

Microbial Control of Greenhouse Gases from Municipal Solid Waste Dumps: A Mitigating Principle in Environmental Sustainability.

Onianwah, F. I.^{1,2,3}, Amhanriamhen, R. I.^{1,3}, and Sowamina, M. N.¹

1. Department of Microbiology, Dennis Osadebay University, Asaba, Delta State.

2. Current Research and Innovations Group, Dennis Osadebay University, Asaba, Delta State.

3. Environmental Health Research Initiative, Dennis Osadebay University, Asaba, Delta State.

Corresponding Author: **Onianwah, F. I**

Tel: +234 8033126090

Email: ifeanyichukwu.onianwah@dou.edu.ng

ORCID ID:0000-0002-2048-5557

ABSTRACT: The impact of greenhouse gas (GHG) emission on global environmental sustainability is an issue of serious concern. This is because of the negative effects of these gases on the environment essentially on its contribution majorly to climate change. The aim of this study is to review the strategies, advantages, processes and current innovations of microbial interventions in waste management. Microorganisms are the best alternative to physicochemical methods of mitigating GHG. Methanotrophs, Phototrophs and some nitrogen fixing bacteria play critical role in this process by consuming GHS gases like carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) as carbon and nitrogen source. Reduction of nitrous oxide by N₂O reductase leads to the production of ammonia which is not a GHG while nitrogen fixing bacteria such as Nitrosomonas and Nitrobacter converts N₂O to nitrite and nitrate used by most microbes for protein synthesis. Carbon dioxide is utilized by phototrophs to carry out photosynthesis while methanotrophs such as Methylobacter sp., Methylococcus sp. and Methylocella sp utilized methane. Therefore, understanding intervention principles and potentially manipulating microbial processes offers a promising means for mitigating microbial greenhouse gas production, consequently, offering solution to climate change and global warming through targeted intervention at the municipal solid waste dumps. Traditional waste management methods of landfill and open dumping are not targeted at mitigating these emissions of GHGs, posing a serious challenge to efforts being made in environmental sustainability. Microbial control, involving the use of specific bacteria and archaea, plays a crucial role in regulating GHG emissions from MSW dumps by enhancing methane oxidation, promoting carbon sequestration, and facilitating bioconversion into less harmful compounds. Despite advancements in landfill technology, the microbial processes that drive GHG production and potential mitigation remain underutilized and poorly managed. There is a pressing need to explore and optimize biological strategies, particularly those involving microorganisms, to reduce the environmental impact of waste dumps. The outcome of this study could influence policy decisions, inform landfill engineering designs, and support the development of green technologies that reduce methane and carbon dioxide emissions from municipal solid waste sites.

[Onianwah, F. I., Amhanriamhen, R. I., and Sowamina, M. N. **Microbial Control of Greenhouse Gases from Municipal Solid Waste Dumps: A Mitigating Principle in Environmental Sustainability.** *World Rural Observation* 2026;18(1):13-19]. ISSN: 1944-6543 (Print); ISSN: 1944-6551 (Online). <http://www.sciencepub.net/rural>. 02. doi:[10.7537/marswro180126.02](https://doi.org/10.7537/marswro180126.02)

Keywords: Bio-cover; Greenhouse gas; Microorganisms; Mitigation; Municipal Solid Waste.

Contribution/Originality

Increase in global greenhouse gas generation due to the activities of methanogens and chemical reduction processes on municipal solid wastes is a global concern that requires urgent mitigation principles. The use of methanotrophs as depicted in this research offers immense contribution towards reduction of greenhouse gas emissions and consequently mitigating their negative effects of climate change.

The authors accept responsibility for the originality of this work and declare their consents on its publication.

Introduction.

Municipal Solid Waste Management (MSWM) is the collection, transportation, processing, and disposal of solid waste generated in urban areas. Effective MSWM is crucial for environmental protection, public health, and resource recovery. Traditional disposal

methods, such as landfilling and open dumping, pose significant environmental risks. Modern approaches focus on the 4Rs: reduce, reuse, recycle, and recover energy [1]. Municipal solid waste (MSW) dumps are significant sources of greenhouse gases (GHGs), particularly methane (CH₄) and carbon dioxide (CO₂), which result from the anaerobic decomposition of organic matter [2]. These emissions contribute to global warming and climate change, necessitating innovative strategies to mitigate their impact. Microbial control, involving the use of specific bacteria and archaea, plays a crucial role in regulating GHG emissions from MSW dumps by enhancing methane oxidation, promoting carbon sequestration, and facilitating bioconversion into less harmful compounds [3]. Besides, these bacteria and archaea most of which are mainly photosynthetic utilizes CO₂ as carbon and energy source during photosynthesis [4]. Open dumps, especially in low- and middle-income countries like Nigeria, lack gas capture systems, exacerbating emissions and contributing significantly to climate change [5]. This review explores the role of microorganisms in controlling GHGs from waste dumps, discussing their metabolic pathways, applications in engineered landfill bio-covers, and potential for mitigating climate change effects.

Microbial Communities and Waste Decomposition processes in Landfills

Landfills are engineered facilities designed for the controlled disposal of municipal solid waste (MSW), typically involving layers of compacted waste covered by soil or synthetic liners to isolate waste from the environment [6]. Modern sanitary landfills include systems for leachate collection, gas recovery, and environmental monitoring, distinguishing them from open dumps. They are a common waste management solution worldwide but are also significant sources of greenhouse gases—mainly methane—due to the anaerobic decomposition of organic materials. Landfills are home to diverse and dynamic microbial populations that vary with depth, age, and waste composition. Dominant bacterial phyla of landfills

include *Firmicutes*, *Proteobacteria*, and *Bacteroidetes*, while methanogenic archaea such as *Methanosarcina* and *Methanobacterium* are essential in anaerobic methane production. These communities adapt over time, significantly influenced by factors like temperature, pH, and moisture [7]. Although many microorganisms in the waste play important role in degrading persistent wastes, one of the most interesting microbes is methanotrophs, which play protection role in global warming and natural resource contamination. They utilize methane as their sole carbon and energy source [8]. Over 300 persistent biodegraded compounds such as aliphatics, alkanes, aromatics and chlorinated hydrocarbon are co-metabolized by enzyme methane monooxygenase (MMO) from methanotrophs [9,10]. It is reported that some types of methanotrophs such as *Methylobacter sp.*, *Methylococcus sp.*

and *Methylocella sp.* are the principal decomposer of plastic degradation in simulated open dump site where methane is available in waste beds [8]. Because both methane and oxygen are available in a waste bed of a semi-aerobic landfill, there is a lot of methanotrophs residing in this type of landfill. This is because oxygen is a key factor in methane oxidation [11].

Methane monooxygenase (MMO) is an enzyme use by these methanotrophs in the oxidation of methane, this is usually all known aerobic methanotrophs first step in the conversion of methane into methanol by using MMO. In the second step the methanol further oxidized into formaldehyde, after which it has two options, first is to convert into biomass and other is the further oxidation into formate and then into CO₂. Two iso-enzymes of MMO is known: soluble MMO (sMMO), found only as subset of known methanotrophs, and also membrane bound (or particulate) MMO (pMMO). The pMMO is located in specialized internal membrane structures, called ICMS [10]. sMMO and pMMO both have mixed function of oxidation, (that is one atom from O₂ goes to methanol and the other to water), involving the input of 2 electrons and 2 protons.

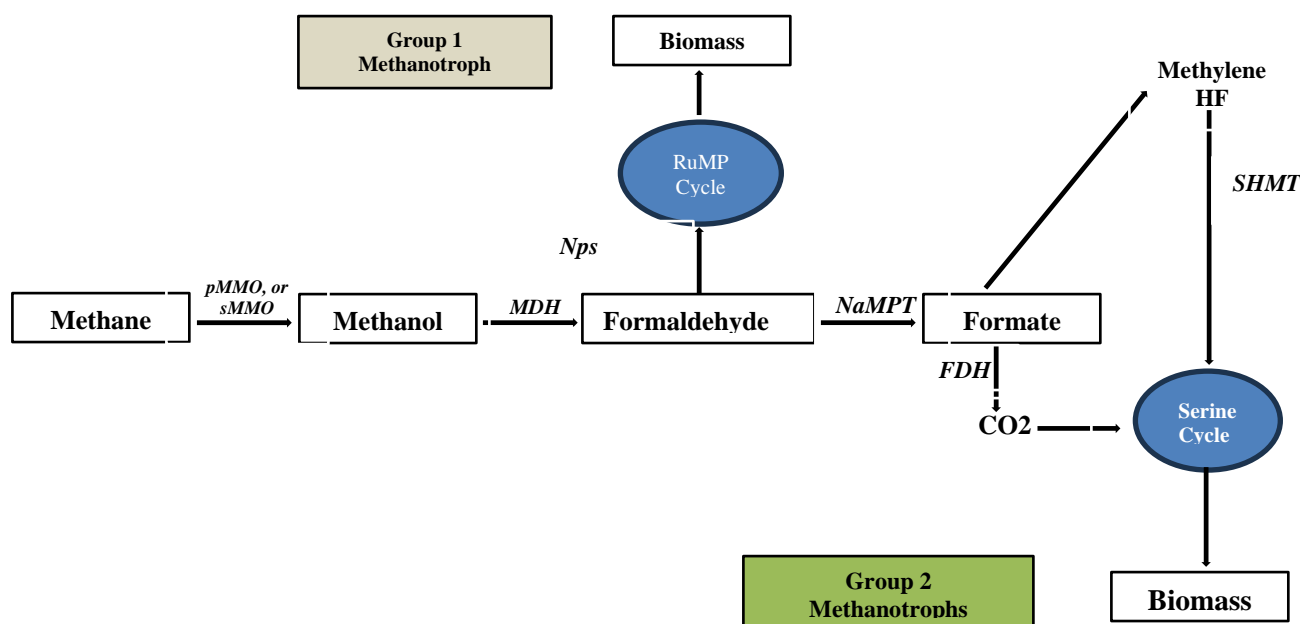
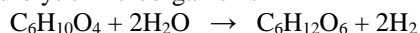


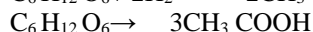
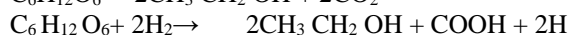
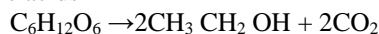
Figure 1: A flowchart of Methanotroph and Methanotrophic metabolism for methane utilization [10]

Microbial communities play a critical role in breaking down organic and synthetic waste materials through aerobic and anaerobic processes. Recent studies by Liu *et al.* [12] have shown that bacteria such as *Pseudomonas* and fungi like *Trichoderma* are actively involved in decomposing plastics and organic matter in landfill environments, utilizing specialized enzymes to degrade complex polymers [12]. Enzymes such as catalase, oxidase, peroxidases and laccase are used to breakdown complex organic compounds into simpler biodegradable forms [13,14]. According to Xiaoli *et al.*, [15] bacterial decomposition of organic waste occurs in five stages, with different gas compositions produced. These processes are driven by consortia of microorganisms that sequentially convert complex substrates into simpler compounds and gases like CO₂ and CH₄. Recent reviews highlight the importance of microbial synergy, particularly between fermentative bacteria and methanogens, for efficient waste-to-energy conversion [16,17]. The following five stages are involved in solid organic wastes decomposition:-

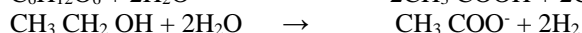
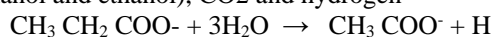
1. **Hydrolysis/Aerobic degradation:** Solubilization of complex solid organic material by the enzymes excreted by hydrolytic microorganisms



2. **Fermentation:** Soluble organic components, including the hydrolysis products, converted into alcohols and organic acids



3. **Acetogenesis:** Also known as acidogenesis because bacteria anaerobically convert organic acids created by aerobic bacteria into the various class of acids such as acetic acid, lactic and formic acids along with alcohols (methanol and ethanol), CO₂ and hydrogen



4. **Methanogenesis:** products obtained after acetogenesis undergoes conversion into methane, hydrogen and carbon dioxide. It is the anaerobic process wherein a large amount of landfill gases is generated.

$$\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$$

$$2\text{C}_2\text{H}_5\text{OH} + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{CH}_3\text{COOH}$$

$$\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2$$
5. **Oxidation:** Here aerobic microorganisms convert the methane produced during the methanogenesis to water and carbon dioxide.

Factors Influencing Microbial Activity

Microbial activity in waste systems is regulated by multiple factors such as temperature, pH, oxygen levels, and the presence of inhibitors. Current research indicates that amending waste with materials like biochar improves microbial habitat quality and enzyme activity, thereby accelerating decomposition and enhancing compost quality [18]. Proper environmental control is essential to optimize microbial performance in both composting and anaerobic digestion.

Heat is generated during the decomposition process due to the physical and chemical reactions taking place within the dump site. Temperature is especially important for the activity of microorganisms responsible for the decomposition of waste materials. The suitable temperature in the center of a household waste deposit is necessary to maintain optimal microbial activity. Higher temperatures promote efficient decomposition, while lower temperatures may slow down the process. This is usually divided into three phases: (a) Mesophilic (temperature > 25°C), wherein the metabolism of mesophilic microbes breaks down simple molecules like sugar and amino acids.; (b) Thermophilic (temperature > 50°C), where organic matters like fat, cellulose and lignin are broken down by thermophilic microorganisms; (c) Maturation (temperature < 50°C), this is marked by increase microbial activities and a drop in temperature [19]. Additionally, moisture levels have been reported by Aliaa *et al.* [20] to impact the microbial activity, with an optimal range providing favorable conditions for microorganisms to thrive. Another independent group of factors include micro-moisture, oxygen concentration, and pH value. Micro-moisture availability significantly influences microbial activities during waste decomposition. Optimal moisture level is crucial; too little or too much can hinder microbial growth and activities, affecting the rate and efficiency of decomposition. Adequate oxygen levels promote aerobic decomposition, while anaerobic conditions favor the growth of different types of microorganisms that do not require oxygen. The pH value also plays a crucial role, especially in the proximity of "acidic heavy metal scarification". Certain microorganisms thrive in acidic environments, while others prefer neutral or alkaline conditions. The pH level affects the microbial community composition, which in turn influences the breakdown of waste materials. Proper monitoring and regulation of pH levels can help optimize composting or waste management processes. Water requirement estimation is also essential to ensure efficient waste management[20].

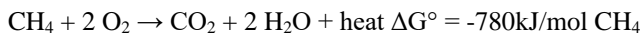
Microbial Control Strategies

Microbial control strategies in waste management focus on enhancing or regulating microbial populations to improve decomposition and reduce harmful emissions. Common methods include bioaugmentation, where specific strains such as *Bacillus subtilis* or *Pseudomonas spp.* are introduced to accelerate degradation. In a comprehensive research conducted by Li *et al.*, [21] he reported that microbial additives such as consortia of *Bacillus*, *Lactobacillus*, and *Actinomyces* are increasingly used to accelerate composting. These additives enhance organic matter breakdown, stabilize nitrogen content, and reduce odor emissions. Huang *et al.*, [22] also reported that combination of microbial inoculants with amendments like biochar has been found to significantly boost enzymatic activity and compost maturity [22]. Biostimulation, which involves optimizing environmental conditions like pH, moisture, and nutrient levels [23] also enhances microbial activities. Bioventing techniques involve controlled stimulation of airflow by delivering oxygen to unsaturated (vadose) zone in order to increase activities of indigenous microbes for bioremediation. In bioventing, amendments are made by adding nutrients and moisture to increase bioremediation. That will achieve microbial transformation of pollutants to a harmless state. This technique has gained popularity among other in-situ bioremediation techniques [24]. Biosparging technique is similar to bioventing in that, air is injected into soil subsurface to improve microbial activities which stimulate pollutant removal from polluted sites. However, in bioventing, air is injected into saturated zone, which can help in upward movement of volatile organic compounds to the unsaturated zone to stimulate biodegradation process. The efficiency of biosparging depends on two major factors specifically soil permeability and pollutant biodegradability [25]. Recent advances also explore genetically engineered microbes for more efficient organic waste conversion [26].

Bio-covers and Bio-filters for Methane Oxidation

An inexpensive way to reduce greenhouse-active methane emissions from existing Municipal Solid Waste (MSW) landfills is to exploit the natural process of microbial methane oxidation through improved landfill cover design. Landfill top covers, which optimizes environmental conditions for methanotrophic bacteria and enhance biotic methane consumption, are often called 'bio-covers' and function as vast bio-filters [27]. Bio-covers, usually composed

of compost or soil enriched with methanotrophs, encourage microbial oxidation of methane to carbon dioxide, a less potent greenhouse gas [28]. The aerobic microbial oxidation of CH₄ occurs in the biosphere wherever CH₄ and oxygen (O₂) are present at the same location. In landfill covers CH₄ and O₂ may appear at the same depth due to emission of CH₄ from the waste and diffusion of O₂ from ambient air, which provides needed conditions for the development of methanotrophic bacteria [29]. Aerobic CH₄ oxidation proceeds according to the following overall reaction, producing a significant amount of heat:



The reaction is carried out by the methanotrophic bacteria (or methanotrophs), which are unique in their ability to utilize CH₄ as a carbon and energy source. Landfill cover soils can exhibit high capacities for CH₄ oxidation. Very high rates of CH₄ oxidation in landfill cover soils (>100 µg CH₄ g⁻¹ h⁻¹ and >200 g CH₄ m⁻² d⁻¹ in batch and column experiments, respectively) have been reported [29]. Similarly, biofilters, which channel landfill gas through beds colonized by methanotrophic bacteria such *Methylosinus trichosporium*, *Methylobacter album*, *Methylomicrobium sp.*, have shown methane oxidation efficiencies up to 90% under optimized conditions [18].

Other Innovative Approaches for Reducing Greenhouse Gas Emissions

Emerging strategies for reducing GHG emissions from waste systems include anaerobic digestion for biogas recovery, waste-to-energy technologies, and carbon capture from composting units. Integration of these technologies with circular bioeconomy models—where waste is converted into biofuels, fertilizers, or construction materials—is gaining attention for its dual environmental and economic benefits [30,31].

Microbial-based strategies are emerging as effective approaches for controlling GHG emissions from MSW dumps. Methanotrophic bacteria are being utilized to oxidize methane in landfill cover soils, significantly reducing CH₄ emissions before they escape into the atmosphere [29]. Anaerobic digestion using specialized microbial consortia can process organic waste into biogas, offering both emissions reduction and renewable energy generation [3]. Additionally, microbial electrochemical technologies are under investigation for converting waste-derived organics into electricity while reducing GHGs [32]. These approaches integrate well with circular bioeconomy models by recovering energy and nutrients from waste while curbing emissions.

Limitations of microbial control strategies.

Alfonso [25] reported some limitations to microbial control of waste compounds that are biodegradable. This method is susceptible to rapid and complete degradation.

1. Specificity

Biological processes are highly specific. Important site factors mandatory for successful degradation include; the presence of metabolically capable microbial populations, suitable environmental growth conditions, and appropriate levels of nutrients and contaminants.

2. Scale up limitation

It is difficult to scale up bioremediation process from batch and pilot scale studies applicable to large scale field operations.

3. Technological advancement

More research is required to develop modern engineer bioremediation technologies that are suitable for sites with composite combinations of contaminants that are not equally distributed in the environment. It may be present as solids, liquids and gases forms.

4. Time taking process

Bioremediation takes longer time compare to other treatment options, such as excavation and removal of soil from contaminated site.

5. Regulatory uncertainty

We are not certain to say that remediation is 100% completed, as there is no accepted definition of clean. As such, performance evaluation of bioremediation is difficult, and there is no acceptable end point for bioremediation treatments [25].

Advantages of Microbial control of greenhouse gases from municipal solid waste.

Microbial interventions present a promising, low-cost strategy for reducing greenhouse gas emissions from municipal solid waste dumps. By harnessing the natural metabolic pathways of methanotrophs and anaerobic microbes, it is possible to significantly reduce methane and CO₂ outputs during and after waste decomposition [3, 29]. Integrating microbial systems into landfill design or retrofit projects can enhance environmental performance, especially when combined with energy recovery technologies. To fully realize these benefits, continued investment in research, monitoring, and scalable deployment is necessary.

Also, microbial control technologies contribute directly to sustainable waste management by lowering emissions, producing renewable energy, and enhancing nutrient recovery from organic waste [30]. These approaches support

circular economy goals by converting waste liabilities into environmental assets. Moreover, microbial systems are often adaptable, low-cost, and suitable for decentralized or low-resource settings—making them especially relevant for developing countries with unmanaged or open dumps [31]. However, success depends on proper operational conditions and integration with broader waste handling strategies.

Challenges and Prospects

Microbial solutions for GHG control in MSW dumps hold promise due to their low-cost, nature-based foundations and compatibility with existing waste management systems [30]. However, challenges include maintaining optimal conditions (e.g., moisture, pH, temperature) to support microbial activity, which can be inconsistent in real landfill environments [29]. Moreover, scaling microbial treatments to large or unmanaged dumpsites is technically complex and may require infrastructure upgrades. Regulatory gaps, limited field validation, and variability in microbial performance across sites pose further limitations to widespread adoption [31]. Microbes hold significant promise for mitigating greenhouse gas (GHG) emissions through various natural processes and biotechnological applications. Microorganisms play a vital role in the global fluxes of key biogenic GHGs like carbon dioxide, methane, and nitrous oxide. By understanding and manipulating these microbial processes, we can potentially reduce emissions and even sequester greenhouse gases. Below are some GHGs and microbial prospect in their mitigation

- **Carbon Dioxide (CO₂):**

Microbes are central to carbon cycling, both as producers and consumers of CO₂. Understanding and optimizing these processes can influence atmospheric CO₂ levels.

- **Methane (CH₄):**

Methanogens produce methane, while methanotrophs consume it. Microbial communities in various ecosystems, like wetlands and agricultural lands, can be managed to enhance methane oxidation and reduce emissions.

- **Nitrous Oxide (N₂O):**

Microbial nitrification and denitrification processes in soil and water release N₂O. Research focuses on manipulating these processes to reduce N₂O emissions, particularly in agricultural settings.

- **Bioremediation:**

Microbes can convert toxic pollutants into less harmful substances, including water, carbon dioxide, and other compounds.

- **Bioaugmentation:**

Introducing specific microbial strains to enhance the degradation of pollutants or GHGs in a particular environment.

Future Directions for Research and Development

Future research should focus on engineering microbial communities with enhanced methane oxidation and carbon sequestration capacities for landfill environments [3]. Development of bioaugmentation techniques—adding specific strains to boost microbial performance—could enhance consistency and scalability. Smart monitoring technologies (e.g., biosensors, AI-assisted gas tracking) are also needed to optimize microbial systems in real-time [32]. Additionally, long-term field trials and life cycle assessments are essential to evaluate the environmental and economic viability of microbial GHG control in diverse waste management contexts [30].

Recommendations to Policy Makers, Researchers, and Practitioners

1. Policy Makers should promote microbial technologies through funding, regulatory incentives, and inclusion into national climate programme and waste management policies.
2. Researchers must focus on strain development, bioaugmentation techniques, and field-scale testing across varied landfill conditions to close knowledge gaps.
3. Practitioners should integrate microbial controls into landfill operation protocols, train personnel on biological treatment methods, and adopt real-time monitoring systems for effectiveness and compliance.

Conclusion

This paper x-rayed the microbial control of greenhouse gases from municipal solid waste dumps and it focused on understanding the processes, advantages, challenges and mitigation measure of using microbes to control greenhouse gases. The research indicated dump sites as home to microbial populations which convert complex substrates to simpler compound and gases which contribute largely to greenhouse gases. The control of the activities of these microorganisms will serve as good way to control greenhouse gases emission

The findings revealed that modern sanitary waste management approach of leachate collection is ineffective for greenhouse gas emission control as they are also source of greenhouse gases and hence the need to research on more effective way of reducing greenhouse gases emission.

Bioaugmentation and biostimulation have proven to be effective in regulating microbial population to improve decomposition and reduce harmful emissions. More so, genetically engineered microbes, Biocover and biofilters can

be introduced to dump sites for efficient organic waste conversion from methane to carbon dioxide, a less potent greenhouse gas, by improving microbial habitat quality and enzyme activity, thereby accelerating decomposition and enhancing compost quality. This study, also showing anaerobic digestion using specialized microbial consortia as a sustainable and innovative method of converting solid organic waste into biogas, offers reduced emissions and renewable energy generation.

Authors' Contribution

All the authors contributed to this research paper ranging from the research work to the writing and proofreading of the manuscript.

Conflict of Interest

There is no conflict of interest on the part of the authors with regards to the publishing of this article.

Funding

This research was self-sponsored. There was no external funding.

REFERENCES

- Zhu, Z., Asnani, P. U., Chris, Z., Mani, S., & Anpolysky, S. (2008). Improving Municipal Solid Management in India: A Sourcebook for Policy Makers and Practitioners, World Bank Publications–Books, The World Bank Group Number 6916.
- Bogner, J. M., Abdelrafie, Ahmed, C., Diaz, A. Faaij, Q., & Hashimoto, S. (2007). Climate Change 2007: Mitigation Contribution of Work Group III. In the Fourth Assessment Report of The International Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Kumar, A. (2021). Microbial control of greenhouse gas emissions. *Journal of Environmental Science and Technology*, 18(2), 112-128.
- Onianwah, F. I. and Stanley, H. O. (2018). Odour Control in Fresh Water Fish Farm Using Living Cells of *Chlorella Vulgaris*. *Research and Review: Research Journal of Biology*. 6(3):6-12.
- Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P. & Monni, S., Faaij, A., Gao, Q., Zhang, T., Abdelrafie Ahmed, M., Sutamihardja, R. T. M., & Gregory, R. (2008). Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). *Waste Management & Research*. 26(1):11-32.
- Siddiqua, A., Hahladakis, J. N., & Al-Attiya W. A. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. *Environmental Science and Pollution Research*. 29:58514–58536.
- Zhang, C., Dong, H., Geng, Y., Liang, H., & Liu, X. (2022). Machine learning based prediction for China's municipal solid waste under the shared socioeconomic pathways. *J. Environ. Manag.* 312:114918
- Hadiqa, A. Areej, S. K. & Nayab, K. (2018). Methanotrophs: The Natural Way to Tackle Greenhouse Effect. *J Bioremediat Biodegrad.* 9(2):432.
- UNEP (2022). Emissions Gap Report. Pp 2021.
- Semrau JD, DiSpirito AA, Yoon S (2010) Methanotrophs and copper. *FEMS Microbiology Reviews*. 34: 496-531.
- Chiemchaisri, W., Chiemchaisri, C & Boonchaiyuttasak, J. (2013). Utilization of stabilized wastes for reducing methane emission from municipal solid waste disposal. *Bioresource and Technology*. 141: 199-204
- Liu, B., Han, B., Liang, X. and Liu Y. (2024). Hydrogen production from municipal solid waste: potential prediction and environmental impact analysis. *Int. J. Hydrog. Energy*. 52: 1445-1456.
- Onianwah, F. I. Stanley, H. O. Eze, V. C. Ifeanyi, V. O. & Ugboma, C. J. (2020a). Evaluation of Enzymes Production Activity of *Trichoderma*, *Aspergillus* and *Rhizopus* Species in Paraeorce (Herbicide) Degradation. *South Asian Journal of Research in Microbiology*;5(3): 1-7.
- Onianwah, F. I., Eze, V. C. & Ifeanyi, V. O. (2020b). Analysis of Enzymes and Metabolites of Paraeorce Degradation Using Living Yeast Cells and *Aspergillus Spinosus*. *Global Advance Research Journal of Agricultural Science*. 9(6): 128-137.
- Xiaoli, C., Ziyang, L., Shimaoka, T., Nakayama, H., Ying, Z., Xiaoyan, C., Kamiya, T., Ishizaki, T., & Zhao, Y. (2010). Characteristics of environmental factors and their effect on CH₄ and CO₂ emission from a closed landfill. *Waste Management*, 30: 446 – 451

16. Rani, V., Usha, V., Lakshmi, D., Kumari, R., Reddy, G. & Meena, A. (2022) Households' Waste Disposal Practices and Its Impact on Health. *International Journal of Environment and Climate Change*. DOI: 10.9734/ijecc/2022/v12i121461
17. Onianwah, F. I. (2018). Role of Microorganisms in Bioconversion of Solid Wastes and Economic Development. *Scholar J. Food and Drug Research*. Vol 1: 1-6.
18. Chen, L., Wang, H., & Zhao, Y. (2024). Methane oxidation in compost-based biofilters for landfill emission control. *Waste Management*, 172, 105342.
19. Kumari, S., Kayasth, M., Gangrade, T., & Parshad, J. (2024). Role of Microorganisms in Composting and Factors affecting the Process. *Vigyan Varta*5(6): 202 – 205.
20. Aliaa, J. I., Ali Abdul., H. M. N., Ali Mustafa H., & Milad M. Z. (2024). The Role of Microorganisms in the Disposal of Biological Waste. 1st Ed. AkiNik Publications. pp 1-7.
21. Li, X., Zhou, Y., & Chen, G. (2021). Effects of microbial additives on composting performance of food waste. *Environmental Technology and Innovation*, 24, 101785.
22. Huang, T., Zhang, Y., & Lin, M. (2023). Enhancing composting with microbial inoculants and biochar: A review. *Bioresource Technology*, 370, 128671.
23. Singh, R., Kumar, N., & Das, S. (2023). Microbial management in solid waste: Innovations and challenges. *Environmental Science and Pollution Research*, 30(11), 12345–12360.
24. Höhener P, and Ponsin V. (2014). In situ vadose zone bioremediation. *Current Opinion in Biotechnology*. 27:1-7. DOI: 10.1016/j.copbio.2013.08.018.
25. Alfonso., M., Saldarriaga-Noreña, H., & Saeid, A. (Eds). (2021). Trace Metals in the Environment –*New Approaches and Recent Advances*. Intech Open. doi: 10.5772/intechopen.83504.
26. Wang, Q., Liu, H., & Wang, Z. (2024). Synthetic biology approaches for microbial waste degradation. *Biotechnology Advances*, 68, 108238.
27. Huber Humer M. and Lechner P. (2008): Impact of Different Biocover Designs on Methane Mitigation. In: Pawlowska M., Pawlowski L. (Eds.): Management of Pollutant Emission from Landfills a Sludge. Selected Papers from the international workshop on Management of Pollutant Emission from Landfills and Sludge, Kazimierz Dolny, Polen, Taylor and Francis Group, London, UK; ISBN13: 978-0- 415-43337-2 (hbk), 978-0-203-93218-6 (ebook); pp. 21-36.
28. Zhou, J., Li, Y., & Zhang, D. (2022). Performance of biocover systems in methane mitigation at landfills: A meta-analysis. *Science of the Total Environment*, 820, 153233.
29. Scheutz, C., Kjeldsen, P., Bogner, J. E., De Visscher, A., Gebert, J. & Hilger, H. A., (2009a). Microbial Methane Oxidation Processes and Technologies for Mitigation of Landfill Gas Emissions. *Waste Manag. Res.* 27, 409–455.
30. Rahman, M. A., Lee, J., & Kwon, E. E. (2022). Waste-to-energy systems for sustainable waste management. *Renewable and Sustainable Energy Reviews*, 153, 111764.
31. Gupta, R., Sharma, M., & Patel, R. (2023). Circular bioeconomy strategies for reducing GHG emissions from organic waste. *Journal of Environmental Management*, 332, 117392.
32. Li, G., Liu, J., & Giordano A. (2022). Robust optimization of construction waste disposal facility location considering uncertain factors. *J. Clean. Prod.* 353.