (Srivastava & Chakma, 2020). However, average installation capital costs involved in collection and flare systems are nearly $24,000/acre, annual operation and maintenance costs are about $4,100/acre (US-EPA, 2012). This is very high investment considering the monetary limitations of municipalities. Therefore, biocover systems may prove to be conducive and cost effective method where such conventional systems are not feasible. Biological techniques like application of compost biocover with 40 cm thickness has shown to be sufficient to give maximum methane oxidation (Yusnan et al., 2020). However, to reduce emissions to the atmosphere, it is important to evaluate the rate of degradation of organic waste, generation of landfill gases under different weather conditions, amount of organic material present in the waste along with the levels of humidity (Moreira & Candiani, 2016).

Processes involved in methane emissions from landfills

The characteristics and composition of MSW depend mainly on the economy, standards of living, type of activities, food habits, religious rituals, literacy, energy sources, climatic and topographical conditions of the area (Adeleke et al., 2021). MSW comprises of many categories of waste such as compostable organic matter, recyclable matter, some toxic substances, etc. (Sharma & Jain, 2020). Organic waste has been known to contribute the majority in this case due to the decomposition of the putrescible components into CH_4 and CO_2. The organic matter containing proteins, carbohydrates and fats are broken down in the process of hydrolysis by anaerobic bacteria in the absence of oxygen. Thus these insoluble products become available to other bacteria for utilization in simple forms like sugars, amino acids and other organic acids. Further, the acetogenic bacteria convert the organic acids produced in previous step into acetic acid amongst other compounds which are finally converted to methane and carbon dioxide by methanogenic bacteria **(Figure 1)**.

Earlier studies have been classifying municipal refuse into mainly two categories based on their sortable nature. These are needed primarily for the recycling studies and for the overall planning of Solid waste management (SWM). However, data of the chemical composition of the refuse is required for a discussion on the refuse decomposition and in turn its effect on gaseous emissions and the leachate characteristics (Vaverková et al., 2020). Knowledge relating to the organic fraction of MSW is essential when recovering energy through biological pathways, these characteristics are also responsible in affecting the quality of the digestate obtained (Seadi et al., 2012). The main biodegradable components of refuse are cellulose and hemicelluloses which make for maximum of the methane potential (Li et al., 2018).

Landfills are the most used method for MSW disposal. On a global scale 71% of the generated MSW is disposed in landfills (Abdel-Shafy & Mansour, 2018). Landfilling is a method of waste

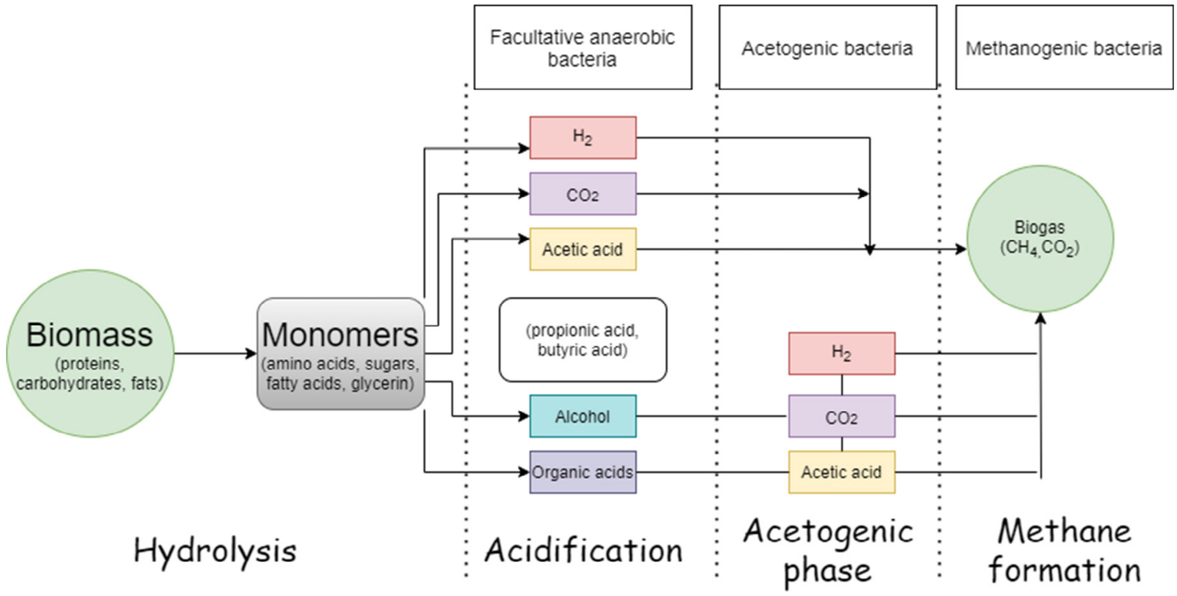

Fig.1. Process of anaerobic degradation

Table 1. Flux of methane from tropical landfills in different seasons

Sr. no.	Site	CH_4 emissions in $g/m^2/d$		Reference
		Wet	Dry	
1.	Ouagadougou, Burkina Faso	15.7	29	(Haro et al., 2019)
2.	Nuevo Leon, Mexico	-	4.47	(Gonzalez et al., 2021)
3.	Kuala Lumpur, Malaysia	267.2	173.3	(Abushammala et al., 2016)
4.	Guwahati, India	66	87	(Gollapalli & Kota, 2018)
5.	Delhi, India	0.31 to 1.4	1.98 to 7	(Rawat & Ramanathan, 2011)
	Air Hitam	30.58	-	
6.	Jeram	267.28	181.92	(Abushammala et al., 2014)
	Sungai Sedu	153.95	88.50	
7.	Recife, Brazil	-	0 to 984.7	(Maciel & Jucá, 2011)
8.	Salvador, Brazil	0 to 356		(Machado et al., 2021)

disposal in cells that are protected and specially created for depositing waste on land or dug into the land surface (Vaverková, 2019). Landfilling is a reliable method for disposing of the waste immediately but not a sustainable practice of waste management to consider for a long time period. They are a serious threat to human health, environment and also play a part in affecting the socio-economic aspects by causing impacts such as LFG emissions, hazards due to explosion and asphyxiation, landfill fires, affecting the groundwater quality in its vicinity, leachate generation, etc. (Ozbay et al., 2021). LFG is produced when the microorganisms act on the organic matter dumped in the landfills and lead to its decomposition. CH_4 and CO_2 are the main gases that constitute the LFGs. 120 to 150 trace components were identified in LFG, constituting about 1% by volume (Parker et al., 2002). LFG emissions continue for a long time even after the landfills are closed or abandoned as the biochemical reactions still continue (Guo et al., 2022). Emissions of methane vary throughout a landfill due to different environmental conditions within the waste, its diverse nature and depending on the stage of degradation the waste is in. Moreover, various activities on the site which disturb the waste increases the gas emissions (Ngwabie et al., 2019).

After initial waste collection, the piles are often accumulated before dumping them on the designated dumping area. This transition phase also contributes to the emission of CH_4 into the atmosphere. Shallow windrow piles used for MSW stabilization generate higher CH_4 than deeper piles (Wangyao et al., 2021). In tropical countries during rainy season, landfills emit higher CH_4 than summer or winter season (**Table 1)**.

Also, managed landfills give out higher CH_4 than unmanaged ones in similar conditions (Wangyao et al., 2010). Methane emissions from major tropical landfills estimated by modelling are listed in (**Table 2)**.

CH_4 concentrations ranging between 5 to 15% in the air are considered to be explosive and hence should be managed to avoid any mishaps (Kundu et al., 2016). Capturing and disposing LFG from old landfills is technically complicated and is considered not to be cost effective (Boerboom et al., 2010). CH_4 emissions from MSW landfills are estimated to increase by 21% during 2005 to 2030 (USEPA 2011). Typical LFG composition is listed in (**Table 3)**.

There are five phases of microbial decomposition of organic matter in a landfill site which generate specific greenhouse gases (**Figure 2)**.

Lou and Nair (2009) observed that GHG emissions were found to be considerably higher for landfills as compared to composting systems. Like this study, Deesing (2016) also affirmed that even though composting is responsible for some release of GHGs, it was found to be less than 10% of what is produced by landfilling for every ton of waste.

Methanotrophic Bacteria and their diversity in tropical landfills

Methanotrophs are found to be of two main types depending upon the process utilized for carbon assimilation. Ribulose monophosphate pathway RuMP (type I) and serine pathway (type II) are the two processes utilized by methanotrophs for carbon assimilation. Although it is reported that these pathways may also be utilized simultaneously in the same organism (Whittenbury et al., 1976). The pathway utilized by methanotrophs for CH_4 oxidation and formaldehyde assimilation are described in detail by Hanson and Hanson,(1996). The enzyme methane monooxygenase is responsible for catalyzing the methane oxidation reaction into

Table 2. Methane emissions from tropical landfills estimated by models

Sr. no.	Site	CH_4 emissions in m^3	Reference
1.	Tirupati, India	2.56 e5	(Ramprasad et al., 2022)
2.	Trichy, India	1.87 e7	(Chandrasekaran & Busetty, 2022)
	Thanjavur, India	1.67 e7	
3.	Machala, Ecuador	1.03 e7	(Barragán-Escandón et al., 2020)
4.	Mare chicose, Mauritius	3.62 e7	(Purmessur & Surroop, 2019)
5.	Lahore, Pakistan	4.04 to 4.65 e5	(Alam et al., 2022)
6.	Abidjan, Ivory Coast	7.97 e7	(Rodrigue et al., 2018)
7.	Trinidad and Tobago	3.03 e7	(Pillai & Riverol, 2018)

Table 3. "Typical" Landfill gas composition (Robertson & Dunbar 2005)

Component	Percent by Volume
CH_4	45 to 60
CO_2	40 to 60
N_2	2 to 5
O_2	0.1 to 1
Ammonia	0.1 to 1
Non-Methane Organic Compounds	0.01 to 0.6
Sulfides	0 to 1
Hydrogen	0 to 0.2
CO	0 to 0.2

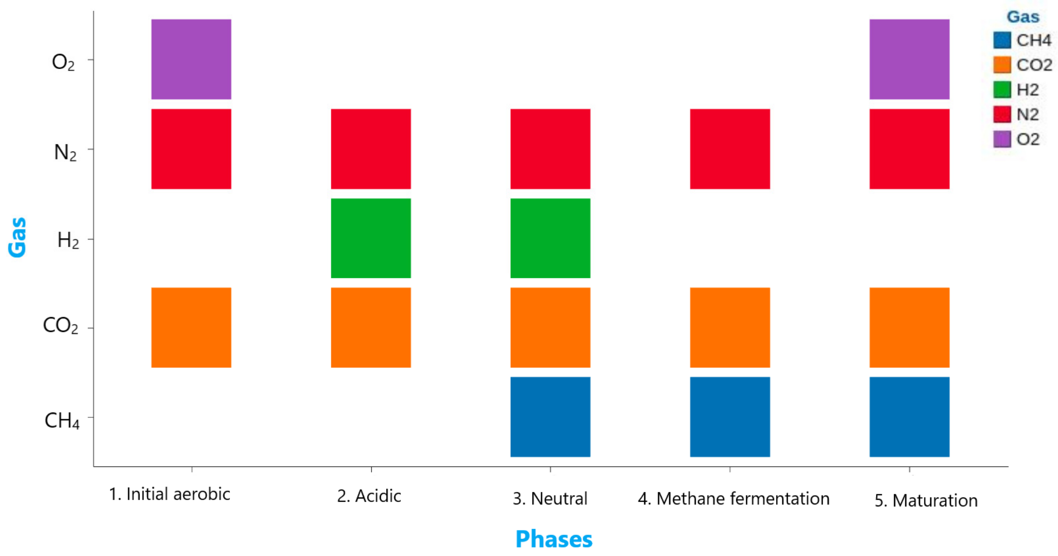

Fig. 2. Phase wise generation of principal landfill gases (Rao et al., 2016)

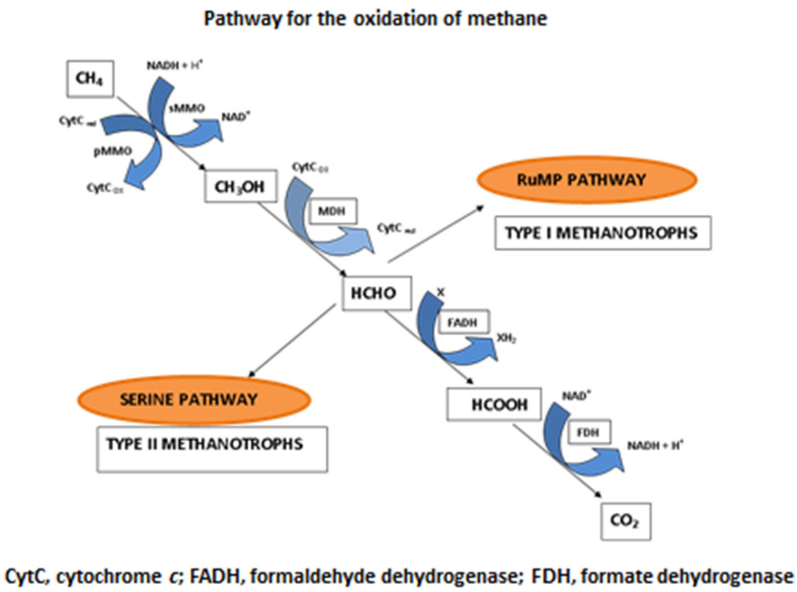

Fig. 3. Pathway for methane oxidation (Hanson & Hanson, 1996)

methanol by methanotrophs. Methanol is converted into formaldehyde by the enzyme methanol dehydrogenase. Formaldehyde plays a central role in this process by assimilation into the cell matter. The carbon fixation takes places by two pathways: Ribulose monophosphate pathway which is utilized by Type I and Serine pathway by Type II methanotrophs. Further, enzymes like formaldehyde dehydrogenase and formate dehydrogenase are responsible for conversion of formaldehyde into formate and ultimately into CO_2 **(Figure 3).**

Methanotrophs are ubiquitous in nature and isolation studies have shown that these organisms can be found in peatlands, rice paddies, and soils and sediments; also, in freshwaters and marine systems (**Table 4**).

They have also been found in places bearing extreme conditions like acidic hot springs,

Table 4. Methanotrophs isolated from various sources

Source	Site	Type	Nature/ Significance	Species	Reference
Sphagnum moss	Acidic peat bog at Mariapeel nature reserve, Netherlands	I and II	Acidophilic	*Methylomonas, Methylovulum, Methylosinus, Methylocystis*	(Kip et al., 2011)
Sewage outfall	Hyperion sewage outfall, near Los Angeles, California	I	Halophiles	*Methylomonas*	(Lidstrom, 1988)
Paddy soil	Tangerang, Indonesia	I and II		*Methylophilus leisingeri, Methylomonas koyamae*	(Setiawan & Sudiana, 2019)
Bark of *Melaleuca quinquenervia*	Forests in subtropical north-eastern New South Wales (NSW), Australia	I	Reduce methane emissions from trees	*Methylomonas* genus	(Jeffrey et al., 2021)
Recreational lake, gravel and bog sediment sample	A lake and a bog in England	II	Poly-3- hydroxybutyrate production	*Methylocystis rosea, Methylocystis parvus*	(Rumah et al., 2021)
Aquatic plant in eutrophic lake	Lake Biwa, Japan	II	Aquatic methane uptake	*Methylosinus and Methylocistis* genus	(Yoshida et al., 2014)
Tropical methane seep topsoil	Sylhet, Bangladesh	I	Moderately thermophilic and acid-tolerant	*Methylocaldum* genus	(Islam et al., 2016)
Landfill site	Incheon, Korea	I and II		*Methylobacter, Methylococcus, Methylosinus*	(Han et al., 2016)
Faeces of Indian antelope	Rajiv Gandhi Zoological Park and Wildlife Research Centre, Pune	I	Isolated from ruminant gut	*Methylobacter*	(Khatri et al., 2021)
Hot spring soil	Geothermal field in Republic of Korea	I	Thermotolerant	*Methylococcus*	(Awala et al., 2020)

alkaline soda lakes, mud pots, cold environments (Smith, 2009). High oxidation capacities of methanotrophs have been found in soils above the landfill sites (Stralis-Pavese et al., 2006).

Different methanotrophic communities with varying quantities are observed in landfills. This mainly depends on the various environmental and spatial factors of the area concerned. Type I methanotrophs dominate the landfill cover soil. q-PCR (Quantitative polymerase chain reaction) and T-RFLP (terminal-restriction fragment length polymorphism) are commonly utilized techniques to assess the methanotrophic communities present in the landfill soil. By studying the varying populations of methanotrophs with depth, *Methylocaldum* group dominated for a long residence time whereas *Methylocystis* were dominant in the deeper samples of tropical alkaline landfill (Chang et al., 2010). In a different study, *Methylocystis* community isolated from a tropical agricultural soil has shown to be effective for in-situ bioremediation of trichloroethylene (TCE) (Shukla et al., 2009). A shift in the dominance of type I methanotrophs from type II can be observed in landfill cover soils as it is influenced by the flux of CH_4. The type II methanotrophs surpass the type I in a high oxygen and low methane atmosphere while the later favor opposite conditions (Jang et al., 2011). Hence, as the CH_4 flux gradually increases in the landfills a community shift can be seen from *Methylocystis* (type II) to *Methylobacter* and *Methylococcales* (type I) (Xing et al., 2017). *Methylocaldum* and *Methylococcaceae* do not show optimal growth in low O_2 conditions, whereas *Methylobacter* shows the tendency to grow at low O_2 concentrations of upto 5% while *Methylosinus* showed preference to high CH_4 and O_2 concentrations (Wei et al., 2015).

Stored waste shows higher microbial biodiversity than cover soil in landfills. *Methylohalobius* dominated the microbial community of the cover soil by showing an abundance upto 24 percent in the study (Wang et al., 2017). In enrichment culture experiments, *Methylobacter* genus are shown to dominate upto temperature of 30°C while thermophilic group *Methylocaldum* were abundant at higher temperatures like 40°C (Reddy et al., 2019). Seasonal studies show that Type-I methanotrophs namely *Methylobacter* show relative abundance during all seasons. Close to threefold increase in the community is observed during early summer when compared to winter season while again a slight decrease can be seen in late summer (Yun et al., 2018). Invertebrates like earthworms present in the soil tend to shift the methanotrophic community as more Type I methanotrophs (*Methylobacter, Methylomonas, Methylosarcina*) are found in study than Type II methanotrophs (*Methylocystis*) while also improving the methane oxidation in landfill cover soil (Héry et al., 2008; Kumaresan et al., 2011).

Methane oxidation (MO) in cover soil

Methanotrophs are obligatory aerobic microorganisms that utilize CH_4 as a sole carbon source (Hanson & Hanson, 1996), they fall under the methylotrophic community of bacteria which oxidize the compounds which do not have C-C bonds or C1 compounds (Murrell et al., 1998). They play an important part in the process of oxidizing CH_4 occurring naturally in the environment due to the metabolism of methanogenic bacteria under anaerobic conditions as well as for reducing the impact caused due to release of CH_4 from landfill sites, rice paddy fields and wetlands. Aerobic methanotrophic bacteria are mainly active in the upper layer of landfill cover soil. Methane oxidation capacity of cover soil is enhanced during the spring and summer conditions as opposed to winter in tropical climate (Yun et al., 2018).

Landfill cover is placed to dissociate the waste from the outer environment using various materials. Biocovers consists of organic materials which provide favourable conditions to methanotrophic bacteria to enhance their methane oxidation capacity. These covers are placed on top of a distribution layer consisting of coarse materials for proper dispersal of LFG (Pehme et al., 2020). Such materials applied for enhancing methane oxidation are studied under tropical conditions (**Table 5**).

Table 5. Methane oxidation using various soil cover material

Sr. no.	Material	CH_4 oxidation in µmol h^{-1} g dry soil $^{-1}$	Reference
1.	Aged refuse (50%) with soil	19.23	(H. He et al., 2022)
2.	Landfill soil	0.50	(Reddy et al., 2019)
3.	Biochar amended soil	0.081	(Reddy et al., 2014)
4.	Slightly acidic peat soil	10.6	(Cébron et al., 2007)
5.	Sewage sludge and mineral soil	1.17 and 1.57	(Börjesson et al., 2004)

Biocover materials majorly used are described as follows:

Clay covers

Landfill clay covers are made up only of a simple clay topsoil sequence without the use of any geoembranes (Bogner et al., 1997). It is an impervious layer composed of soil rich in clay which is used to contain MSW safely by controlling water percolation leading to leachate pollution and LFG emissions. Oxidation of methane microbiologically in landfill cover soil is an effective measure to mitigate emissions especially from old landfills or dumping sites that contain wastes generating methane at low rates (Rachor et al., 2011). The ability of the methanotrophic community in soil cover to oxidize methane is depended on the supply of oxygen from the atmosphere. Hence the physical properties of the cover soil play an important role in this aspect. According to this soils like sands, sandy loams, loamy sand and some coarse loams can be effectively utilized for biocover purposes (Gebert et al., 2011). In a recent study use of bentonite as an amendment to clayey soil is studied which show improvement in physical properties of the cover soil (Qasaimeh et al., 2020). However, lower concentrations of bentonite amendments show better results in this respect (Kumar & Yong, 2002). Soil-like fine fractions (<40 mm) excavated from the landfill itself have also been utilized as a bioactive cover layer providing a useful substitute as a biocover substrate (Pehme et al., 2020).

Compost

Use of compost as an alternative biocover is observed in several studies, as the use of this portion of solid waste supports green sustainability (Abdelzaher, 2022). Methane oxidation is higher in cover soils with higher organic content than in clay matrix (Chanton & Liptay, 2000). Compost of leaf, yard waste, kitchen waste, sawdust, landfill mining, MSW, etc. are widely used in studies. Improvement of cover soil by addition of compost is considered to be superior when compared with other methods like inclusion of inorganic compounds as nutrients (benefitted methanotrophic acivity for short time span) or decompacting the soil to free up soil pores (Maanoja & Rintala, 2018). However, use of inorganic material namely expanded vermiculite in mixture with organic compost has given superior metahanotrophic activity for potential use in biofiltration of CH_4 emissions (Brandt et al., 2016). Compost has a strong control on methane oxidation in soil-compost mixtures as 1:1 ratio of both has shown maximum effectiveness (Rose et al., 2012). Active zones in cover systems wherein methanotrophic activity is highest is deeper in compost as compared to sandy loam soils due to its loose texture allowing for higher oxygen penetration (Tanthachoon et al., 2008). Upto ten-fold reduction in the CH_4 emission rates in such compost biocover systems has been observed which peaks after three months of initial placement due to establishment of suitable community of methanotrophs (Stern et al., 2007). However, if the compost is not matured and of improper texture there is a risk of the cover producing methane rather than oxidizing it (Barlaz et al., 2004). Maturation, thickness of the biocover and compaction rate are the major factors that influence CH_4 emissions

(Kristanto et al., 2015). During winters compost cover can play an important role due to its low thermal conductivity thus providing a favorable growth temperature to methanotrophs and thus improving MO (Bajwa et al., 2022). Moderate MO in dry conditions are observed in tropics and hence leachate recirculation is suggested (Tanthachoon et al., 2008).

Biochar

Biochar is a carbon-rich material derived by thermally converting biomass in an oxygen deficient environment which provides a large surface area and has a porous structure which can be profitably taken advantage of in landfill cover systems (Yaashikaa et al., 2020). High porosity of biochars along with high organic content and longer stability in the cover soils makes them an attractive option (Sadasivam & Reddy, 2015). Amending cover soil with 2.45-2.78% of biochar produced at 400°C has shown to be optimal for MO (Huang et al., 2019). Use of biochar in a biocover system facilitates adsorption and oxidation by methanotrophic bacteria simultaneously (Sadasivam & Reddy, 2014) by improving gas transport properties thereby limiting the formation of extracellular polymeric substances (EPS) within the cover system (Sadasivam & Reddy, 2015). Also, improvement in the water holding capacity and maintaining nutrients which support growth of methanotrophs are other advantages of biochar amendments (Huang et al., 2019). External aeration is shown to enhance MO capacity of biochar amended cover soil upto 90% having abundance of *Methylocystis,* a type II methanotrophic bacteria (Huang et al., 2020). A novel procedure by producing hydrophobic biochar by coating a silane coupling agent has shown to reduce the excess water content and thus improving diffusion and oxidation of CH_4 in the cover soil (Wu et al., 2020).

Along with MO, biochar which is modified with sludge can also be applied for complete removal of other common pollutants emitted in landfills like volatile organic carbon (VOCs), hydrogen sulfide and ammonia (Qin et al., 2020). Application of biochar amendment to cover soil have shown lasting effects of improved MO by maintaining moisture content which prevents cracking and fugitive emissions (Reddy et al., 2021).

Waste material

Majority of studies include biocover containing organic rich materials like compost, which increase the MO when compared with conventional soil biocovers. Due to application of such material being expensive it is suggested for application on hot-spots wherein the flux of CH_4 is high (Mei et al., 2015). Hence, waste materials readily available in landfills may prove to be an economical and viable option in this regard. A combination of aged refuse (14 years) to aged sludge in the ratio of 7:3 has shown MO capacity upto 78.7% which can potentially decrease the need of these wastes to be disposed of in landfills and also replacement of natural soil as LF cover (Lou et al., 2011). Similarly, under specific recommended properties a cover material of aged refuse modified with leachate has shown MO capacity similar to that of compost (Mei et al., 2016). A 20 cm cover of refuse aged for more than 10 years is ideal for maximum MO and can also be helpful in reducing the production of leachate by retaining rainfall (Warmadewanthi et al., 2021). After displaying a lag period yard waste has also shown good results in MO studies while a blend of such wastes enhances the oxidation capability of metahanothophs (Niemczyk et al., 2021).

Creating a cover by soil-like fraction mined from the landfill site itself is another feasible technique for places where availability of any low permeable material or other cover material at all is not possible. Using material mined from the same landfill may also prevent wastage of natural soils or synthetically manufactured liners (Pehme et al., 2020).

Environmental factors affecting methane oxidation in landfill cover soils

Oxidation of CH_4 is an important factor for limiting escape of the gas generated during decomposition of organic matter dumped in landfills. This process is affected by several factors that influence the release of CH_4 into the atmosphere. Different factors like temperature, soil moisture, soil texture, availability of oxygen, addition of nutrients, etc. are responsible.

Temperature

Temperature is a critical factor as it is responsible for various chemical processes and the enzymatic activity of methanotrophs (Börjesson et al., 2004;Chi et al., 2015; Christophersen et al., 2000; Scheutz et al., 2009)**.** The optimum temperature for MO is within the range of 20 to 38°C as indicated by batch assay studies (Gebert and Gröngröft, 2006; Scheutz and Kjeldsen 2004). Börjesson et al., (2004) suggested that temperature determines the population of methanotrophs present in the cover soil. It was inferred that type I methanotrophs populations increased at low temperatures between 5 to 10°C while type II methanotrophs at 20°C. High temperatures have shown to have more effects on the MO abilities of these organisms than lower temperatures. They show optimum performance between 15 to 35°C which decline above 40°C and drop to zero by 50°C (Zeiss, 2006). In another study optimal temperature for MO was reported to be between 30 to 36°C, wherein the effect of high temperature in tropics caused drying of the top surface of soil. Thus causing no MO even after existing aerobic conditions (Visvanathan et al., 1999). However, MO is also observed in environmental samples at temperatures as low as 0 to 10°C, albeit in significantly less amounts than at optimum temperatures (Einola et al., 2007). On-site oxidation rates in landfills are shown to be significantly higher in warmer climates. Temperature affects solubility of CH_4 in water which is also one of the factors affecting MO by intervening in CH_4 uptake rates (De Visscher et al., 2001).

Soil moisture and texture

Water content also influences the MO rate (He et al., 2011) and optimum moisture content in the soil for MO rate to occur effectively is affected by soil type and porosity (Zeiss, 2006). High soil moisture content affects both the advective and diffusive properties in the cover soils. Soil pore size decreases with an increasing water content which restricts the advective flow of gas. In addition, the diffusion coefficient of CH_4 which is lower than that of air by a magnitude of 4, limits the diffusion of gas when the soil is saturated. This effect may drive more gas through soil macropores and cracks. The compaction of soil affects volume of soil pores and moisture condition by restricting lateral water flow (Czepiel et al., 1996). Lei (2006) concluded in his studies that there were three essential roles of moisture content in MO process. First, optimum moisture content provided an optimum environment for methanotrophic bacteria to carry out their activity. Second, the moisture content significantly influenced the diffusion of oxygen into the soils whereby oxygen was the primary activator in MO process. Third, moisture content was one of the controlling factors of soil porosity that influenced gas transportation throughout the soil. Rainfall during monsoons in tropical countries lead to significant decrease in the methanotrophic community mainly due to washout of bacteria along with the depletion of oxygen due to water flooding on the soil surface (Chang et al., 2010).

Maximum microbial biomass is supported by optimum soil moisture content. When soil moisture reduces from 10 to 5% a significant decrease is observed in MO rates, whereas an increase in soil moisture above 10% also showed similar reductions (Boeckx et al., 1996; Cai and Yan, 1999). Maximum MO is observed in tropical cover soils with moisture between 15 and 20% whereas negligible oxidation was observed at low moisture concentration of 6% (Visvanathan et al., 1999). Too little water reduces or stops the growth of microorganisms. Similarly, too much water tends to replace the air pockets in soil, affecting some microorganisms, mainly aerobes (Chiemchaisri et al. 2012). Low moisture content causes the water to drain out of the cell body due to osmotic pressure causing lysis of bacterial cells leading to the death of the microbes.

Soil texture is mainly classified as: sand, loam and clay. These play an important in the diffusion of gas and water in soil which in turn affects the activity of microbes in soil (Shukla et al., 2013). Silt or sandy loam soil is optimum for landfill cover soils (Chiemchaisri et al., 2001; Henneberger et al., 2012). Pawlowska (2008) in their study observed maximum values of MO in coarse sand material when carrying out experiments with four different grain size mineral materials. Any increase or decrease from this grain size caused the MO capacity to decrease. Soil when grinded and sieved has shown higher MO potentials as opposed to normal or control soil (Kumaresan et al., 2011).

Oxygen availability

Methanotrophs are aerobic in nature hence oxygen is one of the primary requirement for their proper growth, activity and diversity (Amaral & Knowles, 1995). MO rates are dependent on the availability of oxygen. If an ample quantity of oxygen is present in the soil, the MO capacity is doubled (Alshareedah & Sallis, 2016).. Ambient levels of oxygen are more favourable for the oxidation of CH_4 in landfill cover soils (He et al., 2011). However, after reaching peak of CH_4 oxidation, O_2 concentration of 5% was sufficient to carry out the MO process (Wei et al., 2015). Studies also show the existence of both communities of different functional guilds as well as single type of microbes involved in MO. These associations are dependent on different components, availability of oxygen being one of the major factor that determine these specific partnerships (Hernandez et al., 2015). A depth of 15 to 40 cm showed maximum zone of MO in tropical cover soils due to ample oxygen diffusion (Visvanathan et al., 1999).

CONCLUSION

GHG emissions due to anthropogenic activities pose a grave risk to human beings and also to the environment. Effects of excessive GHG emissions due to rampant activities are quite visible in today's world. Global warming and climate change, thawing of permafrost, sea level rise leading to flooding, intense natural disasters, species migration to name a few. Carbon dioxide is the GHG with the maximum atmospheric concentration but CH_4 is a more potent GHG ascribed to its high global warming potential. Both natural and anthropogenic sources are responsible for CH_4 levels in the atmosphere with maximum CH_4 contribution from sectors like energy, industry, agriculture, and waste management. LFG emissions resulting from anaerobic decomposition of organic matter in the landfill or dumpsite contribute to 10% of CH_4 and hence it is a major contributor to CH_4 generation globally. Management of CH_4 emitted from landfills faces many challenges in countries having tropical climates due to rapid degradation of organic waste in hot and humid climates.

To curb these emissions gas collection systems are installed in the landfills which can extract the CH_4 which can be utilized or flared of. However, these technologies have limitations due to factors like being expensive, difficult to install on existing dumpsites and dumpsites which are spread in a small area and accumulate limited amount of waste. A more feasible alternative to such techniques is by application of microbial MO by methanotrophs. Methanotrophs are methane oxidizing aerobic bacteria that can grow by utilizing CH_4 as their only carbon source and energy due to the presence of a unique methane monooxygenase or MMO enzyme. These bacteria can survive extreme conditions and can be successfully utilized to reduce the impacts of CH_4 emissions from MSW dumpsites. Amount of organic biodegradable matter accounts for the top portion of MSW waste and indiscriminate and unscientific dumping procedures and the limited capital allocated towards MSW management, application of methanotrophs to reduce CH_4 emissions from MSW dumpsites can prove to be a big step in this front. Diverse variety of methanotrophs are observed in the tropical covers dispersed above waste in landfills. The oxidation capacities of these microbiota can be enhanced by providing favorable environmental conditions by studying their applications with different cover materials.

Extensive literature is available towards experimental procedures including various column and flask level studies under controlled conditions using amendments like various nutrients, biochar, sewage sludge, etc. to enhance the oxidation activity of methanotrophs but limited data is available on actual field applications of the same where conditions are variable depending on the local ambient environments. Keeping above points in mind further studies are required to resolve the problems associated with CH_4 emitted from landfills and to assess the effectiveness and feasibility of application of these microbial oxidation techniques.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

AUTHOR CONTRIBUTION

M. Suresh Kumar conceptualized and supervised while Tanmay Srivastava and Vartika Srivastava were involved in preparation of the manuscript. All authors discussed and commented on the manuscript.

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