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Ammonia and Greenhouse Gas Emissions from Organic Manure Composting: The Effect of Membrane Cover

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Abstract

The use of membrane covers in organic manure composting shows potential in mitigating greenhouse gas emissions and reducing ammonia volatilization. This study evaluates the efficiency of membrane covers, ProfiCover® and a market leading expanded polytetrafluoroethylene (ePTFE) membrane cover in reducing ammonia and greenhouse gas emissions during the thermophilic phase of organic manure composting at an industrial-scale composting facility. Gas measurements were collected from inside and outside of covered and uncovered compost piles during thermophilic phase on 5th day of composting. Statistical analyses including Shapiro-Wilk normality test, Mann-Whitney U test, Levene's homogeneity test, independent sample t-tests and emission reduction percentages were utilized to compare emissions between covered and uncovered piles. Both the membrane covers significantly reduced ammonia and GHG emissions compared to the uncovered pile based on the median values and statistical tests. The ePTFE membrane cover significantly reduced gaseous emissions: 90.84% for Ammonia, 59.63% for Carbon Dioxide, 23.08% for Nitrous Oxide and 44.80% for Propane equivalent. In contrast, ProfiCover® achieved greater reductions: 93.25% for Ammonia, 85.92% for Carbon Dioxide, 55.63% for Methane, 56.67% for Nitrous Oxide, and 84.47% for Propane equivalent. A comparative analysis was also conducted to investigate the efficacy of emission reduction by the membrane covers inside the compost piles. The results of the comparative analysis highlighted the reduction of emissions inside the covered piles which resulted in reducing nitrogen losses and suggest better nitrogen retention in the compost with the use of the membrane covers. The results indicate that membrane covers can be an effective strategy to reduce ammonia and greenhouse gas emissions during industrial-scale organic manure composting. Further research is needed to optimize materials and integration with other emission control methods for a comprehensive solution.

Keywords: Composting, Membrane covers, GHG emissions, Ammonia, Organic Manure

1. Introduction

Organic manure composting is a common practice in agriculture for managing livestock waste and producing nutrient-rich soil amendments. However, this process can lead to the emission of greenhouse gases (GHGs) such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), which contribute to climate change (Hao et al., 2001). Additionally, the release of ammonia (NH3) during composting can have negative impacts on air quality and human health (Pagans et al., 2006).

Mitigating NH3 and GHG emissions from composting is crucial for environmental sustainability. To address these environmental concerns, researchers have explored various strategies to reduce GHG emissions and ammonia volatilization during composting. One approach that has shown promise in reducing these emissions is the use of membrane covers. Membrane covers act as impermeable barriers placed over composting piles, minimizing gas exchange between the composting material and the atmosphere (Mosier et al., 2006). The use of membrane covers, which are impermeable barriers placed over the composting piles to minimize gas exchange between the composting material and the atmosphere (Hao et al., 2001). Studies have shown that membrane covers can effectively reduce GHG emissions during composting. Smith et al. (2015) conducted a field experiment comparing compost piles with and without membrane covers and found that the use of membrane covers significantly reduced GHG emissions by creating a more anaerobic environment, inhibiting the activity of methane-producing microorganisms (Hao et al., 2001).

The use of membrane covers in composting has several potential benefits. Firstly, they can create a more anaerobic environment, which inhibits the activity of methane-producing microorganisms and reduces CH4 emissions. Secondly, membrane covers can limit the volatilization of NH3 (Hou et al., 2014). Wang et al., 2013 conducted a laboratory study on pig manure composting and found that the use of a membrane covers significantly reduced ammonia volatilization compared to uncovered compost piles. This reduction in ammonia emissions is important for improving air quality and human health, as high levels of atmospheric ammonia can contribute to the formation of particulate matter and smog (Pagans et al., 2006). Additionally, membrane covers may help to retain moisture in the composting piles, promoting optimal microbial activity and nutrient retention (Cardoso et al., 2023).

While the use of membrane covers in composting shows promise, further research is needed to fully understand their effectiveness and optimize their implementation (Makhloufi et al., 2014). Factors such as the type of membrane material, design, and management practices need to be considered to maximize their benefits (Makhloufi et al., 2014). Additionally, the long-term effects of membrane covers on compost quality, nutrient cycling, and overall sustainability need to be evaluated (Lin et al., 2023).

This thesis aims to contribute to the existing knowledge by investigating the effect of membrane covers on ammonia and GHG emissions during organic manure composting and providing recommendations for their practical implementation in agricultural systems.

The existing literature highlights a significant knowledge gap concerning the effectiveness of membrane covers in mitigating ammonia and greenhouse gas emissions during the composting process of organic manure, particularly at industrial-scale facilities. The predominant focus has been on pilot-scale studies with a lack of comprehensive research at an industrial scale, exploring different types of composting materials and varied composting conditions. This gap potentially hinders the optimization of membrane cover technologies for larger-scale applications, necessary for significantly reducing emissions and improving air quality and environmental sustainability in agricultural waste management.

1.1 Objectives of the Study

The primary aim of this investigation is to evaluate the emissions of Ammonia, greenhouse gases and VOC emissions during the composting process of organic manure. Specifically, the study centers on the application of the ProfiCover® and a market leading ePTFE membrane cover (Cover 2), evaluating thier efficiency in mitigating the emissions during the thermophilic phase of composting. This phase is characterized by a temperature range between 69.8°C to 75.9°C, typically occurring around 5th day of the composting process.

The study aims to:

1. Understand the effectiveness of membrane cover in reducing gas emissions.
2. Evaluate the difference in emissions between covered and uncovered compost piles.
3. Explore the influence of membrane cover on gas emissions inside the compost pile and nitrogen retention.

1.2 Research Questions/Hypotheses

1. How effective is the membrane cover in reducing gas emissions during the composting process?
2. What is the difference in emissions between compost piles covered with membrane covers and those that are uncovered?
3. How does the membrane cover influence the emissions within the compost pile, and how does it affect nitrogen retention?

This study endeavors to fill the identified research gaps by providing a thorough understanding of the impact of membrane covers on gas emissions during composting at an industrial scale. The insights gleaned from this research could contribute to the development of effective strategies for emissions reduction, thereby aiding in the mitigation of the environmental impact of organic manure composting. Moreover, the findings could provide valuable recommendations for the practical implementation of membrane cover technology in agricultural waste management systems, promoting environmental sustainability.

The investigation is confined to the evaluation of the membrane cover and its impact on gas emissions, compared to uncovered compost piles. Limitations of this include the specificity of the composting unit design and the singular focus on the thermophilic phase of composting.

2. Literature Review

2.1 Composting: An Overview

Composting is a bio-oxidative process that involves the controlled decomposition of organic materials into compost, a humus-like substance (Hoitink, 1998). This process is facilitated by microorganisms such as bacteria, actinomycetes, fungi, nematodes, and earthworms (Rastogi et al., 2020). Organic manure composting is a sustainable method of waste management and soil enrichment. It involves the decomposition of organic materials such as agricultural by-products, manures, liquid manures, straw, and plant residues (Ujj et al., 2021). Composting is a natural process that breaks down organic matter into nutrient-rich humus, which can be used as a fertilizer to improve soil fertility and structure. The composting process involves the activity of microorganisms that break down organic matter, releasing nutrients and creating a stable and beneficial end product (Kovács et al., 2017).

Microorganisms play different roles at different stages of composting. Initially, mesophilic bacteria break down easily degradable compounds, while thermophilic bacteria and actinomycetes degrade tougher materials like cellulose and lignin. Fungi also contribute to the breakdown of complex materials. The activity of microorganisms in composting is influenced by physical parameters such as temperature, pH, and moisture content. Mesophilic microorganisms thrive at temperatures between 20°C and 45°C, while thermophilic microorganisms prefer temperatures above 45°C. The pH level affects nutrient solubility and microbial activity, with a near-neutral pH being optimal for most compost microorganisms. Moisture is essential for microbial mobility and metabolism, with an optimal moisture content ranging from 50% to 60% (Rastogi et al., 2020).

Several factors affect the composting process. The carbon-to-nitrogen (C/N) ratio is crucial for efficient decomposition and odor control, with a balanced ratio of around 25-30:1 being ideal. Adequate moisture is necessary for microbial metabolism, but excessive moisture can impede aeration. Aeration is vital to supply oxygen to aerobic microorganisms and regulate temperature. Particle size and the presence of bulking agents like straw or wood chips also impact composting, as smaller particles increase microbial activity but may impede aeration, while bulking agents maintain porosity and facilitate optimal microbial activity (Ryckeboer et al., 2003).

Composting has numerous benefits, including diverting organic waste from landfills, reducing methane emissions and leachate production, and returning vital nutrients to the soil. The resultant humus from composting enhances soil structure, provides essential nutrients, and improves water retention, creating a favorable environment for plant growth (Hoitink, 1998). Composting also plays a role in waste management, as it can effectively decompose degradable organic waste under moist, self-heating, and aerobic conditions (Palaniveloo et al., 2020). Additionally, composting has been shown to have positive effects on soil aggregation, erosion control, and revegetation (Wortmann & Shapiro, 2007; Sultana et al., 2020).

The use of organic manure compost also has several benefits for soil health and plant growth. It improves soil structure by increasing water holding capacity and carbon content (Gulyás et al., 2022). Compost also enhances nutrient availability and promotes the growth of beneficial microorganisms in the soil (Ujj et al., 2021). In addition to that compost application can help in maintaining or increasing organic carbon content in agricultural practices, which is a significant challenge (Holes et al., 2014).

Organic manure composting can contribute to the circular economy by recycling bio-waste. It provides a sustainable solution for managing agricultural by-products and other organic waste materials (Ujj et al., 2021). By diverting these waste materials from landfills and converting them into valuable compost, organic manure composting helps to reduce environmental pollution and greenhouse gas emissions (Uveges et al., 2020).

2.2 ASP (Aerated Static Pile) Composting

ASP (Aerated Static Pile) composting is a method used for the decomposition of organic waste materials. It involves the creation of compost piles that are aerated using passive or forced aeration systems (Ogunwande, 2010; Sylla et al., 2006). The piles are typically formed using a mixture of organic waste materials such as food scraps, yard waste, and manure (Iñiguez-Covarrubias et al., 2018). The aeration process helps to maintain optimal conditions for microbial activity, which is essential for the breakdown of organic matter (Zheng et al., 2018).

A study by Abdoli et al., 2017, compared ASP composting with vermicomposting and found that both methods were effective in producing high-quality compost from rural organic wastes and cow manure. Another study evaluated the use of a V-shaped pipe for passive aeration composting and found that it effectively distributed air uniformly within the composting pile.

The effectiveness of the aeration pipes was measured by their ability to distribute air uniformly within the composting pile (Ogunwande, 2010).

ASP composting has been shown to be a viable alternative to mechanically mixed windrow composting, as it helps to eliminate fly problems and reduce odor nuisance complaints (Iñiguez-Covarrubias et al., 2018). The method involves the creation of static piles that are aerated using passive or forced aeration systems (Iñiguez-Covarrubias et al., 2018). The piles are carefully monitored for temperature, moisture, and oxygen levels to ensure optimal conditions for microbial activity (Miguel et al., 2022). The composting process can be further enhanced by turning the piles and providing additional aeration (Stegenta-Dąbrowska et al., 2019; Oliveira et al., 2022).

The quality of the compost produced through ASP composting can be assessed using various parameters such as temperature, moisture, pH, total organic carbon, and different forms of nitrogen (Qian et al., 2014). These parameters can help determine the maturity of the compost and its suitability for use as a fertilizer (Qian et al., 2014). It is important to monitor the composting process to ensure that the temperature does not exceed the threshold at which microbial activity is inhibited (Miguel et al., 2022). However, it is important to monitor the composting process to ensure optimal conditions for microbial activity and to minimize the risk of pathogen survival and bioaerosol exposure. (Pereira-Neto et al., 1986).

2.3 Environmental Challenges: NH_3 and GHG Emissions

Ammonia (NH_3) and greenhouse gas (GHG) emissions are significant environmental challenges that have detrimental effects on air quality, climate change, and ecosystem health. NH_3 is primarily emitted from agricultural activities, such as livestock production and fertilizer application, while GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are released from various sources, including agriculture, energy production, and transportation.

NH_3 emissions originate from agricultural activities, particularly livestock production and fertilizer application (Behera et al., 2013). Livestock farming contributes to NH_3 emissions through animal waste and manure management (Gerber et al., 2013). Fertilizer application in agriculture also releases NH_3 into the atmosphere (Riddick et al., 2016). NH_3 emissions have significant environmental implications, including soil acidification, eutrophication of water bodies, and formation of fine particulate matter (PM2.5) and secondary aerosols. NH_3

deposition can lead to nitrogen pollution in terrestrial and aquatic ecosystems, affecting biodiversity and ecosystem functioning (Behera et al., 2013).

GHGs, including CO_2, CH_4, and N_2O, contribute to global warming and climate change. CO_2 is primarily emitted from fossil fuel combustion, deforestation, and land-use changes (Bellarby et al., 2012). CH_4 is released from various sources, including livestock enteric fermentation, rice cultivation, and anaerobic decomposition of organic waste. N_2O emissions mainly result from agricultural activities, such as nitrogen fertilizer use and manure management (Gerber et al., 2013). GHGs trap heat in the atmosphere, leading to the greenhouse effect and global warming, which have far-reaching consequences, including rising temperatures, sea-level rise, and extreme weather events (Bellarby et al., 2012).

Addressing NH_3 and GHG emissions requires the implementation of effective mitigation strategies. For NH_3 emissions, improving agricultural management practices, such as optimizing fertilizer application and enhancing manure management, can significantly reduce NH_3 release (Liu et al., 2019). Additionally, the use of feed additives and dietary modifications for livestock can help mitigate NH_3 emissions (Gerber et al., 2013). GHG emissions can be reduced through various approaches, including energy efficiency improvements, renewable energy adoption, and carbon capture and storage technologies (Ramaswami et al., 2011). In the agricultural sector, practices such as precision farming, agroforestry, and sustainable manure management can contribute to GHG mitigation (Llonch et al., 2017).

2.4 NH_3 and GHGs Emissions from Organic Manure Composting

Composting of organic manure can result in the emission of greenhouse gases (GHGs) and ammonia (NH_3), which can have negative environmental impacts. Several studies have investigated the emission profiles of NH_3 and GHGs during organic manure composting and have identified factors that influence these emissions.

A study by Hao et al. (2001) focused on GHG emissions during cattle feedlot manure composting. The study found that the emission of GHGs, such as carbon dioxide (CO_2) and nitrous oxide (N_2O), during composting reduces the agronomic value of the final compost and contributes to the greenhouse effect. Another study by Hao et al. (2004) investigated the carbon and nitrogen balances and GHG emissions during cattle feedlot manure composting. The study highlighted that GHG emissions, including CO_2, N_2O, and methane (CH_4), occur during composting, and the emissions can be influenced by factors such as bedding materials.

Impraim et al. (2020) compared the emissions of NH_3 and GHGs between lignite-amended and unamended cattle manure during forced aeration composting. The study found that lignite amendment improved the quality of the compost and mitigated the emissions of NH_3 and GHGs. Similarly, a study by Hao et al. (2005) investigated the effect of phosphogypsum on GHG emissions during cattle manure composting. The study revealed that various GHGs are emitted during composting, and factors such as C and N content in manure, aeration, and amendment additions can influence these emissions. Xu et al. (2007) studied the GHG emissions during co-composting of cattle mortalities with manure. The study observed significantly higher CO_2 and CH_4 emissions during the co-composting of cattle mortalities compared to manure composted with straw. Pertiwiningrum (2020) reported that the decomposition and stabilization of cattle manure by biogas and compost technology can also result in GHG emissions. Wang et al. (2013) investigated the effects of biochar on manure composting and found evidence supporting the relationship between N_2O emission and denitrifying community. Li et al. (2016) studied the emissions of N_2O and CO_2 from soils amended with compost and manure from cattle fed diets containing wheat dried distillers' grains with solubles. The study found that organic amendments significantly increased N_2O and CO_2 emissions compared to the control, with manure resulting in higher CO_2 emissions than compost.

Several studies have also explored the microbial processes and nitrogen cycle during manure composting. Maeda et al. (2011) investigated the microbiology of the nitrogen cycle in animal manure compost and detected various bacteria involved in nitrification and denitrification processes. Wang et al. (2015) studied the spatial nitrification of microbial processes during composting of swine, cow, and chicken manure.

Composting is an effective method for reducing greenhouse gas emissions compared to landfilling. Studies have shown that composting emissions can be 38-84% lower than equivalent landfilling fluxes. For example, in California, composting has the potential to save 1.4 million metric tons of CO2e by the year 2025 (Pérez et al., 2023). Compost application is also beneficial for mitigating greenhouse gas emissions from agricultural soils. It has been found that increasing compost application rates can lead to a reduction in greenhouse gas emissions, including N2O and CO2, in vineyards (Wong et al., 2023). Additionally, agricultural soil and manure contribute a significant portion of global greenhouse gas emissions, with 10-14% of total emissions coming from this source (Shakoor et al., 2021).

Furthermore, composting can also help to reduce air pollutant emissions. A study on composting emissions found that the emission factors for volatile organic compounds (VOCs) during digestate composting are lower compared to non-digestate composting, suggesting that anaerobic digestion may reduce VOC emissions from composting (Nordahl et al., 2023).

2.5 VOC Emissions from Organic Manure Composting

Organic manure composting is a widely used method for recycling organic waste and producing nutrient-rich compost for agricultural purposes. However, during the composting process, volatile organic compounds (VOCs) can be released into the atmosphere, contributing to air pollution and potential health risks. Several studies have identified the major contributors to VOC emissions during composting. Staley et al. (2006) found that organic chemicals, fatty acids, and volatile air pollutants are significant sources of VOC emissions during the decomposition of municipal solid waste components. Similarly, Pagans et al. (2006) observed that VOC emissions during composting of the organic fraction of municipal solid waste decreased along the thermophilic range of temperatures. Zhang et al. (2019) also found that livestock waste and composting emissions are significant sources of VOCs.

Various factors can influence VOC emissions during organic manure composting. Airflow velocity, ammonia, nitrous oxide, methane, and VOC concentrations on the surface of the composting pile or bin can affect gas outlet emission rates (Colón et al., 2012). The use of biochar as an amendment in manure composting has been shown to reduce nitrite availability and mitigate N2O emissions (Wang et al., 2013). Additionally, the type of waste being composted can impact VOC emissions. For example, Maulini-Duran et al. (2013) found that different types of waste, such as yard waste and food waste, emit different VOCs at different stages of the composting process.

To mitigate VOC emissions from organic manure composting, several strategies can be employed. Biofiltration has been shown to effectively reduce VOC emissions from composting (Pagans et al., 2006). Nordahl et al. (2023) observed a decrease in VOC emissions from composting post-anaerobically digested sludge relative to untreated sludge. Additionally, proper aeration during composting can help reduce the emission of sulfur compounds and incomplete degradation byproducts (Colón et al., 2009). The use of advanced aeration strategies has also been investigated to minimize VOC emissions during composting (Maulini-Duran et al., 2013).

2.6 Commonly Used Emission Mitigation Techniques in Literature

Mitigation techniques for reducing NH3 and GHG emissions from manure composting can be implemented through various strategies. Zhang (2021) suggests adjusting the initial substrate properties, controlling the composting process conditions, and applying additives to mitigate carbon (C) and nitrogen (N) losses during pig manure composting. Studies by Hou et al., 2014 and Bai et al., 2020 highlights the importance of composting methods and the initial total carbon (TC) and total nitrogen (TN) content in mediating gaseous emissions, with turning compost resulting in larger losses compared to other methods These studies also emphasize the effectiveness of strategies such as lowering dietary crude protein content, acidification, and proper manure application techniques in reducing NH3 and GHG emissions throughout the manure management chain. Studies from Borgonovo et al., 2019 and Maurer et al., 2017 focus specifically on ammonia (NH3) mitigation in swine manure treatment, suggesting strategies such as the use of biochar and other bio-based products.

Gerber et al. (2013) reviewed potential technical options for mitigating direct methane and nitrous oxide emissions from livestock, highlighting the importance of understanding potential pollution swapping when reducing one GHG or emission source. Pardo et al., 2014 suggest that adjusting the structure of compost through bulking agents addition/substitution and monitoring key process parameters can reduce GHG emissions and improve control over nitrogen losses. The use of biochar co-compost was investigated to improve nitrogen retention and reduce carbon emissions in a winter wheat cropping system (Gao et al., 2023) Hwang et al., 2020 studied the effect of different additives on composting process and gas emissions during food waste composting, highlighting the importance of additives in reducing NH3 volatilization and N2O emissions. Sayara & Sánchez (2021) discussed various mitigation technologies to reduce gaseous emissions from composting. They highlighted the use of biochar as a novel mitigation technology. Biochar can be incorporated into the composting process and help absorb and retain gases, thereby reducing emissions. This demonstrates that the use of specific materials, such as membranes or biochar, can effectively mitigate gaseous emissions during composting.

2.7 Covers in Composting: Types, Mechanisms, and Previous Applications

Membrane cover types used in composting include semipermeable membranes, functional membranes, molecular membranes, and physical coverings. These covers are used to improve the composting process, control gas emissions, enhance microbial community succession, and prevent the diffusion of dust, aerosols, and microorganisms. Functional membranes have been found to reduce gas emissions and influence bacterial community dynamics during aerobic composting. These membranes play a role in controlling gas emissions and improving the efficiency of the composting process (Ma et al., 2021). Molecular membranes have been used to cover biogas residue composting, reducing odor emissions, and influencing microbial community succession. These membranes help to control odor emissions and maintain a stable microbial community during composting (Li et al., 2020). Physical coverings, such as insulated pool tarps or permeable polypropylene coverings, have been shown to achieve high temperatures during composting, effectively inactivating pathogens (Shepherd et al., 2011). These coverings provide insulation and prevent heat dissipation, improving temperature distribution within the compost pile (Patel et al., 2015).

The field of composting system covers has continued to evolve with ongoing research, material innovations, and technological advancements. Researchers have investigated the use of semi-permeable membranes to cover composting systems, which can affect greenhouse gas and ammonia emissions (Sun et al., 2018). Additionally, studies have examined the effects of combined membrane-covered systems on compost quality, emissions of nitrogen-containing gases, and the efficiency of fermentation (Cao et al., 2022; Li et al., 2022; Sun et al., 2022). The use of winter cover crops as covers for composting has also been explored, with potential benefits for soil carbon sequestration and nitrogen availability (White et al., 2020; White et al., 2022).

2.7.1 Impermeable covers

In the decade from 2002 to 2012, Engineered Compost Systems (ECS) developed and implemented large Covered Aerated Static Pile (CASP) systems with impermeable fabric covers. These covers were made from a durable, UV-stabilized fabric similar to heavy-duty truck tarps and had strategically placed aeration orifices to facilitate controlled air movement through the compost pile. The covers were designed to create a negative pressure environment beneath them, effectively containing odors and particulates within the system and minimizing fugitive emissions. This approach ensured compliance with environmental regulations and reduced the environmental impact of the composting process (Bunch et al., 2008).

However, the impermeable fabric covers presented challenges, such as a lack of insulation and operational difficulties in large-scale operations. To address these challenges, other companies explored alternative cover solutions, such as adapting polyethylene silage bags for composting. These alternative covers provided different methodologies for managing composting materials and processes (Bunch et al., 2008).

The development of composting system covers has been driven by the need to optimize functionality, comply with environmental regulations, and ensure operational feasibility. Ongoing research and technological advancements continue to contribute to the improvement of composting system covers, with the aim of achieving efficient and sustainable composting processes.

2.7.2 Fleece / macro-porous covers

Fleece covers, also known as macro-porous covers, are made of a non-woven polyester fabric that is approximately 1/16" thick. These covers have the unique ability to shed rainfall through capillary action, thanks to the intrinsic properties of the fabric. Fleece covers are commonly used to envelop passively aerated piles or turned windows, especially during inclement weather, to regulate moisture content in compost piles. Unlike semipermeable membrane covers, fleece covers are not typically used for odor or VOC control, but they do have a scrubbing effect due to the moisture present within and beneath the fleece (Boldrin et al., 2009).

Tarp-like fabrics with engineered aeration holes can also be used as an alternative to fleece covers. These fabrics have customizable aeration holes that can measure up to 1/16" in diameter, allowing for sufficient airflow while keeping rainwater at bay. Macro-porous covers are compatible with both negative and positive aeration systems, providing flexibility in their application. One advantage of macro-porous covers is their ease of airflow, with a pressure drop of only 0.5" W.C., compared to 2-3" W.C. for semipermeable membrane covers at typical aeration rates. However, it is important to note that the pressure drop differences become more pronounced at peak aeration rates.

Despite their advantages, macro-porous covers have experienced a decline in popularity due to performance challenges such as ripping and efficacy issues. Composting facilities have been exploring alternative covering options as a result.

2.7.3 Biolayer covers

Biolayer covers are a valuable component of composting systems as they serve a dual purpose of acting as an insulation layer for pathogen destruction and a surface biofilter. These covers are typically composed of stable and pathogen-free organic materials such as post-Process to Further Reduce Pathogens (PFRP) compost, unscreened compost, or screened overs. The minimum depth of a biolayer cover should be 6 inches, although in extremely cold climates or as per regulatory requirements, a depth of 12 inches may be mandated (Palaniveloo et al., 2020).

The effectiveness of biolayer covers in reducing volatile organic compounds (VOCs) and odor emissions is influenced by surface temperature and moisture. Surface irrigation can be employed to manage the temperature of the biolayer cover, which significantly mitigates VOC and odor emissions. This approach is cost-effective and operationally efficient, as the biolayer material is typically sourced or produced on-site in commercial composting facilities, incurring no additional costs. Additionally, the biolayer cover can be integrated into the compost at the end of primary composting, eliminating the need for cover removal and associated operational costs (Palaniveloo et al., 2020).

It is important to note that biolayer covers are not required for secondary composting or any stage that has already met PFRP criteria. In terms of airflow, biolayer covers do not present a noticeable restriction compared to fabric covers, thus not increasing fan power requirements. This makes biolayer covers a viable and cost-effective alternative in certain composting scenarios (Palaniveloo et al., 2020).

The strategic management of biolayer covers is crucial for optimizing their functionality and efficacy in commercial composting operations. By ensuring the appropriate depth, managing surface temperature and moisture, and integrating the biolayer cover into the composting process, composting facilities can effectively reduce pathogen risks and mitigate VOC and odor emissions.

2.8 Semipermeable Membrane Covers

Semipermeable membrane covers, constructed with an expanded polytetrafluoroethylene (ePTFE) membrane, are widely used in composting applications due to their ability to allow air movement while maintaining a waterproof barrier. These covers have a micro-porous nature, with pore sizes ranging from 0.02 to 40 microns, which effectively blocks rainwater from permeating the compost pile. The selective passage of air and gases through the micro-porous membrane allows for aeration in the compost pile. However, the impermeability of the fabric limits the airflow, resulting in low Cubic Feet per Minute per Cubic Yard (CFM/CY) of material (Tian et al., 2015).

One advantage of semipermeable membrane covers is their ability to trap moisture and odors within the compost pile. While water vapor can pass through the membrane, the majority of moisture condenses on the cooler underside of the fabric cover. This moisture layer inadvertently traps some odors, providing a scrubbing effect as volatile organic compounds are absorbed into the liquid film. However, this moisture can also lead to excess condensation, which gravitates toward the ground (Tian et al., 2015).

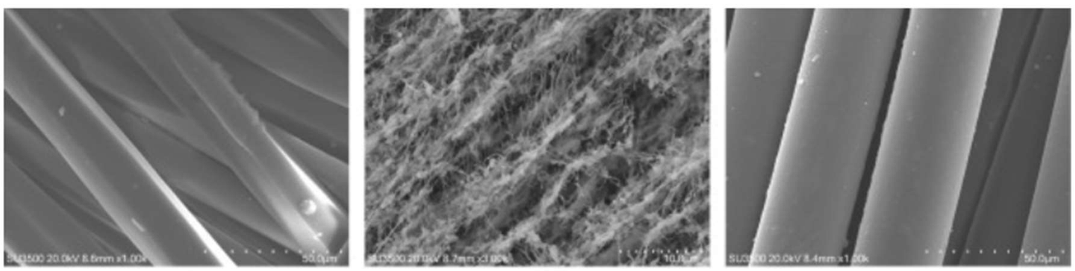
Semipermeable membrane covers are effective in meeting pathogen reduction requirements but offer minimal insulation, potentially allowing pathogens to linger on the surface. Additionally, these covers are more expensive compared to alternative cover types due to the production costs of the fabric and the need for semi-frequent replacement.

These membranes improve the humification process and bacterial community succession during composting (Song et al., 2022). They allow for the outward diffusion of micro molecules while preventing the diffusion of dust, aerosols, and microorganisms (Li et al., 2022). Semipermeable membrane covers have been extensively studied and applied in composting systems to mitigate greenhouse gas and ammonia emissions (Sun et al., 2018). Research conducted by Sun et al. (2018) investigated the impact of a semipermeable membrane-covered composting system on greenhouse gas and ammonia emissions in the Tibetan Plateau. The study found that the membrane covers significantly reduced emissions of greenhouse gases and ammonia compared to uncovered composting systems.

Another study by Chen et al. (2021) examined the effects of a semipermeable membrane covering coupled with intermittent aeration on gas emissions during aerobic composting of dairy manure. The results demonstrated that the membrane cover effectively reduced gas emissions, including ammonia and nitrous oxide, during the composting process. Additionally, Soto-Herranz et al. (2021) conducted a study on the application of an ePTFE semipermeable membrane cover system in a farm-scale composting process. The research showed a 65% reduction in ammonia emissions with the use of the membrane cover.

The use of semipermeable membrane covers in composting systems also affects the physicochemical properties of the composting materials and the activities and community composition of microbes involved in the composting process (Song et al., 2022). This suggests that the membrane cover can influence the overall composting process and the quality of the final compost product. Furthermore, studies have demonstrated that combining semipermeable membrane-covered composting systems with greenhouses can enhance fermentation efficiency and improve the characteristics of the fermentation feedstock (Li et al., 2022).

The use of semipermeable membrane covers in composting systems has been proven effective in reducing emissions of greenhouse gases and ammonia. These membrane covers can alter the physicochemical properties of the composting materials and influence the activities of microbial communities involved in the composting process. The combination of membrane covers with other technologies, such as intermittent aeration and greenhouse systems, can further enhance the efficiency and effectiveness of composting processes.



(a) (b) (c)

Figure 1(a-c): Scanning electron microscope images of the membrane: (a) inner layer (×1.00 k); (b) middle layer (×3.00 k); (c) outer layer (×1.00 k). (Fang et., al 2021)

2.9 Mechanism of Semi-Permeable Membrane Covers in Reducing NH3 and GHG Emissions

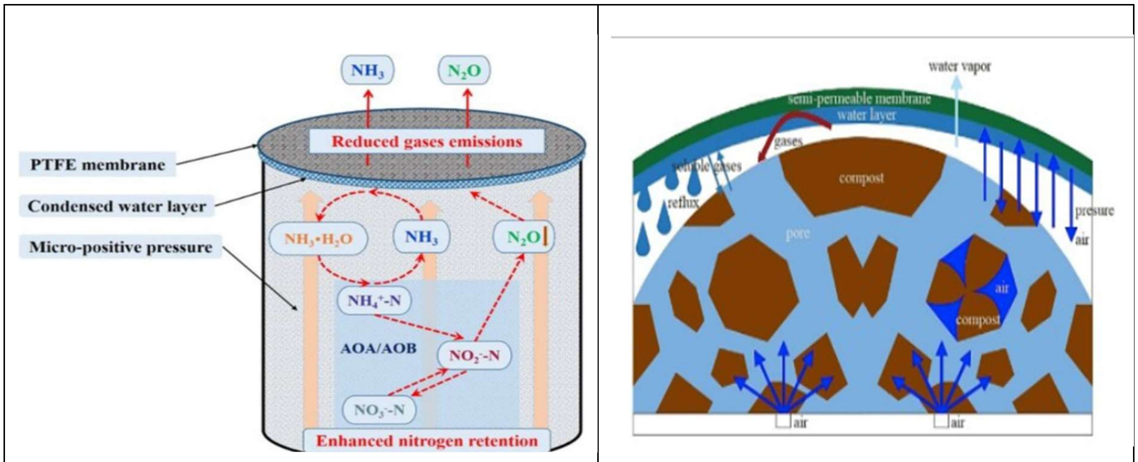
The use of semi-permeable membrane covers in composting systems and other related processes has garnered significant attention due to its efficacy in reducing ammonia (NH3) and greenhouse gas (GHG) emissions. The underlying mechanisms that contribute to this reduction are multifaceted and have been the subject of extensive research.

Foremost, the semi-permeable membrane cover establishes a controlled environment within the composting system. This controlled environment can enhance the spatial homogeneity and efficiency of fermentation, as studied by Sun et al. (2022). Such an environment aids in maintaining optimal conditions for microbial activity, which in turn can optimize the decomposition of organic matter. The optimized decomposition process can thereby curtail the production of GHGs, a phenomenon supported by the findings of Sun et al. (2018).

Concurrently, the membrane's intrinsic property of low permeability to NH3 serves as a pivotal factor in mitigating NH3 emissions. Acting as a barrier, the membrane obstructs the egress of NH3 into the atmosphere. Given that the decomposition of organic matter in composting systems can be a significant source of NH3 emissions, the ability of the membrane to inhibit its escape proves crucial. Notably, NH3 is recognized not only as a potent greenhouse gas but also as a salient contributor to air pollution, as indicated by Song et al. (2022). Furthermore, this membrane technology offers an avenue for NH3 recovery. The captured NH3, prevented from escaping, can be repurposed as a valuable nitrogen source for agricultural applications. This dual benefit of reducing NH3 emissions while facilitating its reuse underscores the membrane's potential for sustainable nutrient management.

Beyond GHG and NH3 mitigation, the membrane covers render other beneficial effects on the composting process. Studies, such as those by Song et al. (2022), had found that the use of such covers can increase nitrogen preservation rates and concurrently diminish emissions of other gases like H2S. This amplification can culminate in compost of superior quality, characterized by enriched nutrient content. Complementing these mechanisms is the membrane's role in mitigating the release of co-emitted air pollutants, including volatile organic compounds (VOCs) and particulate matter (PM). Both VOCs and PM are recognized as detrimental to air quality and pose potential health risks, as elucidated by West et al. (2013). The membrane, by obstructing the release of VOCs and PMs can significantly contribute to refining air quality.

The semi-permeable membrane also acts as a deterrent to external contaminants, reducing the ingress of potential pathogens and other detrimental microorganisms into the composting system. This safeguard ensures a more hygienic composting process, mitigating risks associated with harmful pathogens. Moreover, odor emissions, often a byproduct of composting, are contained and reduced by these membranes. The role of the membrane in water resource conservation is also noteworthy. By minimizing water loss through evaporation, it ensures water conservation within the composting system. (Sun et al. 2022). This attribute is especially vital in regions with water scarcity, reinforcing the membrane's contribution to sustainable water management.



(a) (b)

Figure 2: Mechanism of membrane covers in reducing emission, (a) Membrane covered static composting system (Li et., al 2023), (b) Membrane covered ASP system (Sun et al. 2018)

2.10 Effect of Membrane Cover on Compost Quality

Composting is an effective method for organic waste management and soil amendment. However, the loss of nitrogen during the composting process can be a significant concern, as it not only reduces the nutrient value of the compost but also contributes to environmental pollution.

Several studies have investigated the impact of membrane covers on nitrogen retention during composting. Sun et al. (2022) found that membrane covers increased the oxygen utilization rate, leading to improved fermentation efficiency and nitrogen retention in composting piles. Xiong et al. (2022) demonstrated that functional membrane covering techniques enhanced nitrogen succession during aerobic composting, resulting in increased nitrogen retention. Li (2023) also reported that membrane-covered aerobic composting effectively retained nitrogen during kitchen waste disposal.

In addition to nitrogen retention, membrane covers have been shown to enhance compost quality. Cao et al. (2022) observed that membrane-covered technology increased the temperature of compost piles and accelerated the degradation of organic matter, leading to improved compost quality. Al-Alawi et al. (2019) highlighted the advantages of membrane-covered compost technology, including even oxygen distribution, longer duration of high temperatures, and reduced emissions of ammonia and methane.

The use of membrane covers in composting also influences microbial community dynamics and gas emissions. Song et al. (2022) found that membrane covering promoted the participation of specific microbial genera in the formation of humic substances, leading to the development of complex compost structures. Ma et al. (2020) investigated the effects of intermittent aeration and membrane covers on greenhouse gas emissions and bacterial community succession during large-scale composting. They observed that membrane covers reduced greenhouse gas emissions and influenced the composition of the bacterial community.

The use of membrane covers in composting offers several benefits, including improved nitrogen retention, enhanced compost quality, and reduced gas emissions. Membrane covers increase the oxygen utilization rate, accelerate organic matter degradation, and promote the formation of complex compost structures. These findings highlight the potential of membrane covers as a valuable tool for optimizing composting processes and improving the sustainability of organic waste management.

2.11 Summary of Existing Literature on Effect of Membrane Covers on NH3 and GHG Emissions

Reference	**Summary**
Fang et al., 2021	The results of this study showed that the covered group could maintain a positive micro-pressure environment. The CO2, CH4, N2O, NH3 emissions outside the membrane during the aeration interval were reduced by 64.23%, 70.07%, 54.87%, and 11.32%, respectively, compared with that inside the membrane. It was also found that the CH4 and N2O emissions from the Covered group were reduced by 99.89% and 60.48% relative to the Control group, during organic manure composting.

Soto-Herranz et al., 2021	The study found a reduction in NH_3 and CH_4 emissions of 20-30% and 40%, respectively, in aerobic composting with the use of ePTFE membrane covers at lab scale.
Ma et al., 2021	The study found that covering with a functional membrane can effectively decrease greenhouse gas emissions. The Global Warming Potentail for the Gore and ZT groups (membrane covers) were 16.97% and 53.41% lower than for the control group (uncovered).
Sun et al., 2018	The use of the semi permeable membrane covered composting system reduced the total emissions of CO_2 , CH_4 , N_2O and NH_3 outside the membrane being 73%, 96%, 80% and 65% lower than those inside the membrane, respectively. The maximum cumulative concentrations of CO_2 , CH_4 , N_2O and NH_3 outside the membrane were 98%, 95%, 72% and 58% lower than those inside the membrane.
Cao et al., 2022	The membrane covered technology decreased N_2O and CO_2 emissions by 68.4% and 1.56%, respectively, and NH_3 and H_2S emissions by 58.6% and 38.1%, respectively. The rate of loss of total N from the compost pile reduced by 17.3%, while the ammonium nitrogen and nitrate nitrogen contents of the pile increased by 37.7% and 11.8%.
Li et al., 2023	The application of the membrane reduced the emissions of NH_3 and N_2O by 48.5% and 44.1%, respectively, thereby retaining 7.9% more nitrogen in the compost.

2.12 Gaps in Current Research

The existing literature reveals several gaps in the current research landscape regarding the impact of membrane covers on ammonia and greenhouse gas emissions during organic manure composting, particularly at industrial-scale facilities. These gaps highlight the need for further investigation and emphasize the novelty and importance of the proposed research.

A significant gap is the lack of comprehensive studies conducted at an industrial scale to understand the effects of membrane covers on gas emissions during composting. While a study explored the effects of a semi-permeable membrane in combination with intermittent aeration on gas emissions during aerobic composting of dairy manure at an industrial scale, it does not provide a thorough understanding across different types of composting waste and varied composting conditions (Karion et al., 2015). This gap indicates the need for more research that encompasses a broader range of composting materials and conditions.

Another gap is the preference towards pilot-scale studies in the existing research. While pilot-scale studies, such as the investigation of the effect of pile mixing on greenhouse gas emissions during dairy manure composting using large flux chambers, provide valuable insights, they leave a substantial knowledge gap concerning industrial-scale composting facilities (Brandt et al., 2014). Therefore, there is a need for more studies conducted at an industrial scale to bridge this gap.

The existing research also exhibits a lack of variety in the composting materials investigated. For example, a study by Amlinger et al., 2008 delved into membrane-covered aerobic fermentation for vegetable waste composting but highlighted that this approach is seldom applied to vegetable waste, indicating a potential research gap in understanding the effects of membrane covers across a broader spectrum of composting materials, including organic manure. Therefore, further research is needed to explore the effects of membrane covers on a wider range of composting materials.

While some studies similar to that of Hansen et al., 2006 on a large semi-membrane covered composting system underscored that functional membranes could exert a barrier effect on carbon dioxide emissions, it falls short of providing a comprehensive understanding of how membranes impact other greenhouse gases and ammonia emissions, especially in industrial-scale composting scenarios. This gap highlights the need for more research to investigate the effects of membrane covers on a broader range of greenhouse gases and ammonia emissions.

Furthermore, the concerns regarding the environmental repercussions of emissions from manure management have spurred research efforts towards emission abatement. However, unresolved questions regarding the efficacious abatement of manure-related emissions indicate a notable gap. This gap could be addressed by investigating the effects of membrane covers on emission reduction at an industrial scale (Hansen et al., 2006).

The existing research on the impact of membrane covers on ammonia and greenhouse gas emissions during organic manure composting at industrial-scale facilities has several gaps. These gaps include the lack of comprehensive studies at an industrial scale, the predominance of pilot-scale studies, the limited variety in composting materials investigated, the incomplete understanding of membrane effects on different gases, and the unresolved questions regarding emission abatement. Addressing these gaps through further research will contribute to a more comprehensive understanding of the effects of membrane covers on gas emissions during composting.

3. Materials and Methods

3.1 Composting Units Under Study

The composting units under study were 2 Membrane-covered side-walled Aerated Static Pile (ASP) systems with ProfiCover®, a market leading ePTFE membrane cover (Cover 2), and an uncovered ASP unit. All the composting units had dimensions of 25 meters in length and 8 meters in width. One of the critical phases of composting is the thermophilic phase with temperature range of 69.8-75.9°C, In this phase highest amount of emissions are observed, which is starts by the fifth day from the start of composting.

The Aerated Static Pile (ASP) system was fully operational, and the aeration was turned on during the whole sampling period, the aeration can introduce substantial variability in microbial activity which can determine the decomposition rate of the organic matter and subsequently the profile of the emissions.

3.2 Sampling Procedures and Techniques

3.2.1 Gas Collection

For gas collection, a gas collecting cone was utilized to measure the gaseous emissions from the top of the compost piles. This technique is suitable for comprehensive capture of gases originating from outside compost piles. The study identified 6 sampling points on top of the cover laminate, in line with the protocol instituted by the MATE Institute of Environmental Chemistry and Waste Management in 2016 (Zsolt Varga et al., 2017). This protocol was adopted to ensure uniform and consistent sampling across all the 3 piles. For measuring the composting material's internal gaseous emissions, penetration probe sampling was used at 3 different sampling points inside each pile. This involved the insertion of a probe roughly 1 meter into the compost pile, providing emission measurement of its internal gaseous state. The approximate location of the sampling points is given in Figure 1.

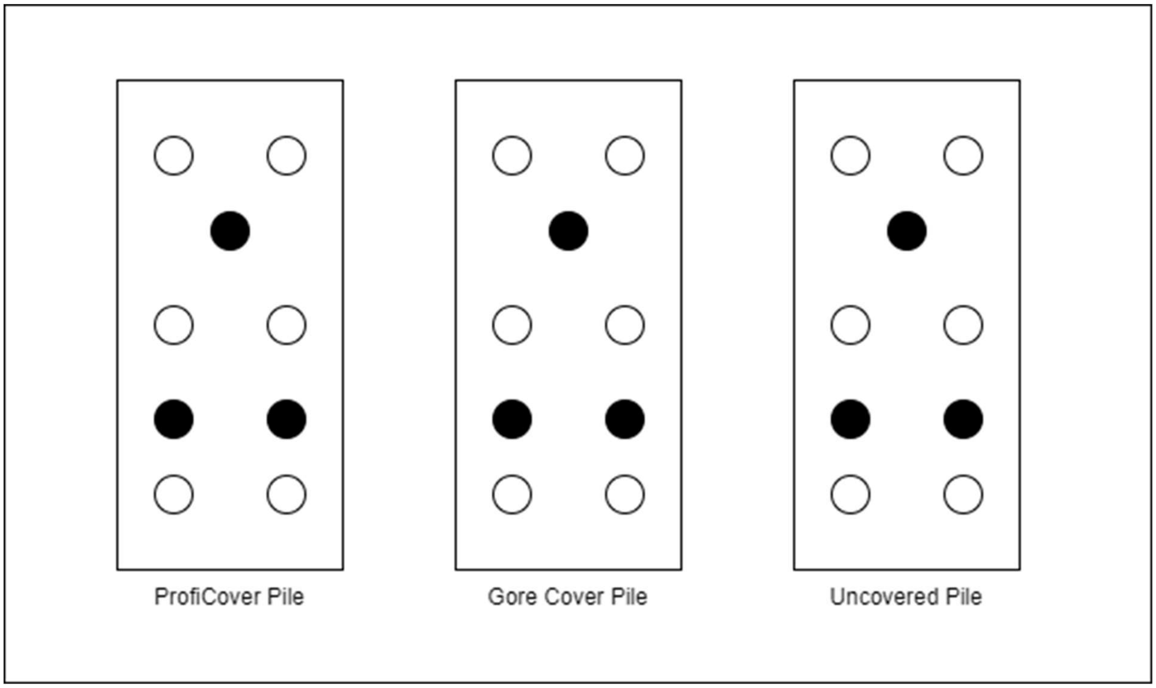


Figure 3: Sampling Point Location (white points represent sampling points outside the pile and the black points represent sampling points inside the pile.)

(a) (b)

(c)

Figure 4(a-c): On-site Sample Measurements

3.2.2 Sampling Equipment

The sampling apparatus utilized was a PSS gas sampler, a product of GASMET Technologies Oy/Ansyco GmbH, with the product ID 09204. It featured a Swage lock connection of 6mm/8mm dimensions. The equipment was consistently operated at a temperature of 180 ºC to maintain the integrity of the gas samples. This consistent temperature ensured the preservation of the gas sample integrity throughout the collection process.

3.3 Measurement Protocols and Techniques

3.3.1 Ammonia Measurement

The measurement of ammonia emissions was based on the ASTM D6348-3 Standard test method, due to its efficacy in determining gaseous compounds via Extractive Direct Interface Fourier Transform Infrared (FTIR) Spectroscopy. The VDI 3862 Blatt 8 was incorporated alongside the FTIR to formaldehyde emissions in combustion engine exhausts using the FTIR methodology. The study was done according to the technical guidelines outlined in TGN M22 (Environmental Agency, v3, March 2012).

3.3.2 VOC Measurement

Volatile Organic Compounds (VOCs) measurements were done using the EN 12619: 2013 method. This approach is suitable for stationary air pollutant sources and emphasizes n determining the mass concentration of gaseous carbon in organic compounds through the continuous flame ionization detection method.

3.3.3 Greenhouse Gas Emissions Measurement

ASTM D6348-3 Standard's FTIR spectroscopy technique was used for greenhouse gas emissions measurement. This method is able to identify up to 50 distinct gases based on their individual IR spectra. Some of the spectra were developed using certified material samples, facilitating device-specific calibrations, others were procured from the spectrum library of GASMET Technologies Oy/Ansyco GmbH.

3.4 Environmental Conditions during Sampling

A comprehensive knowledge of both operational and ambient conditions during the sampling phase is important as these conditions can significantly modulate the results and their interpretations. The ambient air temperature during the sampling fluctuated between 38.5°C and 42.1°C. The relative humidity levels were between 32% and 34.5%. The wind speeds were between 0.4 m/s to 1.5 m/s and primarily from the west/southwest direction, the patterns can determine the dispersion trajectory of the emissions and influence the moisture evaporation rate from the compost pile.

3.5 Data and Statistical Analysis

To find out the impact of the covers on the gaseous emissions from the different compost piles, a series of statistical analyses were done. The emissions under investigation were Ammonia, Greenhouse Gases (including Carbon dioxide, Methane, and Nitrous oxide), and Volatile Organic Compounds represented by Propanol equivalent (FTIR).

The preliminary step in the statistical analysis was the Shapiro–Wilk test, it was used to evaluate the normality of the data. Determining the data's distribution in the beginning is fundamental as it directly influences the selection of subsequent statistical tests. Given that not all data subsets conformed to a normal distribution, the primary metric for comparing emissions across the compost piles were the median values. The use of median values is appropriate for non-normal datasets as it offers a robust measure of central tendency and is unaffected by outliers or extreme values.

For the comparison of gaseous emissions from the inside versus the outside of each compost pile, the Mann-Whitney U test was chosen. This decision was made due to the test's nonparametric nature which makes it ideal for datasets that don't necessarily follow a normal distribution. Additionally, it allows for comparing two independent groups and is not affected by unequal sample sizes, given the discrepancies in sample sizes in the dataset. The Mann-Whitney U test is a non-parametric statistical test used to determine if there are statistically significant differences between two groups when the level of measurement for the dependent variable is ordinal (Santiago & Kang, 2022). It is commonly used when comparing outcomes between two groups and the researchers need to decide whether to use parametric methods, such as the t-test, or non-parametric methods, like the Mann-Whitney test (Cessie et al., 2020). The test is appropriate for investigating differences between two independent groups for non-normally distributed data sets (Ibrahim & Borhan, 2021)

Before employing parametric tests, it was necessary to ensure that the assumption of homogeneity of variances was met. For this, Levene's test for homoscedasticity was conducted. This test determines whether the variances across different groups are equal. It was applied to the inside emissions data of the covered piles in comparison to the uncovered pile. To examine the efficacy of the covered piles in comparison to the uncovered pile, the independent sample t-test was applied for the inside emissions. This test was selected due to its increased sensitivity, allowing it to identify even subtle differences, which is a key point given our interest in the potential advantages of the covers. When its assumptions are met, the t-test, being parametric, provides more detailed understanding, especially with smaller sample sizes.

It's important to highlight that while these statistical tests provide insights into significant differences, they don't give the magnitude or practical significance of these variances. Therefore, emission reduction percentages were calculated for both the cover types to see the efficiency of these covers in mitigating the emissions. The reduction percentage from inside to outside was calculated using Eq 1 and the reduction of emissions inside the covered piles vs the uncovered pile was calculated using Eq 2.

$$\text{Reduction Percentage} = \frac{E_{\text{outside}} - E_{\text{inside}}}{E_{\text{outside}}} \times 100\% \qquad \text{------ (Eq 1)}$$

where:

- E_{inside} is the median emission inside the cover.
- E_{outside} is the median emission outside the cover.

$$\text{Reduction Percentage Inside Covered Piles} = \frac{E_{\text{uncovered\_in}} - E_{\text{covered\_in}}}{E_{\text{uncovered\_in}}} \times 100\% \quad \text{------ (Eq 2)}$$

where:

- $E_{\text{uncovered\_in}}$ is the median emission inside the uncovered pile.
- $E_{\text{covered\_in}}$ is the median emission inside the covered pile.

All computational and statistical analyses were performed using Python (version 3.8.5; Python Software Foundation, 2020). The following Python libraries were employed: Pandas (version 1.1.0; Pandas Development Team, 2020) and SciPy (version 1.5.2; SciPy Developers, 2020). MS Excel 16 (Microsoft, USA) was used for data processing, calculating reduction percentages, and creating graphs.

4. Results and Discussion

4.1 Analysis of Emissions: Inside vs. Outside of Compost Piles

4.1.1 Shapiro-Wilk Test Results on Data Distribution

Interpretation of p-values:

- $p<0.05$: Indicates a statistically significant difference or that the data does not adhere to a normal distribution.
- $p \geq 0.05$: No significant difference or the data is normally distributed.

The Shapiro-Wilk test results on data distribution indicated that many data subsets for specific emissions and pile types were normally distributed (p-values greater than 0.05). However, some data subsets did not follow a normal distribution (p-values less than 0.05). This was evident from the examination for emissions of Carbon Dioxide, Methane, and Propanol Equivalent for Cover 2 (Outside) and Methane and Propanol Equivalent for Uncovered (Outside). The variation in data distribution led to the decision to proceed with median comparison and employ the nonparametric Mann-Whitney U Test, as mentioned in the methodology. This approach is appropriate when dealing with non-normally distributed independent data.

4.1.2 Mann-Whitney U Test Results on Inside vs. Outside Emissions

Table 1: Mann-Whitney U Test Results for ProfiCover® Pile

Measurement	Mann-Whitney U Test p-value
Ammonia	0.0238
Carbon Dioxide	0.0238
Nitrous Oxide	0.0256
Propanol Equivalent (FTIR)	0.0238
Methanol Emissions	0.0238

Table 2: Mann-Whitney U Test Results for Cover 2 Pile

Measurement	Mann-Whitney U Test p-value
Ammonia	0.0357
Carbon Dioxide	0.0357
Nitrous Oxide	0.0347
Methanol Emissions	0.0357

The results of the Mann-Whitney U test indicated that there were significant differences between the emissions inside and outside of the compost piles for both the ProfiCover® and Cover 2 Compost Piles. Specifically, significant differences were found for ammonia, carbon dioxide, nitrous oxide, and propanol equivalent (FTIR) emissions in the ProfiCover® pile, and for ammonia, carbon dioxide, and nitrous oxide emissions in the Cover 2 pile.

These findings corroborate the observations made by Song et al. (2022), who found that covering compost piles with a semi-permeable membrane not only improved nitrogen preservation rates but also notably reduced the emission of NH3 and H2S. These findings are further strengthened by the study by Soto-Herranz et al. (2021), who achieved a substantial 65% reduction in NH3 emissions using an ePTFE semipermeable membrane cover system in a farm-scale composting process. This evident reduction in ammonia emissions mirrors the results observed, signifying the consistent performance of membrane covers across different scales and conditions. Additionally, Cao et al. (2022) demonstrated a similar trend where a membrane-covered approach diminished NH3 emissions during anaerobic composting. Such consistent findings across multiple studies indicate a reliable effect of membrane covers on ammonia emissions.

While the primary focus of this analysis was on the emissions of ammonia and greenhouse gases, it is noteworthy to consider the broader implications of membrane covers on composting processes. Furthermore, not all studies have exclusively reported reductions in gas emissions with added materials or alterations to the composting process. For instance, Wei et al. (2017) observed that the incorporation of cornstalks led to decreased hydrogen sulfide emissions but had negligible effects on ammonia. This underscores the importance of specific cover materials and their interactions with composting substrates. The studies by Ma et al. (2018, 2020, 2021) and Li et al. (2020) had also highlighted the role of membrane covers on gas emissions and bacterial community succession during composting. These works emphasize the multifaceted impacts of membrane covers, spanning beyond just emission reductions to influencing microbial community dynamics.

4.2 Levene's Test for Homoscedasticity

Levene's test for homoscedasticity showed that the variances were equal across the groups for all emissions, satisfying the assumption of homogeneity of variances for the independent sample t-test. This indicates that the groups being compared have similar variability in emissions. For all emissions (Ammonia, Carbon Dioxide, Methane, Nitrous Oxide, Propanol Equivalent), the variances are equal across the groups, satisfying the homogeneity of variances assumption for the independent sample t-test.

4.3 Comparative Analysis of Emissions from Covered and Uncovered Piles Using the Independent Sample T-test

Both ProfiCover® and Cover 2 demonstrated a significant reduction in emissions when compared to the Uncovered pile. Table 3 showcases median values for each emission type, differentiated by pile type and measurement location (inside vs. outside).

Table 3: The median values for each emission type, differentiated by pile type and measurement location (inside vs. outside)

Pile Name	In/out	Ammonia NH3 [ppm]	Carbon dioxide CO2 [v/v%]	Methane CH4 [ppm]	Nitrous oxide N2O [ppm]	Propan equivalent (FTIR) [ppm]
Cover 2	in	4259.8	1.09	39.9	1.3	56.7
Cover 2	out	390.1	0.44	81.2	1	31.3
ProfiCover®	in	3343.8	1.42	69.3	1.5	79.2
ProfiCover®	out	225.8	0.2	30.75	0.65	12.3

The comparative analysis of covered (ProfiCover® and Cover 2) and uncovered piles using the independent sample t-test revealed interesting findings regarding emissions. For ammonia emissions, both ProfiCover® and Cover 2 demonstrated a significant reduction compared to the uncovered pile. This aligns with previous research that has shown the potential of covering compost piles to mitigate ammonia emissions (Dennehy et al., 2017, Cao et al., 2022; Li et al., 2022; Sun et al., 2022)

The median values for each emission type, differentiated by pile type and measurement location (inside vs. outside), highlighted variability in emissions between the inside and outside of compost piles and across different pile types. For example, the median values for ammonia emissions were significantly lower inside the covered piles (ProfiCover® and Cover 2) compared to the uncovered pile. However, for carbon dioxide, methane, nitrous oxide, and propanol equivalent emissions, no significant difference was found between the emissions from inside the covered piles and the uncovered pile. This suggests that the impact of membrane covers on other emissions such as carbon dioxide, methane, nitrous oxide, and propanol equivalent may be limited.

These findings are also consistent with the studies which investigated the effect of covering on gaseous emissions from composting, for example, Bernal, Lopez-Real, and Scott (1993) explored the impact of covering composting material with zeolite minerals. Their study found that the combination of mixing pig slurry with easily degradable straw and covering the composting material with zeolite minerals led to a marked reduction in ammonia emissions. This suggests that the physical barrier provided by covers can play a pivotal role in preventing the direct release of ammonia into the atmosphere (Bernal, Lopez-Real, & Scott, 1993). Similarly, Chadwick (2005) emphasized the potential of compacting and covering manure heaps in reducing ammonia emissions. The research indicated that such practices are particularly effective when the manure contains high ammonium-N contents. This aligns with the present findings, reinforcing the idea that covering composting piles can be a crucial strategy in environmental management (Chadwick, 2005). The study by Sun et al. (2018) also demonstrated the advantages of using a semi-permeable membrane-covered composting system. It not only highlighted a reduction in ammonia production and emissions but also in greenhouse gases. This suggests that certain covers might offer dual benefits by optimizing the composting process and further reducing harmful emissions. Furthermore, Berg, Brunsch, and Pazsiczki (2006) investigated the efficacy of different materials for covering liquid manure storage facilities. Their findings highlighted the importance of maintaining a lower pH value to effectively reduce ammonia emissions, emphasizing the role of environmental conditions in conjunction with covering techniques (Berg, Brunsch, & Pazsiczki, 2006). The consistent findings across different studies underscores the importance of using covers in composting or manure storage practices.

4.4 Emission Reduction Analysis

To evaluate the efficacy of the compost covers in modulating gaseous emissions, an in-depth analysis focusing on emission reduction was conducted. The main emissions investigated were Ammonia, Greenhouse Gases (including Carbon dioxide, Methane, and Nitrous oxide), and Volatile Organic Compounds, denoted by Propanol equivalent (FTIR). The composting piles under examination were covered by ProfiCover® and Cover 2.

Reduction from Inside to Outside

The emission reduction percentages from inside of the piles to the outside the membrane cover were calculated using Eq 1, previously described in the methodology to evaluate the efficacy of the compost covers in modulating emissions. The reduction percentages for both the covered piles are presented in Table 4 and Figure 3.

Table 4: Emission Reduction Percentages (Inside vs. Outside of Compost Piles)

Cover	Ammonia NH3 [ppm]	Carbon dioxide CO2 [v/v%]	Nitrous oxide N2O [ppm]	Propane equivalent (FTIR) [ppm]
Cover 2	90.84	59.63	23.08	44.80
ProfiCover®	93.25	85.92	56.67	84.47

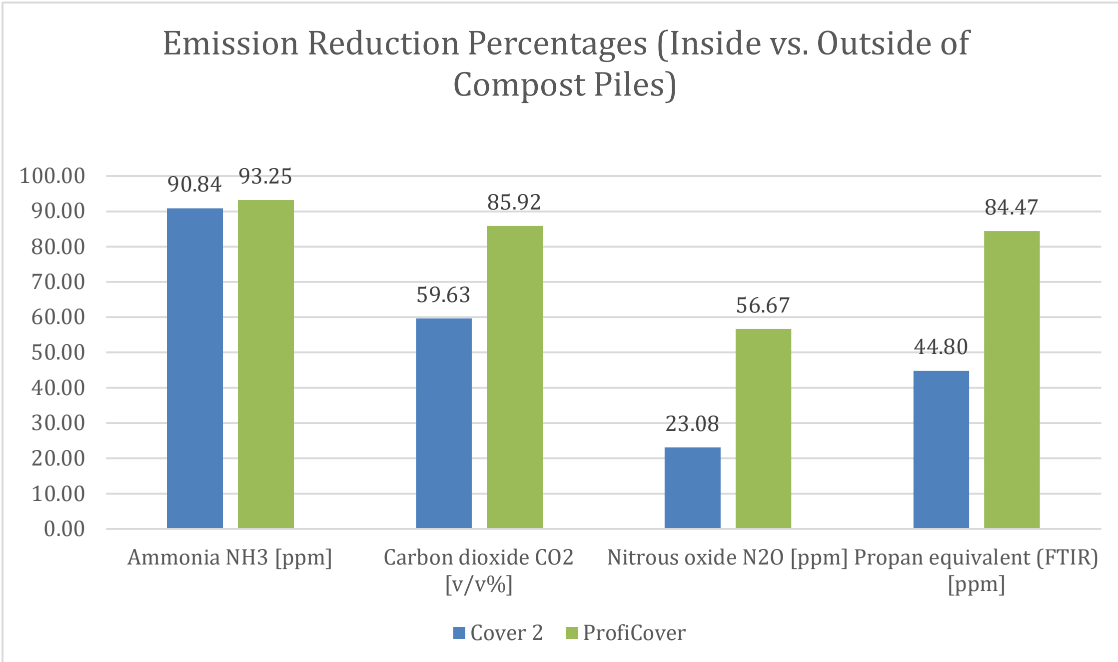


Figure 5: Emission Reduction Percentages (Inside vs. Outside of Compost Piles) Bar Graph

For Cover 2, the reduction percentages indicate a significant reduction in ammonia emissions (90.84%), nitrous oxide emissions (23.08%) and carbon dioxide emissions (59.63%) when transitioning from inside to outside the compost pile. However, there was a slight increase in methane emissions (3.51%) and which could be accounted for due to several different factors and could be investigated further. The reduction in propanol equivalent emissions (44.80%) suggests a positive impact of the cover in reducing volatile organic compounds. Similarly, for the ProfiCover®, there is a substantial reduction in ammonia emissions (93.25%), carbon dioxide emissions (85.92%) methane emissions (55.63%), nitrous oxide emissions (56.67%), and VOC (propanol equivalent) emissions (84.47%) while transitioning from inside to outside the compost pile.

The observed reductions align with the existing studies on the potential of cover technologies in minimizing composting emissions. For instance, the notable reduction in ammonia emissions under both covers is supported by findings from Sun et al. (2018) and Soto-Herranz et al. (2021), affirming the effectiveness of membrane technologies in reducing ammonia volatilization. However, the ProfiCover® exhibited a slightly higher reduction in ammonia emissions (93.25%) compared to the Cover 2 (90.84%), suggesting a marginal superiority in performance, albeit within a close range. The primary reason for reduction in NH3 emissions is the condensation droplets formed under the membrane partially evaporated and NH_3 was discharged to the environment, thus decreasing the emission rate inside the membrane. (Chen et al., 2021) Similarly, the substantial reduction in carbon dioxide emissions, especially under the ProfiCover® (85.92%), resonates with the findings of Cao et al. 2022, however at a different magnitude. The variance in reduction percentages could be attributed to the distinct characteristics of the membrane technologies employed, or the additives used in the composting process as suggested by Cao et al. 2022. The slight increase in methane emissions under the Cover 2 contradicts the general trend of methane emission reduction observed in other studies like that by Chen Fang et al. (2021) and suggests further investigation to investigate the underlying factors. The reduction in nitrous oxide emissions, although significant, is lower compared to the reduction in other gases. This is consistent with the relatively lower reduction of N_2O emissions reported by Cao et al. 2022. The dynamics of N_2O production and emission during composting might be more resilient to modulation by cover technologies, hence necessitating further research to explain the mechanisms and improve mitigation strategies.

Starting with our primary observation, both the Cover 2 and ProfiCover® have demonstrated considerable efficacy in reducing ammonia and carbon dioxide emissions during composting. This aligns well with the study by Cao et al. (2022), which reported a 25.8% reduction in NH_3 emissions and a 13.1% reduction in N_2O emissions using a membrane-covered technology. This study also mentioned the use of superphosphate, an additive that has been previously documented to reduce the loss of nitrogen and certain greenhouse gas emissions, including NH_3, CH_4, and H_2S. The incorporation of such additives can be prominent. For instance, Yuan et al. (2018) highlighted that phosphor-gypsum and dicyandiamide could curtail CH_4 and N_2O emissions substantially, though with a counteractive increase in NH_3 emissions. Similarly, Jiang et al. (2014) found that superphosphate not only facilitated the composting process but also significantly decreased NH_3 emissions during the thermophilic phase, in contrast to bentonite, which increased NH_3 emissions. Ma et al. (2021) reported findings that further support our observations. Their research identified a decline in NH_3 and N_2O emissions by 11.77% and 26.40%, respectively, using the Cover 2 membrane, and a remarkable reduction in N_2O emissions by 68.44% with the ZT membrane. This decline in emissions was also associated with an improved bacterial community, suggesting a possible biological dimension to the emission reductions observed. No additional additives were cited in this study, implying that the membranes' impact was primary in achieving these results. Li et al. (2023) focused on the composting of kitchen waste and found a 48.5% and 44.1% reduction in NH_3 and N_2O emissions, respectively, with membrane-covered composting. Their study also attributed the reduction in NH_3 emissions to the adsorption by the condensed water layer under the inner membrane and the N_2O emission reduction to micro positive pressure in the reactor promoting oxygen distribution similar.

On alternative strategies, Zuokaitė et al. (2013) explored the use of natural covers like wood bark, sawdust, peat, and a grass layer, presenting potential alternative or complementary solutions in scenarios where membrane covers may not be feasible. Ermolaev et al. (2014) also provided a different perspective, suggesting broader variables like temperature, moisture content, mixing frequency, and the amount of added waste could significantly influence gas emissions during composting.

4.5 Reduction of Emissions Inside the Covered Piles Compared to Uncovered Piles

To gain a deeper insight into the efficiency of the covers, a comparative analysis was conducted to gauge the emission reductions from the covered piles (ProfiCover® and Cover 2) against the Uncovered pile for inside measurements. The results of this analysis are illustrated in Table 5 and Figure 6.

Table 5: Emission Reduction Percentages (Inside Compost Piles)

Measurement	ProfiCover®	Cover 2
Ammonia NH_3 [ppm]	52.60	62.79
Carbon dioxide CO_2 [v/v%]	69.64	60.45
Methane CH_4 [ppm]	95.02	91.35
Nitrous oxide N_2O [ppm]	63.89	58.33
Propane equivalent (FTIR) [ppm]	82.42	75.45

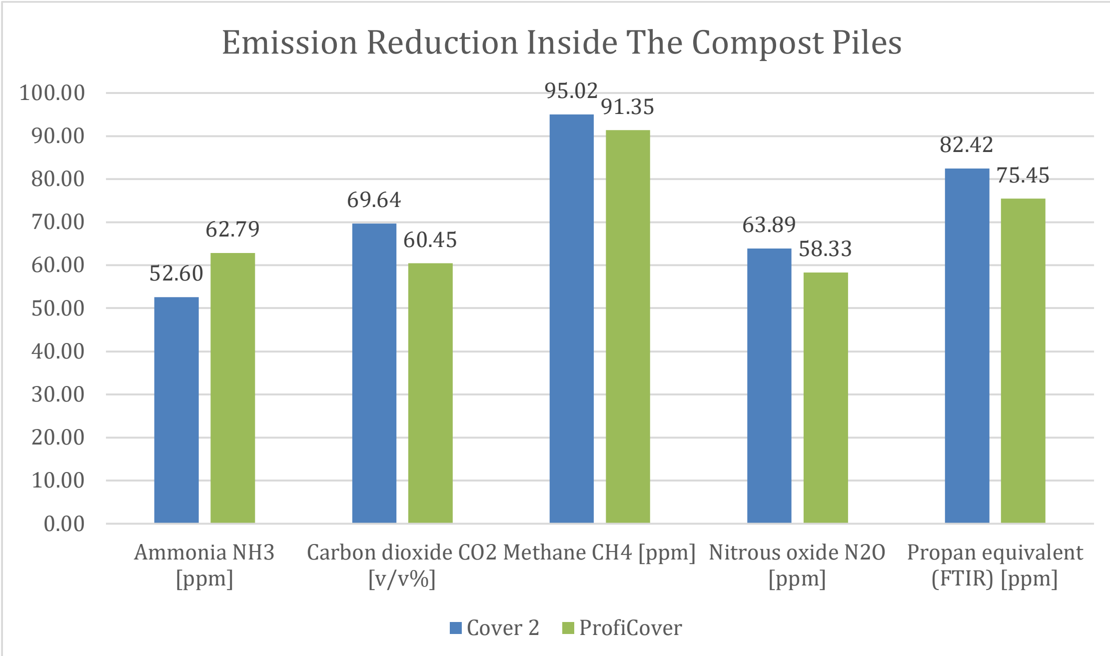


Figure 6*:* Emission Reduction inside The Compost Piles Bar Graph

The results of the comparative analysis show the reduction percentages of various emissions inside the piles from the covered piles (Cover 2 and ProfiCover®) compared to the Uncovered pile. Inside measurements indicate that both covers resulted in reductions in emissions of ammonia (NH3), carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and propane equivalent. The Cover 2 showed greater inside reductions in NH3, CO2, CH4, and N2O compared to the ProfiCover®. Specifically, the ProfiCover® reduced CO2 emissions by approximately 70%, which is higher compared to the reduction by Cover 2 at around 60%. On the other hand, the Cover 2 reduced NH3 emissions by around 63%, which is higher than the reduction by ProfiCover® at around 53%. This divergence in performance implies a potential trade-off in emission reduction efficacy between the two covers. Nevertheless, the implication is that the use of either cover substantially decreases emission production, thereby enhancing the compost quality and increasing nitrogen retention in the compost, which are pivotal for the environmental sustainability and efficiency of the composting process.

The comparative analysis of emission reductions within covered and uncovered compost piles corroborates the findings from previous research that investigated the effect of cover technologies on gas emissions during composting. For instance, the substantial reductions in CH4 emissions echoed the findings of Sun et al. (2018) and Fang et al. (2021), where membrane-covered composting systems were found to significantly mitigate CH_4 emissions. Similarly, the observed decrease in NH_3 emissions conforms with the findings across several existing studies, underscoring the efficacy of cover technologies in reducing ammonia volatilization. Hou et al. (2014) found that mitigation measures, such as covering, can help reduce ammonia emissions. Soto-Herranz et al., (2021) studied the reduction of ammonia emissions from laying hen manure in a closed composting process using gas-permeable membrane technology and observed that the emission rate inside the membrane decreased compared to the uncovered condition, which aligns with our findings.

Furthermore, the reduction in emissions inside the covered piles, as shown in our study, suggests an increase in nitrogen retention within the compost, which is instrumental for improving compost quality and environmental sustainability of composting processes. Although our study did not delve into the specifics of nitrogen retention mechanisms, the referenced papers provide insights into potential pathways such as reduced ammonia volatilization and filtrate leaching, as well as the transformation of organic nitrogen into NH_4^+ through mineralization processes (Ma et al., 2021). Ma et al. (2021) further supports our results; they observed that the membrane covers significantly reduced gas emissions compared to the uncovered control. The membrane cover created a controlled environment that minimized the release of gases, leading to a more efficient composting process.

Cao et al. (2022) demonstrated that a membrane-covered composting system decreased NH_3 and H_2S emissions and reduced the loss of total nitrogen from the compost pile. Li et al. (2022) also found that combined membrane-covered systems improved the aerobic composting process and reduced gas emissions. Cao et al. (2022) examined the effects of membrane-covered technology on compost quality and nitrogen-containing gas emissions during aerobic composting. The study highlighted that the membrane-covered sample had significantly lower emissions compared to the control sample. Specifically, the membrane-covered sample had a germination index (GI) of 50% and 80%, approximately 2 and 9 days earlier, respectively, than the control sample. This indicates that the membrane cover facilitated faster composting and reduced the release of nitrogen-containing gases.

The disparity in emission reduction efficacy between the ProfiCover® and Cover 2 suggests that different cover technologies may exhibit varying levels of performance in mitigating specific emissions. This is consistent with the variance in emission reductions reported in the papers which employed different cover technologies and additives. For example, Cao et al.

2022 reported a reduction in N2O and CO2 emissions by 68.4% and 1.56% respectively, using membrane covered technology, which presents a contrasting degree of CO2 emission reduction when compared to our findings.

5. Conclusions and Recommendations

The study's comprehensive evaluation of emission reductions underscores the significant efficacy of compost covers, particularly ProfiCover® and Cover 2, in mitigating gaseous emissions during the composting processes, especially during the thermophilic phase of organic manure composting. A comparative analysis between inside and outside emissions revealed that both covers played a pivotal role in emission containment. Cover 2 manifested a reduction in most gaseous emissions, with decreases of 90.84% for Ammonia and 59.63% for Carbon Dioxide. Methane emissions increased suggesting its potential entrapment within this cover. Other gases, including Nitrous Oxide and Propane equivalent, experienced reductions of 23.08% and 44.80%, respectively. On the other hand, ProfiCover® presented even more compelling reductions. Emissions for Ammonia and Carbon Dioxide plummeted by 93.25% and 85.92%, respectively. Methane, contrasting with the Cover 2, observed a significant reduction of 55.63%. Concurrently, Nitrous Oxide and Propane equivalent followed with substantial reductions of 56.67% and 84.47%, respectively.

When comparing the emission reductions inside the covered piles to those of uncovered piles, ProfiCover® stood out with striking reductions, registering 52.60% for Ammonia, 69.64% for Carbon Dioxide, a noteworthy 95.02% for Methane, 63.89% for Nitrous Oxide, and 82.42% for Propane equivalent. Cover 2, not far behind, showcased notable reductions as well. The values were 62.79% for Ammonia, 60.45% for Carbon Dioxide, 91.35% for Methane, 58.33% for Nitrous Oxide, and 75.45% for Propane equivalent.

Statistical testing with the Levene's Test confirmed the homoscedasticity of the data, ensuring the robustness of these findings. Meanwhile, the Mann-Whitney U test indicated significant differences in emissions between the inside and outside of both compost piles, corroborating the mitigative capabilities of membrane covers. Interestingly, while the median emission values for ammonia were found to be lower inside the covered piles, the independent sample t-test specifically underlined a significant reduction in ammonia emissions for both covers. This aligns with prior research advocating the advantages of compost covers. While both covers effectively reduced ammonia and carbon dioxide emissions compared to uncovered compost piles, their impact on other greenhouse gases, notably methane and nitrous oxide, was somewhat limited, calling for further research. It's also worth noting the potential of these covers in diminishing volatile organic compounds, as indicated by the decreased propanol equivalent emissions. In summation, this investigation reinforces the idea that the application of membrane technologies like ProfiCover® and Cover 2 plays a consequential role in ameliorating environmental impacts, particularly in reducing detrimental emissions such as ammonia and carbon dioxide during large-scale organic manure composting.

Further research should investigate integrating membrane cover technologies with additional emission control strategies like biofilters or amendments to develop an optimized and comprehensive solution. More studies are needed focused explicitly on optimizing cover design, materials, and implementation practices to enhance the mitigation impact, especially on greenhouse gases beyond carbon dioxide. Long-term and life cycle assessments of membrane covers should be performed to evaluate sustainability implications and impacts on compost quality over time. Cost-benefit analyses would provide helpful information for industrial facilities considering adopting these technologies. Exploring the use of alternative sustainable materials for membrane covers could be worthwhile to reduce environmental impacts. Developing functionalized "smart" membrane materials could present opportunities to selectively control gas transport and modulate emissions. Communication and knowledge sharing between researchers and industry partners is key to translating these technologies into widespread adoption. Overall, membrane covers show promise as an effective tool for reducing certain harmful emissions from organic manure composting, but ongoing research and development focused on optimization and integration with other methods is important.

Summary

The use of membrane covers in organic manure composting shows promise in mitigating greenhouse gas emissions and reducing ammonia volatilization. This study investigates the utilization of membrane covers, namely ProfiCover® and a market leading ePTFE membrane cover, in organic manure composting at an industrial-scale facility as a viable strategy for mitigating greenhouse gas emissions and decreasing ammonia volatilization. The study was conducted during the thermophilic phase (5th day) of composting and gas measurements were collected from inside and outside of covered and uncovered compost piles. Statistical analyses comprising of Shapiro-Wilk normality test, Mann-Whitney U test, Levene's homogeneity test, independent sample t-tests and emission reduction calculations demonstrated a significant reduction in emissions. Each of the membrane covers displayed significant reductions in ammonia emissions when compared to the uncovered pile supported by median values and statistical tests.

The ePTFE membrane cover exhibited a significant reduction in most gaseous emissions, with 90.84% for Ammonia, 59.63% for Carbon Dioxide, 23.08% for Nitrous Oxide and 44.80% for Propane equivalent (VOC). In contrast, ProfiCover® showed more profound reductions, with emissions for Ammonia and Carbon Dioxide decreasing by 93.25% and 85.92%, respectively. Methane observed a significant reduction of 55.63%, while Nitrous Oxide and Propane equivalent showed substantial reductions of 56.67% and 84.47%, respectively.

A comparative analysis was conducted to investigate the efficacy of emission reduction inside the compost piles by the membrane covers. The results of the analysis illustrated that ProfiCover® significantly mitigated emissions within the covered piles, as evident by the reductions in gaseous emissions: a 52.60% decrease in Ammonia, 69.64% in Carbon Dioxide, 95.02% in Methane, 63.89% in Nitrous Oxide, and 82.42% in Propane equivalents. In contrast, the ePTFE membrane cover demonstrated considerable efficacy, with reductions of 62.79% for Ammonia, 60.45% for Carbon Dioxide, 91.35% for Methane, 58.33% for Nitrous Oxide, and 75.45% for Propane equivalents. These findings highlighted the reduction of emissions inside the covered piles which resulted in reducing nitrogen losses and suggest better nitrogen retention in the compost with the use of the membrane covers.

Both the covers efficaciously reduced ammonia and greenhouse gas emissions compared to uncovered compost piles. This study supports the idea that membrane technologies like ProfiCover® play a significant role in mitigating environmental impact of composting, particularly in reducing harmful emissions like ammonia and carbon dioxide during large-scale organic manure composting, at the same time enhancing the compost quality by increasing nitrogen retention.

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DECLARATION

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