

**COMPARATIVE ACCOUNT ON INFLUENCE OF ORGANIC
AND CHEMICAL FERTILIZERS ON GROWTH AND YIELD
OF RICE AND METHANE EMISSION IN FIELD CONDITIONS**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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MANAGEMENT**

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**COMPARATIVE ACCOUNT ON INFLUENCE OF ORGANIC AND
CHEMICAL FERTILIZERS ON GROWTH AND YIELD OF RICE AND
METHANE EMISSION IN FIELD CONDITIONS**

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**In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in
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SUPERVISOR'S CERTIFICATE

This is to certify that the Ph.D. Thesis entitled, " **Comparative Account on Influence of Organic and Chemical Fertilizers on Growth and Yield of Rice and Methane Emission in Field Conditions** " is a bonafide work assigned to Naorem Twinkle Devi having Reg. No. MZU/Ph.D./1885 of 25.08.2021, Department of Environmental Science for Department of Environmental Science for partial fulfilment for the Degree of Doctor of Philosophy under Mizoram University.

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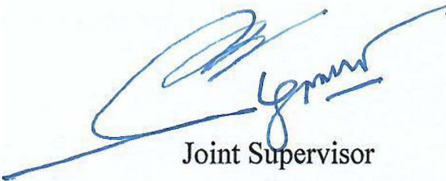
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I **NAOREM TWINKLE DEVI**, hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to do the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/Institute.

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1. INTRODUCTION

1.1 General Introduction

Rice (*Oryza sativa* L.) is a major cereal crop belonging to the *Gramineae* (*Poaceae*) family. It grows primarily in Asian countries like China, India, Bangladesh, Indonesia and Vietnam. Rice is one of the three major cereal crops produced worldwide, with 15% of the total crop production rate after maize and wheat (FAO, 2023). It has been an important staple food for almost half of the world's population. The demand for rice has been increasing with the growing population, mostly in developing countries. By 2050, the global population is expected to reach nine billion people and agricultural production should increase by 60% by this year in order to feed them (FAO, 2014). The increasing rate of demand could be met through higher yield per hectare rather than expanding cultivable land (FAO, 2010). The practice of sustainable farming, wise use of available land by ensuring proper irrigation, and nutrient management will improve food demand of the global population. After China, India ranks second with 138 million tonnes rice production in 2024, which was an increase of 3.2% from 2021(MAFW, 2024), however, its yield growth rate per year is low, which may not be able to meet global food security by 2050 (Ray et al. 2013). Moreover, the population of a country like India is still accelerating. And to ensure the food demand of the increasing population, intensive production of crops in a sustainable manner is needed. In India, the areas under rice cultivation are varied and unevenly distributed across the country. Around 52% of the total rice-cultivated areas depend on rain, while the remaining areas are irrigated (Gupta et al. 2021).

Rice has three distinct growth stages, *i.e.* vegetative stage, reproductive stage and ripening stage. During the vegetative stage, tillering starts and plant height increases gradually. The reproductive stage is characterized by the development of panicle primordium, followed by heading and anthesis. At the ripening stage, grain size increases, leaves senescent and colour of the grains turns yellow as they mature (Yoshida, 1981). Rice plants need N to promote their growth and tillering, which will influence the rice yield, number of panicles, and spikelet sterility (Artacho et al.

2009). Crops require essential nutrients such as N, P, and K for improved yield (Shrestha *et al.* 2020), which are typically supplemented through chemical fertilizers. Besides increasing yield, crop production needs to ensure the maintenance of soil quality. To meet the food demand of the growing population, chemical fertilizers have been used extensively. The unwise use of chemical fertilizers resulted in nutrient imbalance, decline of soil fertility, and increasing greenhouse gas (GHG) emissions (Krasilnikov *et al.* 2022). Continuous application of chemical fertilizers depletes soil qualities resulting in declining rice yield by 38% (Singh *et al.* 2001). Therefore, attention needs to be shifted towards use of alternatives, like organic fertilizer, which is eco-friendly as well as economically viable, to improve the productivity of soil and crops. Recycling organic waste from households, farming, etc, not only helps in the management of waste but also its application in soil provides multiple benefits such as improving soil nutrients, water holding capacity, and increased organic matter.

1.2 Effects of chemical fertilizer

Chemical fertilizers play a fundamental role in ensuring food security for the growing global population. It provides essential nutrients, mainly nitrogen (N), phosphorus (P), and potassium (K), in the readily available forms which are crucial for plant growth and development. Over the past few years, the use of chemical fertilizers has increased exponentially, which has led to the doubling of the world's cereal production between 1960 and 2000 (Tilman *et al.* 2002). Nevertheless, its intensive use could cause serious environmental problems. The use of chemical fertilizers significantly increases greenhouse gas (GHG) emissions, which in turn harms the environment (Banik *et al.* 1996). Excessive application of N fertilizers leads to the release of GHG that disrupt climate stability. Typically, N fertilizers are only 25 – 40% efficient, with majority of N being lost to the environment (Lenka, 2016). Overuse of chemical fertilizer causes several soil-related issues, such as acidification and the disruption of soil structure. Excess N application upsets the nutrient balance among N, P, and K, eventually causing deficiencies in essential micronutrients. One of the main drawbacks of chemical fertilizers is their high

content of strong acids, such as hydrochloric and sulphuric acids, which elevate soil acidity. The increased acidity can harm N-fixing bacteria, vital for supplying N to plants. Relying solely on chemical fertilizers poses long-term risks, including soil contamination and degradation (Laird et al. 2010). Prolonged use of chemical fertilizers can also result in the accumulation of toxic heavy metals like arsenic, cadmium, and uranium in soil. These effects are often severe and irreversible (Sonmez and Sonmez, 2007).

Inorganic fertilizers provide plants with immediate nutrients when needed, unlike organic fertilizers which release nutrients slowly over time. These fertilizers act quickly and can be applied in precise amounts according to the farm's requirements. They are also generally more affordable than commercial organic fertilizers and can be used in larger quantities. Chemical fertilizers play an important role in boosting crop yields. Although they enhance plant growth and help meet global food demands, crops grown with such inputs often lack desirable qualities like strong root and shoot development, nutritional value, and adequate ripening time (Kumar et al. 2019). In systems of continuous cultivation, relying heavily on inorganic fertilizers—especially using nitrogen or nitrogen-phosphorus combinations cannot sustain optimal crop production over time and may impair the natural functioning of agricultural crops (Thakur et al. 2001). Moreover, excessive nitrogen use can lead to symptoms such as browning of crop tips, yellowing of leaves, weak stems, and lodging of crops. Overapplication of chemical fertilizers can damage plants, reduce yields, and cause leaf discoloration. Therefore, it's crucial to recognize that increasing dependence on chemical fertilizers for crop production is harming both the environment and the ecosystem.

As the population increases, it is a challenge to improve crop productivity from the declining cultivable land area per capita without degrading the environment. To boost the productivity of crops, the rate of chemical fertilizers application has increased from year to year. Initially, the supply of chemical fertilizer improves rice yield as chemical fertilizer application releases essential nutrients that are rapidly available for plant uptake. However, their extensive use creates adverse effects on

the environment. It deteriorates soil qualities such as reduced nutrient use efficiency and soil fertility, prone to disease attack of crops, leaching (Chen, 2006), loss of organic matter, reduced crop yield (Moe et al. 2019), which leads to the decline of crop productivity. Due to less nutrient use efficiency, chemical fertilizers are added more than the required quantity. A large amount of added fertilizers are lost in the environment through leaching or runoff. When they fall into the nearby water bodies or seep into the groundwater, they may cause eutrophication or groundwater pollution. Therefore, intensive use of CFs should be reduced. An alternative approach should be considered to maintain the productivity without degrading the ecosystem. The replacement of chemical fertilizer with organic can increase crop yields while decreasing farm capital expenditure (Salam et al. 2021).

1.3 Organic amendment

Compost, a stable humus-like product, is rich in organic matter and used for application in order to improve soil fertility. It acts as a source of plant nutrients and also improves the overall properties of soil (Lalremruati and Devi, 2021). The low productivity in soil is primarily due to poor soil organic matter, plant-nutrient depletion, high water infiltration and low water-holding capacity of soils (Kanton et al. 2016). Such problems can be repaired by blending the soil with organic fertilizer. The dressing of compost adds organic matter to the soil which improves the physical, biological, and chemical properties of the soil. It elevates soil organic carbon, essential macro and micronutrients, resulting in increased crop yields (Liu et al. 2016; Rastogi et al. 2023). It also improves soil microbial activities and enhances N release required by plants (Myint et al. 2011). The amendment of soil with organic manures like trichocompost and vermicompost gives a higher yield of rice crop (Bilkis et al. 2015). The application of compost consistently for a long-term increases soil organic carbon and microbial pools (Nayak et al. 2009). The productivity of crops is greatly influenced by soil organic carbon as it affects soil structure and fertility of the soil. Crop production with excess fertilization degrades soil qualities and results in poor soil carbon storage (Pahalvi et al. 2021). The application of compost protects agricultural land from harmful effects of chemical

fertilizers (Shaji et al. 2021). Compost contains high C and N content, which can be easily utilized as an energy and nutrient source for soil microbes, resulting in enhanced soil microbial growth and activity (Lee et al. 2004). Therefore, applying organic materials solely or in combination with chemical fertilizers has been proposed to increase SOC. This will result in improved soil health. Besides supplying nutrient to the crop, compost act as a soil conditioner by adding organic matter to the soil. Organic matter of soil helps in retaining soil fertility by improving the physicochemical and biological properties of the soil. Gai et al. (2019) recommended using compost as a sustainable alternative to chemical fertilizers in agriculture. Application of fresh manure or organic waste improve soil properties however their direct use in the field causes lots of complication. The untreated organic waste could contained toxic elements including heavy metal, antibiotics, *etc.* which will pose serious health problem if they enter the human food chain (Schlegel et al. 2017). The decomposition of the organic waste releases ammonia which give foul odor, introduced pathogens which may affect the crop as well as human health (Cao et al. 2016). Compared to fresh manure or organic waste, application of composted materials is more beneficial. Compost provides slow-released nutrients, retain the nutrient longer into the soil which help in reducing leaching and runoff, improve soil quality and ensure the crop development (Goldan et al. 2023). It also reduces the amount of chemical fertilizer needed for crop cultivation.

Even though organic fertilizers have proved advantageous, their sole application is unable to meet the essential nutrients of plants because they have low nutrient contents. Therefore, the combination of CFs and compost is recommended in many studies. It was reported that the integrated use of compost and chemical fertilizers increases rice yield and growth of the plant (Bilkis et al. 2015; Nayak et al. 2009; Moe et al. 2019). The study of Kumar et al. (2014) have also observed that combination of organic and inorganic fertilizer significantly increased the number of panicles, panicle weight, grain yield and straw yield compared to sole application of fertilizers. The soil blended with compost and inorganic fertilizer contains a higher value of soil organic carbon, available nitrogen than the application of inorganic fertilizer only (Ghosh and Devi, 2019). Addition of compost with chemical fertilizer

has great impact on N sources, it changes the soil C:N ratio and boosts SOM content (Pinggera et al., 2015; Wang et al., 2023). Hence, Sarkar et al. (2016) considered integrated nutrient management system to be one of the best strategy options for sustainable rice production.

It is widely known that the use of manure by farmers is mainly based on the total weight of fertilizer rather than the amount of mineralizable N. N content in compost is converted into inorganic ends by the soil microbes, as plants can utilize only the mineralized nutrients. Therefore, the total mineralizable N content should be considered while applying organic fertilizers (Moe et al. 2019). The sustainability in crop production can be achieved through proper nutrient management. Nitrate (NO_3^- -N) and ammonium (NH_4^+ -N) are the forms of nitrogen available to plants. The growth and development of plants significantly depend on the rate of N mineralization and availability of the amended organic fertilizer (Claassen and Carey, 2007). The addition of organic fertilizer resulted in higher availability of mineralized N compared to chemical fertilizer application (Thuithaisong et al. 2011).

1.4 Greenhouse gas emission (GHG) from rice field

The current rate of climate change due to human activities has become a major environmental concern in this 21st century. The agricultural sector is one among the important anthropogenic sources of greenhouse gas (GHG) emissions, especially methane (CH_4) and carbon dioxide (CO_2). It is responsible for around 10 -17% of the global total GHG emissions (Panchasara et al. 2021). Rice cultivation accounts for approximately 10% of the total agricultural GHG emissions and around 1.5% of the total anthropogenic GHG emissions (FAO, 2021; Wang et al. 2023). The global warming potential (GWP) from rice cultivation is about four times higher than wheat and maize production (Islam et al. 2020). The flooded and water saturated condition of the soil trigger anaerobic condition in the rice field, which accelerate the CH_4 emission from the rice field (Neue et al. 1997; Baiswar et al. 2023). CO_2 is produced under aerobic condition, when organic matter decompose due to microbial activities. Moreover, the respiration of plant roots and other microorganisms at the soil surface are also responsible for the emission of CO_2 (Hossain et al. 2017). And,

the emission of nitrous oxide (N_2O) from rice field is associated with the amount of N fertilizer applied (Zou et al. 2005). In India, rice cultivation is associated with food security of the country. However, its increasing demand has raised concern and become a threat to the sustainable agriculture as it impacts the global climate change by emitting GHG.

1.5 Methane (CH_4)

Methane (CH_4) is a naturally occurring major greenhouse gas. The increase in its concentration makes it an issue for concern because of its contribution to the current global warming of the Earth. It traps the longer wavelength infra-red radiation which is radiated back from the Earth's surface and keeps the atmosphere warm. At present, the global atmospheric concentration of CH_4 on average reached 1889 ± 2 ppb, which exceeds 262% of the pre-industrial level (WMO, 2021). It has a high global warming potential which is 27 times more than carbon dioxide (IPCC, 2021). Rice cultivation has been identified as an important anthropogenic source of methane emissions (Hou et al. 2000). Approximately 60% of the global CH_4 emissions come from anthropogenic sources (WMO, 2018) where agriculture alone contributes 40% (UNEP, 2021). Indian rice fields covering an area of 43.86 million ha emit 3.37 million tons of CH_4 (84.25 Tg CO_2 equivalents) (Bhatia et al. 2013), thereby ranking in top ten emitters of CH_4 emissions, sharing 10% of the total global CH_4 budget (Crippa et al. 2020). As per the UNEP (2021) report, controlling human-caused methane emissions can reduce around 0.3 °C of global warming over the next two decades and increase crop yields by 26 million tonnes per year globally.

In order to meet the demand of increasing population, global crop production in 2050 must be increased by 60% relative to the crop production in 2007 (Alexandratos and Bruinsma 2012), which can be achieved through increased productivity in the limited cultivable area. This is likely to accelerate the emission of CH_4 from the rice field. Most of the rice cultivation practically grow in standing water for extended period of crop's growth cycle. It limited the oxygen supply and creates anoxic condition of the flooded rice soil. Rice field is a well-known major source of atmospheric methane

which contributes 30 Tg CH₄ y⁻¹ (Jackson et al., 2020). Rice cultivation is identified to contribute 20% of the global methane emission (Forster et al. 2007).

CH₄ from rice fields is produced through the decomposition of organic matter by methanogenic bacteria at anoxic conditions which is developed when soils are flooded (Smith et al. 2021; Shang et al. 2011). The emission of CH₄ from rice fields involves combination of many steps; i.e. CH₄ production in the soil by methanogens, CH₄ oxidation by methanotrophs in aerobic parts of the soil and water column and transport of CH₄ to the atmosphere. In the methanogenic process, the methanogenic bacteria degrade methylated compounds like acetate, dimethylsulfide, and molecular hydrogen with CO₂, leading to the formation of CH₄ as their end product (Wassmann et al., 1992; Conrad and Klose, 2006). The release of CH₄ into the atmosphere has been regulated by diffusion of dissolved methane, ebullition and plant-mediated transport. Out of the three pathways, the gas emitted is transported mainly through rice aerenchyma and ebullition (Kajiura and Tokida, 2021). Rice plant take a significant role in transporting CH₄ from flooded soil to the atmosphere. Emission of CH₄ through rice plant alone contributes 90% of the gas emitted from the rice fields (Schutz et al. 1989). Additionally, according to Cicerone and Shetter (1981), more than 90% of the CH₄ emission from rice field during the reproductive stage was transported through rice plant.

The emission of CH₄ from rice field is controlled by both edaphic as well as agronomic factors (Eixarch-Martínez et al. 2021), some important factors being water management, where the paddy fields that are waterlogged throughout the growing season increase methane emission as compared to paddy fields which does not waterlog (Hou et al. 2012; Hadi et al. 2010; Zhang et al. 2016). Besides water management, fertilization has a significant influence on the emission of CH₄ from the rice fields (Wassmann et al. 2009). Farmers input excess fertilizers in the field to increase productivity, unaware of the damage caused to the ecosystem. The impact of N fertilizer on CH₄ emission has been studied widely but their feedbacks are controversial (Banger et al. 2012). Some studies have reported suppression of CH₄ emission from N fertilizer applied rice field due to increased oxidation of CH₄ by

methanotrophs (Banger et al. 2012; Dong et al. 2011). Meanwhile, N fertilizer application enhanced the growth of plant biomass, which increased the release of root exudates and stimulated CH₄ emission (Ma et al. 2009). Long-term use of chemical fertilizers deteriorates the physico-chemical and biological properties of soil, and makes the soil less productive. Therefore, substitution of chemical fertilizer with organic fertilizer has gained recognition in the last few years. This helps in alleviating the deterioration of soil quality. However, organic fertilizer application provides readily decomposable organic carbon which stimulates the emission of methane (Hou et al. 2000). The study of Yuan et al. (2018) provided that amendment of rice field with organic fertilizer increased CH₄ emission compared to chemical fertilizer treatment. Bhatia et al. (2005) also reported that addition of 100 % N through organic sources added more C substrate to the soil which resulted into emitting higher CH₄.

The magnitude of CH₄ emissions from organic amended rice field is determined by the type and stability of the organic substrate. The study of Jeong et al. (2018, 2019), after a complete life cycle assessment from composting to the land application, shows that the application of stabilized compost declined the emission of CH₄ during the whole rice cropping process and shows positive effect on crop productivity. The use of rapidly composted manure not only improved the rice grain yield but also decreased methane emission considerably (Zhou et al. 2016). It is necessary to mitigate GHG emissions from rice field with proper management practices to maintain sustainable production. The judicious use of fertilizer could help reduce production of methane from rice fields. Although various researches were conducted on emission of CH₄ due to organic amendment (Das and Adhya, 2014; Bharali et al. 2021) there is uncertainty in estimating its effect on CH₄ emissions from rice fields as the strength of emission greatly depend on the types and nature of organic fertilizer use as well as several agroclimatic factors. Hence, it is essential to properly address the impact of different composted materials on CH₄ emission in different rice ecosystems so that a site-specific measure could be implemented to tackle GHG emissions.

1.6 Nitrous oxide (N₂O)

N₂O is a powerful, stable GHG present in trace amounts, with an atmospheric lifetime of 114 years (Forster et al. 2007). N₂O exhibits a high global warming potential of 273 times higher relative to CO₂ over the 100-year time horizon (IPCC, 2021). The role of N₂O in greenhouse effect and ozone depletion is significant. N₂O destruct the stratospheric ozone layer through photochemical degradation (Ravishankara et al. 2009). In the last four decades, the global concentration of N₂O emissions has increased significantly. The increased concentration of N₂O in the atmosphere is mainly due to anthropogenic emissions. The addition of N in agriculture constitutes the largest share of anthropogenic N₂O emission which increased from 2.2 Tg N yr⁻¹ in 1980 to 3.9 Tg N yr⁻¹ in 2020 (Tian et al. 2024).

Rice field emissions accounted for 11% of the global agricultural N₂O emissions (Hussain et al. 2015). N₂O is produced from the soil through nitrification and denitrification processes by the microbial transformation of nitrogen (N) (Islam et al. 2020). In nitrification process, N₂O is produced as a byproduct of ammonium oxidation under aerobic conditions (Ussiri and Lal, 2013). The uptake of N₂O by soils is generally regarded to be small sink on a global scale. It is driven by denitrification by soil bacteria, which convert nitrous oxide into nitrogen gas. Denitrifiers reduce N₂O to N₂ and act as an important sink in anoxic conditions. But denitrification could also result in net N₂O production at oxic-anoxic boundaries (Codispoti et al. 1992), because O₂ inhibits the reduction of N₂O to N₂ more strongly than the reduction of NO₃⁻ to N₂O (Betlach and Tiedje, 1981).

There are various factors that affect the N₂O emissions from rice fields, such as soil pH, N concentration of soil, moisture regime, fertilizer application, and land use management (Pathak, 1999; Signor et al. 2013). In rice cultivation, the N required for plant growth and development is primarily supplied through inorganic N fertilizers. The application of N fertilizers directly influences the N₂O emissions from rice fields. As the chemical fertilizers are applied, the amount of NH₄⁺ and NO₃⁻ available in the soil increases. This will accelerate the nitrification process, and if there is limited oxygen denitrification process can follow afterwards, as a result,

N₂O is produced (Liu et al. 2005; Signor and Cerri, 2013). The N₂O emission from rice fields depends upon the fertilizer type and application rate. It was also found that irrespective of fertilizer types, the emission of N₂O increased with increase in application rate of N fertilizer (Ussiri and Lal, 2013). Besides this, N fertilizer boosts plant biomass production which increases N₂O emissions by supplying carbon source from the residue (Hellebrand et al. 2008). The available C substrate in the soil could also control N₂O emission by stimulating the activities of nitrifiers and denitrifiers bacteria (Bremner 1997). Ciampitti et al. (2008) found that soil moisture and soluble carbon content were significantly correlated with N₂O emissions. That means higher the organic C content of soil, higher the N₂O emissions. A proper fertilizer management strategy could suppress N₂O emissions from rice field by providing a balanced nutrient to crops which will increase the nitrogen use efficiency. Applying balanced fertilizers can be able to supply the required nutrients for plant development, improve plant N uptake and use N more efficiently which reduces N loss in the surrounding. N₂O emissions from rice field is also triggered significantly by water management systems (Pittelkow et al. 2013; Ali et al. 2019). Midseason drainage or intermittent wetting and drying irrigation system has been reported to increase N₂O compared to continuous flooded rice cultivation (Smith et al. 1982; Zou et al. 2005; Jiang et al. 2019). Therefore, an effective fertilizer and water management strategy could help in mitigating N₂O emissions from the rice fields. To combat climate change, it is necessary to identify the primary sources of GHG emissions and reduce its emissions.

1.7 Carbon dioxide (CO₂)

Agricultural soil has a dual nature as it is either a source or a potential sink of GHG (Gupta et al. 2021). The share of C emitted from rice fields plays a significant role in the global as well as regional budget of GHG (IPCC, 2007; Patel et al. 2011). The microbial decomposition of organic materials produces CO₂ from the soil. It is also produced by aerobic respiration of plant tissues or microorganisms (Hamilton and Sippel, 1995). CO₂ is the main GHG, contributing to around 60% of the total greenhouse effect (Liu et al. 2013). The concentration of CO₂ has reached

approximately 405 ppm, which is 46% increase from the pre-industrial level. It raises the global average temperature by 1.0 – 1.8⁰C. The emission rate of CO₂ from rice field is greatly determined by the type and amount of organic material, environmental conditions, and soil processes (Hossain et al. 2017). Agricultural management practices influence CO₂ flux from paddy soil by affecting the soil environment, such as soil moisture, soil pH, C/N ratio of substances, *etc* (Ding et al. 2006; Iqbal et al. 2009). Temperature and soil moisture have a profound impact in regulating CO₂ emission from soil. It was found out that soil CO₂-C emission has a significant positive correlation with soil temperature, air temperature and soil moisture (Adviento-Borde, 2007; Song and Zhang, 2009). These environmental characteristics significantly influence soil microbial activities and help convert plant-derived C into SOM and CO₂ (Franzluebber, 2005). Previous study by Xiao et al. (2005) has shown that application of organic and inorganic fertilizers could stimulate CO₂ flux. N application enhances plant biomass and SOC accumulation, returning the C as CO₂ to the environment (Zheng et al. 2007; Geisseler et al. 2017). As the application of chemical fertilizer has greatly increase, it is essential to understand the effect of chemical fertilizer or the combined application of chemical fertilizer and organic fertilizer to predict the future CO₂ trend from Asian rice paddies and develop possible agricultural approaches to mitigate climate change (Iqbal et al. 2009).

1.8 C-stock in rice field

Rice fields are also considered to have a strong capacity for C sequestration from the atmosphere (Song, 2015), which consequently decreases CO₂ concentration and mitigate climate change. Soil is the largest reservoir of C in the earth's terrestrial ecosystem, storing about 1500 – 1600 Pg of C (Lal, 2018), which is twice the capacity stored in the atmosphere (Davidson et al. 2000). And the capacity of agricultural field to store C has been estimated to reach upto 0.9 Pg year⁻¹ in the next 50 to 100 years (Han et al. 2016). Soil organic carbon is an important parameter that maintains the fertility and productivity of the soil (Katyal et al. 2001). The addition of organic materials improved soil physico-chemical and biological properties of soil, which ultimately increased the organic carbon content of the soil and helps in

accumulating more C in the soil (Urmi et al. 2022). A meta-analysis study (Liu et al. 2021) showed that application of organic fertilizer increased SOC stock by 19%, and combining organic fertilizer with NPK increased by 32%. Rice can grow in wide range of soil types and climatic conditions. As rice grows mostly in flooded soil, the anaerobic condition slows down the decomposition rate of organic matter and helps in accumulating more SOC into the soil (Wu, 2011). Paddy fields occupy around 9% of the world's cropland area and have a key role in the global C cycle, however, the assessment of carbon stocks in rice fields is still lacking (Liu et al. 2021). Moreover, Haque et al. (2016) suggested that controlling CH₄ and CO₂ emissions from rice fields could be an effective measure to mitigate GHG emissions from rice fields. Although the amendment of organic materials stimulates C storage in soil, it may induce CH₄ emission. Likewise, CH₄ emissions decreased when chemical N fertilizer was applied, compared to organic fertilizer treatment, but it increased N₂O emissions. Therefore, a climate-smart nutrient management strategy is required to reduce total GHG emissions from rice fields.

1.9 Compost application in rice field

As the demand for rice increases, it is necessary to adopt a sustainable agriculture management strategy to ensure food security and rural livelihood. Compost application in rice fields is an essential practice to enhance soil health and improve grain productivity. Long-term application of compost uplifts the nutrient content and microbial communities, thereby improving soil fertility and encouraging sustainable crop productivity in rice-based cropping systems (Amat et al. 2024). The study of Danapriatna et al. (2023) demonstrated that compost application in rice fields boosts organic C, total N, and K concentration of soil, which in turn increases panicle length, grain weight and spikelets per plant. Compost application has been proven to be an effective approach in enhancing crop productivity (Kadoglidou et al. 2019). The improved physical, chemical, and biological properties of soil resulting from compost application in rice fields increase nutrient availability and accelerate the nutrient uptake capacity of rice plants (Rahman et al. 2020).

Loktak Lake of Manipur is the largest freshwater lake in Northeast India. The wetland is a recognized Ramsar site. It is also popularly known as the floating lake due to the presence of floating vegetative mats, locally known as *phumdis*. The term *phumdis* refers to a collection of a heterogeneous mass of vegetation, soil, and organic matter at various stages of decomposition. *Phumdis* are found in various forms, sizes and thicknesses. Nowadays, the proliferation of *phumdi* deteriorates the lake ecosystem and shallows the depth of the lake. So, the precious ecosystem of the lake can be controlled by harvesting the *phumdi*. Singh and Kalamdhad, (2014) identified that *phumdi* compost contains higher nutrient content than other green waste compost. The combination of *phumdi* with appropriate amount of cattle manure in composting is quite effective. The harvested biomass of *phumdi* and municipal solid waste can be turned into a resource by composting. Compost made from municipal solid waste is reported to contain optimal amount of N, P and other vital trace elements and due to its higher organic matter content, it improves soil aeration, water holding capacity, microbial response, etc (Salam et al. 2021; Rajaie and Tavakoly, 2016). Moreover, the application of vermicompost in agriculture significantly enhances crops resilience to biotic and abiotic stresses, ultimately leading to higher yields (Vambe et al. 2023). Vermicompost is a good soil amendment that increases organic matter content, water retention capacity, drainage, and microbial activity (Edwards and Burrows, 1988; Domínguez et al. 2004). The nutrient contained in vermicompost are easily available to plants and act as a plant growth media (Edwards and Burrows, 1988; Bejbaruha et al. 2009). A review paper by Dhanuja et al. (2020) highlighted that application of vermicompost in rice field was more beneficial than chemical fertilizer or other types of organic fertilizers.

1.10 Scope of the study

In Manipur, a northeastern state of India, people primarily cultivate rice crop for food as well as for economic sustainability. Most of the livelihood of the people of Manipur depends on agriculture. Although some farmers in Manipur adopt water management practices done through irrigation channels, majority of the rice

cultivation still depends on rain. Rice field is an important source of GHG emissions. And the emission of GHG from rice fields depends on the soil type, climatic conditions of the region and agricultural management techniques.

The study attempts to evaluate the effect of locally available organic fertilizers on the growth and yield of rice production and emission of GHG from the paddy field. Even though many investigations were carried out to study the significant relationship between organic fertilizer amendment and GHG emissions from rice fields, the results were different due to the utilization of different raw materials while making organic fertilizer. Therefore, it is important to study the potential of locally made organic fertilizers on the yield of rice production as well as the changes in the emission of GHG.

It is crucial to identify the types of organic fertilizer that could reduce chemical fertilizer inputs, rejuvenate soil health and mitigate GHG emissions from rice fields without declining crop yield. Moreover, this study was conducted to gain more insight into the C balance and soil properties of rice cultivation under different fertilizer treatments. Similar studies on the impact of application of locally made compost on GHG emissions have not been reported from Manipur so far. Even in Indian context, no data has been available on total GHG emissions (CO₂, CH₄, and N₂O), GWP and emission factor of CH₄ and N₂O from rice fields due to the utilization of vermicompost and *phumdi* compost.

1.11 Objectives

1. To estimate the growth and yield of rice under organic fertilizer and chemical fertilizer.
2. To estimate emission of methane, nitrous oxide and carbon dioxide from rice field in response to treatments.
3. To compare the growth and yield of rice and emission of methane with organic and chemical fertilizer treatments.

4. To estimate the effect of organic fertilizer and chemical fertilizer on soil properties under rice cultivation.

1.12 Structure of thesis

The present thesis consists of seven chapters starting with

Chapter 1- Introduction

Chapter 2- Review of literature

Chapter 3- Materials and methods

Chapter 4- Results and Discussion

Chapter 5- Summary and conclusion

Appendix

References

2. REVIEW OF LITERATURE

Rice is one of the three most important staple foods in the world. It grows in 122 countries, covering a vast area of around 1.38 million km² (Prasad et al. 2017; Yadav et al. 2024). Asia accounts for 90% of global rice production, and India contributes 21.5% of the world's rice production. Globally, India stands second after China, producing 172.58 million tonnes of rice in its 44.50 million ha of arable land (GOI, 2020). In the Asia-Pacific region, the annual production of rice is 524 million tons per year but is estimated to increase by 700 million tons by 2025 (Papademetriou, 2000). The production of rice is associated with food security. As the population increases, the demand for rice also increases. Fertilization of soil is an essential process for maintaining soil quality and providing essential nutrients to crops to enhance productivity. The application of fertilizer has positive effect on biological yield, grain yield, harvest index and 1000-grain weight of rice (Erfani et al. 2020).

Manipur has favorable climatic conditions for agriculture. However, the sustainability of rice cultivation has not been achieved well (Singha and Mishra, 2015). Irungbam et al. (2019) reported that the grain yield of Kharif rice in Manipur valley was found to be highest (43.17 q ha⁻¹) on nutrient management application of 50% RDF + 6t FYM followed by 50% RDF + Azolla (dual crop) @10 t/ha + 3t FYM and 100% RDF respectively.

N fertilizer plays a vital role in rice production, responsible for 38% of rice yield. However, over 50% of N fertilizer added to rice fields is lost to the atmosphere as nitrous oxide N₂O, nitrate and ammonia. This causes adverse impacts/effects on the environment as well as human health. It is believed that applying organic fertilizer improves N uptake by plants and NUE as organic fertilization delays N volatilisation and preserves N in the soil (Luo et al. 2011; Gu and Yang, 2022). Partial substitution of chemical fertilizer with organic fertilizer showed positive effects on the availability of soil N, protease, and leucine aminopeptidase levels, which also increased significantly. The reduction of chemical fertilizer by substituting it with organic fertilizer proved to be an effective way to enhance NUE. The growth of soil

bacteria and fungi abundance was improved when organic fertilizer was applied (Wang et al. 2023).

2.1.Effect of different fertilizers on growth and yield of rice

A study conducted by Urmi et al. 2022 observed that the maximum yield of rice was obtained when 2.5 t ha of vermicompost and poultry manure applied along with 75% of the recommended dose of chemical fertilizers. Therefore, the study recommended integrated nutrient management to ensure sustainable agriculture.

The application of organic fertilizer has become a practical approach to ensure sustainable agriculture. Siavoshi et al. (2011) observed that organic fertilizer has a significant impact on the growth and productivity of rice. The treatment of organic fertilizer with 2.5 tons/ha received the highest grain yield of 4335.88 kg/ha compared to other organic fertilizer treatments (0.5, 1.0, 1.5, 2.0) in the first year of the experiment. In the second year, the combined application of the recommended inorganic fertilizer (NPK) dose and 1.5 ton/ha organic fertilizer gives the maximum grain yield (4662.71 kg/ha). The study suggested that rice yield can be improved by combining organic and inorganic fertilizer, which reduces inorganic fertilizer application and maintains the soil's natural properties.

A study was conducted to determine the effects of integrated organic and inorganic fertilizers on the growth and yield of two rice varieties, *i.e.* Manawthukha, a high-yielding variety and Genkitsukushi, a heat tolerant and high-yielding rice variety, in Japan (Moe et al. 2019a). The results showed that the integration of organic fertilizer with chemical fertilizers resulted in the highest growth and yield components of both rice. The application of 50% poultry manure integrated with 50% chemical fertilizer achieved the highest yield and growth components.

Moe et al. (2019b) added organic fertilizers based on estimated mineralizable nitrogen in rice fields by combining them with chemical fertilizer (CF) to estimate their effects on rice's growth, yield and NPK status. Applying organic fertilizer with total N content greater than or equal to 4% led to higher availability of NPK nutrients

and increased crop yields by around 9% over 100% chemical fertilizer application. The rice yield in 50% chemical fertilizer (CF) with 50% cow dung manure (CH₅₀CM₅₀) and 50% CF with 50% compost (CF₅₀CP₅₀) treatment was lower than 100% CF (CF₅₀) treatment during the first year of study but increased during the second year. This indicates that the effectiveness of cow dung manure and compost application (total N less than 4%) on plant growth and yield get better only after continuous application for two years.

With rapid urbanization, municipal solid waste (MSW) has been generated in massive amounts. It could cause many environmental problems if proper management is not taken. The best and easiest way to manage MSW is composting. The stabilized end product from MSW composting is generally used as organic fertilizer. However, they have low nutrient quality. In order to improve its nutritional value, Sultana et al. (2021) amended MSW compost with some organic raw materials. The rice grain supplied with amended compost resulted in better yield and higher N, P, K and S values.

Aktar et al. (2018) studied the effect of municipal waste compost (MSW) and chemical fertilizers on the biomass production and yield of boro rice (BRRI dhan 50) at the soil science field laboratory of Bangladesh Agricultural University (BAU). They found that the plot treated with 10 t ha⁻¹ of compost plus 100% of the recommended dose of fertilizers produced the highest biomass yield (925 g/m²), grain yield (6.3 t/ha) and straw yield. Therefore, this type of application was recommended for profitable rice production in Old Brahmaputra Floodplain soils. Agrawal et al. (2003) observed that the use of vermicompost along with organic manure resulted in a maximum yield of the wheat plant. The study further reported that, in addition to increased productivity of crop, the application of vermicompost minimize the problem of organic waste disposal. According to Bejbaruah et al. (2013), it was reported that initially, the use of vermicompost has low nutrient use efficiency and productivity of rice. However, its split application increased the grain yield, yield components like panicles, filled grains per panicle and spikelet per panicle.

Dey et al. (2019) reported that the addition of vermicompost of *phumdi* and organic municipal solid waste resulted in higher growth and yield of King Chilli as compared to the compost of the same organic matter. Moreover, the nutrient content was significantly higher in vermicompost. Dhanuja et al. (2019) also found that application of vermicompost resulted into better rice grain weight (21 mg) and grain length (6.3 mm) over chemical fertilizer treatment plot. The application of vermicompost recorded a grain yield of 2300 kg ha⁻¹ which was over 11% increased from chemical fertilizer plot.

The study of Ghosh and Devi, (2019) observed that when compared with other types of amendment (NKP + crop residues and NPK + farm yard manure), the plot blended with NPK + compost yielded the highest quantity of rice. It was also found that the moisture and total carbon of the soil were positively significant on rice yielding. The application of enriched pressmud compost in rice fields significantly increased rice's tiller number and dry matter production compared to non-amended soil. The number of grains per panicle and 1000 grain weight also increased, resulting in higher grain yield than non-amendment soil (Kalaivanan and Hattab, 2016). Razavipour et al. 2018 also reported that the amendment of soil with compost had positive effect on rice growth and yield.

Kumar et al. (2012) developed an organic matrix entrapped urea (OMEU) by using locally available agro-waste and applied in rice fields. Results revealed that OMEU application improved plant growth and biomass, and plant height doubled over free urea treatment plants. Tiller number and productivity were also increased significantly with the application of OMEU.

Kumar et al. (2014) found out that application of combined organic and inorganic resulted in higher yield and yield attributes over control and sole application of organic or inorganic fertilizer. Addition of 125% recommended dose of fertilizer + 5 t ha⁻¹ vermicompost significantly increased number of panicles, panicle length, panicle weight, 1000 grain yield, grain yield, and straw yield by 20.50%, 23.12%, 13.02%, 12.90%, 31.15%, and 37.12% respectively over control.

Husan et al. (2014) carried out an experiment to identify the effect of different sources of N on nitrogen use efficiency (NUE) and grain yield. The study comprised of six different treatments *viz.* control, 78 kg N ha⁻¹ from urea super granule (USG), 136 kg N ha⁻¹ from prilled urea (PU), 58 kg N ha⁻¹ from USG + 3 t ha⁻¹ poultry manure and 58 kg N ha⁻¹ USG + 5 t ha⁻¹ cow dung. In the experiment, it was identified that grain yield, straw yield, N uptake and NUE were significantly influenced by the different treatments of fertilizers. The combined application of USG and poultry manure recorded the highest grain yield, nitrogen uptake, and NUE.

Devi et al. (2019) established four different treatments of fertilizer *viz.* conventional method, 100% recommended dose of farm yard manure, 100% recommended dose of Loktak phumdi compost and 50% farm yard manure +50% phumdi compost. The experiment was carried out at the College of Agriculture, Manipur with an aim to study the effect of different fertilization on growth of black aromatic rice. The results of the experiment revealed that plant height was maximum in conventional method during the first year, however in second year the integrated treatment of 50% farm yard manure and 50% Loktak phumdi compost gave higher growth. The number of tillers per hill was also highest in 50% farm yard manure + 50% Loktak phumdi compost.

Javier et al. (2004) observed that among the different treatments, chicken manure treatment achieved the highest yield of 25.8% increase over unfertilized plot. The rice yield was stabilized during the first two years of organic fertilizer application, but decreased in the third year. The results inferred that sole application of organic fertilizer was unable to sustain the yield, therefore application of combined organic and inorganic fertilizer should be adopted.

Troza et al. (2021) carried out a field experiment in Caraga State University of Philippines to find out the effects of organic and inorganic fertilizer treatments on growth and yield components of rice. The treatments include control, farmers practice (FP) where 159, 21, and 51 kg ha⁻¹ of N, P, and K were added, recommended rate (RR) where 70, 7, 37 kg ha⁻¹ of NPK, organic fertilizer (OF) made from the combination of 50% chicken manure, 25% saw dust and 25% carbonized

rice hill, and 50%RR+50%OF. Application of fertilizer had a profound effect on the growth and yield of rice. FP treatment had the highest plant height (107.14 cm), productive tillers (18), panicle weight (38.87 g), panicle length (27.66 cm), and total number of grains per panicle (113). The maximum grain yield was recorded from FP treatment with 43% increase relative to control treatment.

The study of Srivastava et al. (2014) found out that out of three level of N fertilizer *i.e.* 50%, 75% and 100% recommended dose of fertilizer (RDF) added, 100% RDF gave the highest straw and grain yield. The adequate supply of nutrients throughout the crop cycles improve plant nutrients absorption which resulted in producing more panicles, number of filled grains per panicle with grain test weight. Furthermore, the study also identified that application of organic fertilizer through vermicompost at the rate of 45 kg N achieved the highest grain yield. Harvest index (HI) was recorded highest at vermicompost applied plot (15 kg ha⁻¹). Combined application of 75% RDF + 45 kg N through vermicompost resulted in higher grain yield over other treatments.

Shu (2005) used pea-rice hull compost and cattle dung-tea compost having N content of 24.5 and 26.0 g kg⁻¹ in a pot experiment to determine their effect on rice growth. In the first year 404 g of PRC and 380 g of CTC were added in 3 kg of soil while NPK were applied in the rate of 0.7, 0.25, and 0.35 g pot⁻¹ respectively. And no further composts were added to the compost amended pot in the second year. However, the chemical fertilizer treatment pot received the same quantity of N and P fertilizers. Although the chemical fertilizer treatment recorded maximum tillers number, dry matter yield and nutrients uptake during the early stages of rice growth, PRC treatment had the highest plant height, straw growth and nutrient uptake at the maturity stage. The work also revealed that the effect of composts on rice growth depend on the composition of the composts added. According to Xia et al. (2024), incorporation of biochar made from pyrolyzed maize straw act as an effective strategy to obtain optimal rice yield. It increased rice yield by 6.1% relative to no fertilizer treatment.

2.2.Effect of different fertilizers on GHG emissions

In a study conducted by Soebandiono et al. (2021), it was revealed that the use of indigenous organic fertilizer could be a mitigating option to reduce CH₄ emissions from paddy fields without compromising productivity. Further, it was implied that inorganic fertilizer produced the highest CH₄ emission, and the plant height has an influence on CH₄ emissions where they are negatively correlated. According to Islam et al. (2022), adopting urea deep placement (UDP), an improved method of N fertilizer application, along with alternate wetting and drying irrigation (AWD), could be an effective mitigation measure to control emissions of greenhouse gases from rice cultivation. The study further validates that AWD irrigation reduced net CH₄ emissions by 28% compared to continuous flooding. UDP increased rice yield by 21% compared to combining poultry manure and prilled urea application.

According to Wang et al. (2021), other than the addition of direct carbon inputs, the application of different methods of organic amendment also influenced the availability of photosynthate carbon, which is the methanogenic substrate. Thereby it induced the CH₄ emission from the paddy field. In a study by Traore et al. (2017), CH₄ emissions from rice fields amended with a different type of fertilizers (organic and chemical) were found to be high during the 5 days after peak tillering and 7 days after heading flowering stage. Thus, it was concluded that different fertilizer treatments affect CH₄ emissions at different stages of the growth of rice crops. And the organic fertilizer application creates a suitable environment for methanogenic activities. However, Nungkat et al. (2015) reported that the use of organic fertilizers for rice production was not correlated with CH₄ emissions. The redox potential significantly controlled the increase in CH₄ emission.

Ali et al. (2015) recommended the inoculation of azolla-cyanobacteria with organic and inorganic amendments in paddy fields of subtropical countries to reduce global warming potential (GWP) and greenhouse gas intensity (GHGI). The application of silicate slag with cyanobacteria and phosphor-gypsum with cyanobacteria decreased GWP by 29-30% over the control (NPK only). The application of biochar with cyanobacterial inoculation also decreased in GWP, although cumulative CH₄

emissions significantly increased. The high content of free iron and sulphate inhibits the formation and emission of CH₄, owing to a strong competitor for hydrogen and acetate (Hori et al. 1993; Chidthaisong and Conrad, 2000).

Haque et al. (2021a) identified that amendment of vermicompost with chemical fertilizer reduced GWP, emission factor (EF) of GHG, GHGI and CH₄ emission per kg grain yield from rice fields compared to cow dung plus chemical fertilizer application. Although sole chemical fertilizer application emitted lesser GHG, rice productivity was around 1.36 t ha⁻¹ higher in vermicompost with chemical fertilizer. The study also suggested that a proper rate of vermicompost needs to be identified to reduce the emission of GHG. In another study, Haque et al. (2021b) evaluated the effects of different source of organic manure (vermicompost, cow dung and poultry manure) on CH₄ and N₂O fluxes under two water management method (alternate wetting and drying and continuous flooding). Seasonal fluxes of CH₄, N₂O and CO₂ were significantly affected by the interaction between different fertilizers application and water management ($p < 0.1$). During the study, it was observed that the peak CH₄ fluxes was obtained at 21 – 35 DAT in continuous flooding system while at 28 – 42 DAT in alternate wetting and drying irrigation system. GWP in alternate wetting and drying system was distinctly lower compared to continuous flooding and among the different organic amended plots, vermicompost with chemical fertilizer had the lowest GWP. Therefore, practice of alternate wetting and drying along with vermicompost and chemical fertilizer amendment were recommended to limit GHG emissions from rice field.

Hwang et al. (2017) found that applying cover crop biomass significantly increased the net global warming potential in rice cultivation. Therefore, the author suggested the application of composted biomass in place of green biomass to reduce the emission of CH₄ from paddy fields. In the study of Haque et al. (2016) also, emission rates of GHG significantly increased with the higher rate of cover crop biomass application.

A study was conducted by Kim et al. (2022) to evaluate the long-term effect of compost fertilization on soil chemical properties and methane-related functional gene

abundance. The study found that compost and compost+NPK fertilization increased the nutrient content (organic matter, total N, P_2O_5 , K, Ca, Mg and pH) of the soil. And these changes in soil chemical properties resulted in increased abundance of methane-related genes. The paddy soil in the long-term application of compost showed distinct alternation in soil chemistry from those of unfertilized paddy fields. These changes were also present during the fallow season. Therefore, the study gives proper understanding of how long-term compost fertilization influences chemical and biological properties of soil during and even after the rice growing season which impact methane emission and oxidation from rice fields.

Kong et al. (2019) identified that the addition of N fertilization stimulate CH_4 emissions by increasing methanogenic activities rather than reducing methanotrophic communities in rice fields. The researcher established four different fertilization treatments to identify their impact on CH_4 emission by closely linking them to soil methanogenic and methanotrophic communities. Compared to chemical PK treatment where no N fertilizer was added, NPK treatment, NPK combined with organic manure and organic manure alone increased seasonal mean CH_4 emission by 67.4%, 101.2 % and 20.4%, respectively. Application of integrated chemical fertilizer and organic N added additional C substrate into the soil and increased methanogenic activities, which led to the highest emission of CH_4 .

To identify the performance of vermicompost on CH_4 emission, Dhanuja et al. (2019) selected *Chinna Ponni* rice variety cultivated under intermittent flooding condition. The measurements of the gas were done at five different stages of rice growth. The highest emission was occurred at panicle initiation stage from chemical fertilizer treatment plot. Overall, CH_4 emission was higher in vermicompost applied plot ($111.3 \mu m^{-2} h^{-1}$) compared to chemical fertilizer treatment plot ($71.0 \mu m^{-2} h^{-1}$) but there were no significant differences between the two.

Application of nitrogen fertilizer promote plant biomass which in turn provide more C into the soil (Lu et al. 2009). Hence, the N fertilizer application significantly increased CH_4 emissions and SOC sequestration when compared with no fertilizer treatment, however, no significant effect was shown on CO_2 emissions (Cheng-Fang

et al. 2012). Iqbal et al. (2009) conducted a study to assess the effect of straw and N-fertilization on CO₂ flux. The study selected seven different treatments, *i.e.* control (CK), fertilizer PK (N0), fertilizer NPK (N1) (50% N), fertilizer NPK (N2) (100% N), fertilizer NPK (N3) (200% N), fertilizer NP + straw (N0 + S), fertilizer NPK + straw (N2 + S) (100% N). During the study, it was observed that CO₂ fluxes were significantly higher during the reproductive stage of the crop and lower during the maturity stage. And the application of N fertilizer showed distinct variation in CO₂ flux where the highest flux was found in N2 + S treatment while the lowest flux was found in N0 + S treatment. The study also observed that although N fertilization increased CO₂ flux, the integrated use of N fertilizer and straw could mitigate the global carbon budget by sequestering C into the soil.

Yang et al. (2015) conducted a soil incubation study to investigate the effect of organic amendment on GHG emissions under different soil cultivation regimes. The study revealed that organic amendment significantly influenced the N₂O and CO₂ fluxes of the soils. The C/N ratio of organic fertilizer plays a crucial role in predicting GHG emissions. Organic fertilizer with lower C/N ratio acts better in reducing GWP from agricultural soil relative to higher C/N ratio.

Bharali et al. (2021) conducted a study to identify the effects of organic inputs on methane emissions from a rice field under two rice ecosystems (irrigated and rainfed). The results identified that irrespective of ecosystems, the type of organic inputs have a significant impact on CH₄ emission patterns, soil C dynamics and rice yield. The application of *Azolla caroliniana* compost increases soil carbon sequestration, which lowers the CH₄ emission. And at the same time, it promotes grain yield by 2.8% and 5.1% compared to cow dung and green manure application, respectively. It was also found that the inputs of friable organic manure could reduce methane emission by around 30-36% through the enhancement of porosity, C-storage, and recalcitrant C fractions in soil.

In research conducted by Datta et al. (2013), it was identified that the use of nitrogen fertilizer alone enhanced CH₄ emission from rice fields. However, the integrated application of nitrogen, phosphorus and potassium reduced CH₄ emission to grain

yield ratio significantly. This might be because the addition of P and K fertilizer promotes plant aerenchyma, which helps in reducing CH₄ emissions from rice field. And, the emission of CH₄ was positively correlated with microbial biomass carbon and readily mineralizable carbon.

Das and Adhya, (2014) stated that the combined application of compost and urea-N could be a better option to control greenhouse gas emissions (CH₄ and N₂O) from flooded rice ecosystems without affecting the soil biological properties and yield. They worked on the effect of integrated use of organic manure and inorganic fertilizer on greenhouse gases (CH₄ and N₂O) from rice planted in tropical flooded soil under different nitrogen (N) management, *i.e.*, urea-N (120kg N ha⁻¹), rice straw (RS) (30 kg N ha⁻¹) + urea-N (90 kg N ha⁻¹), compost (C) (30 kg N ha⁻¹) + urea-N (90 kg N ha⁻¹) and poultry manure (PM) (30 kg N ha⁻¹) + urea-N (90 kg N ha⁻¹). Among the treatments, C+ urea-N has the lowest greenhouse gas emissions and highest Carbon efficiency ratio with a relatively higher yield.

The impact of organic farming on GHG emission from agriculture is still unclear. In a study by Malav et al. (2020), the amendment of different combinations of organic materials led to the reduction of GWP by around 3.0 to 29.4% compared to conventional treatment and 67.78% decrease in the non-amended plot. And hence, this indicated that organic practices could replace the conventional system as a way to reduce GHG emissions from rice fields. However, Mohanty et al. (2020) pointed out that although combination of organic matter and chemical fertilizer reduced N₂O and NH₃, there was an increase in GWP due to higher emission of CH₄. The peaked emission of N₂O was observed within 2-3 days after application of N fertilizer. The slow decomposition rate and less availability of N to plant led to a decrease in yield performance to around 9.8 – 20.0% in combined fertilizer treatments compared to urea alone, which resulted in higher GHGI.

In order to understand the impact of N management and crop establishment on GHG fluxes, Mohanty et al. (2017) set up two cropping systems- direct seeding rice under non-puddled and non-flooded conditions (AR) and puddled transplanted rice under flooded conditions (PTR). Seasonal cumulative CH₄ emission was significantly

higher in PTR, which led to higher GWP, although N₂O and CO₂ were emitted significantly higher in AR. The increased emission of CO₂ from AR might affect the soil's biological activity due to the loss of C from the soil. The addition of farm yard manure with prilled urea helped in reducing N₂O emission and maintained higher microbial biomass concentration and soil enzymatic activities in both cropping systems.

Bhatia et al. (2005) suggested that emissions of GHG from rice fields should be considered while adopting an organic amendment to improve soil health and yield of crops. Application of sole organic amendment increased by 60% CH₄ from 100% inorganic fertilizer treatment. Also, the substitution of 25% inorganic fertilizer N for organic fertilizer increased CO₂-C by 17-25%. But, the yield of the crop was highest in the organic and inorganic fertilizer combined treatment. And the lowest yield in 100% organic fertilizer treatment was due to low N availability.

Phosphorus (P) is one of the main essential nutrients for rice growth. P fertilization enhances root growth and rhizosphere activities (Cholitzkul et al. 1980). At the same time, the addition of single superphosphate (SPP) is also known to inhibit CH₄ production from rice fields (Rath et al. 2005). Another study by Adhya et al. (1998) found that SPP application significantly suppressed CH₄ emissions from rice fields. Moreover, the production and inhibition of CH₄ depend on the source of P applied, where the highest emission occurred in Jordan rock phosphate while the lowest in SPP. It was because the S content in SPP limited the emission of CH₄.

Haque et al. (2020) identified that amendment of organic fertilizer in paddy soil not only improved rice yield but also increased CO₂ capturing capacity by 17 – 22 gm kg⁻¹ grain yield compared to chemical fertilizer amendment. The use of organic fertilizer in rice cultivation is recommended as an important practice to sequester CO₂ in tropical countries.

A field experiment was conducted by Thu et al. (2016) in Vietnam to study the effect of water regimes and organic fertilizations on mitigating GHG emission from rice field. The study consisted of two water regimes *i.e.* alternate wet and dry (AWD)

and permanent flooding (PF) and four fertilizer treatments: NPK only, NPK and farm yard manure (FYM), NPK and straw compost, and NPK and straw biochar. The combined strategy of AWD with NPK + straw biochar had positive impact on mitigating GHG emission from rice field which reduce 53.4% CO₂ eq per grain yield compared to PF with FYM.

To study the impact of long-term fertilization on GWP and GHGI, Shang et al. (2011) established six different fertilizer treatments in double rice cropping system. The net annual GWPs of fertilized plots were greatly increased compared to control (no fertilizer). Application of combined organic and inorganic fertilizer increased GWP and GHGI by 86 to 107% and 5% respectively over the control. The study further reported that long-term fertilization of inorganic fertilizer enhanced CH₄ emission from the improved plant growth and SOC sequestration. SOC content was found to be positively correlated with seasonal CH₄ emissions. Among NP, NK, and NPK treatments, the balanced application of fertilizer *i.e.* NPK treatment emitted lesser N₂O emissions. Therefore, they suggested to maintained a balanced fertilizer strategy with crop residue amended in the field during the non-rice drained season to achieve sustainable agriculture with less GHG emissions.

Khalil and Shearer (2006) pointed out that emissions of CH₄ from rice fields varied depending mainly on organic fertilizer use and water management. As the area under rice cultivation changes over the decades, the total annual emissions across the countries were certainly affected. Although the changes of organic fertilizer with nitrogen-based fertilizers decreased CH₄ emission, it would accelerate N₂O emissions from rice fields.

Sun et al. (2020) conducted a research on the impact of controlled-release fertilizer with wheat straw incorporation on GHG emissions from a rice field in China. The incorporation of controlled-released urea with straw significantly stimulated CH₄ and N₂O emissions by around 163.7 – 364.9% and 153.0 – 399.3% respectively compared to chemical fertilizer treatment.

Under rice-wheat cultivation system, Xia et al. (2024) identified emissions of CH₄ from rice cultivation took a greater share in overall GWP of the cultivation system. In two rice cropping season, the total seasonal emissions of CH₄ ranged between 37.44 to 1729.60 kg ha⁻¹. The emissions was significantly higher in first year. Treatment of biochar made from pyrolyzed maize straw resulted in reducing CH₄ emission over direct crop residue return or manure application. Additionally, the treatment can reduce total seasonal N₂O emissions from rice cultivation. Across the cropping seasons, the emissions rate of N₂O reached its peak after fertilizer treatment.

Saha et al. (2017) observed that higher flux of CH₄ occurred in vermicompost amended plot (12.39 to 36.54 mg m⁻² d⁻¹) compared to ammonium sulphate amended plot (-1.08 to 20.72 mg m⁻² d⁻¹). On the contrary, N₂O flux was significantly higher in ammonium sulphate amended plot. During the two experimental years, the emissions of GHG from the rice was significantly different where the highest CH₄ and N₂O fluxes was obtained during the second year. The study recommended to establish regional management options to minimize GHG emissions.

2.3.Effect of different fertilization on soil properties

The properties of soil improve with regular application of organic manure. Clark et al. (1998) identified that continuous use of organic farming for 8 years in California's Sacramento Valley resulted in higher SOC, soluble P, exchangeable K and pH. It also increased nutrient storage and organic matter in the soil. Assefa and Tadesse, (2019) reviewed that both organic and synthetic fertilizers had its role in soil properties. Even though chemical fertilizers give instant benefits, they have long-term effects on the soil. Therefore, organic farming has been recommended to protect soil quality and increase soil productivity. Organic material act as both fertilizer and conditioner to the soil by providing essential needs of the plants as well as soils. The application of organic fertilizer not only supplies nutrients but also helps in mobilizing nutrients from its non-exchangeable source (Liao et al. 2010). SOM and total N contents of soil were 88% and 86% higher, respectively, when cow

dung manure was applied. The effectiveness of organic fertilizer application in providing essential nutrients to plants was more apparent over time (Cen et al. 2020).

The study of Zhong and Cai (2007) proved that organic amendment is necessary to improve soil microbial growth and increase crop productivity. SOC is crucial in increasing microbial biomass, which is essential in determining soil fertility. However, the addition of chemical fertilizer N and P could increase SOC only to a limited extent.

Chemical fertilizers blended with different types of organic fertilizers are also used to reduce the environmental impact of the continuous use of chemical fertilizers. Ghosh and Devi (2019) observed that the input of integrated organic materials and NPK improved various properties of the soil. Similar result of improved soil nutrients was observed by Urmi et al. 2022. In the study the application of organic fertilizers vermicompost and poultry manure integrated with chemical fertilizer significantly increased available K, available P, Ca, Mg content of soil over zero input of fertilizer and sole application of chemical fertilizer. The integrated nutrient treatment also increased SOC stock, TC stock, and OC sequestration.

The study of Liu et al. (2009) identified types and quantities of organic amendment that strongly influence soil microbial content and nutrient availability in a subtropical paddy field. The amount of yearly C input from the organic amendment and rice production leads to the development of soil microbial biomass and increases nutrient availability in the soil. The use of farmyard manure results in superior soil properties over green manure and rice straw.

According to Zia et al. (1998), organic fertilizer not only supplies nutrients to the soil but also improves water holding capacity that assists the soil in maintaining better aeration for root development. Aktar et al. (2018) found that addition of MSW compost is known to give positive effects on soil qualities. It increases soil porosity, TOC, and cation exchange capacity. Soil microbial biomass and dehydrogenase activity were also increased with compost application (Domínguez et al. 2019). This

could imply that MSW compost can be used as an alternate source of synthetic fertilizer and as a way of sustainable waste management.

The study by Ramadass and Palaniyandi (2007) revealed that using enriched MSW in rice fields boosts the availability of crops' macronutrients, thereby improving soil fertility and productivity. In the study, the soil blended with enriched compost contained the maximum amount of $\text{NO}_3\text{-N}$ and $\text{NH}_3\text{-N}$. The available phosphorus, potassium and micronutrients were also found to be maximum in the enriched blended soil. Although MSW compost has been widely used as crop fertilizer, its long-term application on fields needs to be evaluated as there is concern about metal loading into the soil and crops (Bhattacharyya et al. 2006).

Vermicompost, an end product resulting from the decomposition of organic matter by the combined action of earthworms and microorganisms, is rich in nutrients that can be readily available for plant uptake. The application of vermicompost as soil amendment enhances soil microbial activity, water-holding capacity and porosity (Dominguez and Edwards, 2004) and it also contains plant growth hormones (Nielson, 1985).

The application of OMEU made from locally available agro-waste increased SOC, total N and available NPK, which improved the physico-chemical properties of rice cultivated soil; hence the study suggested that OMEU can be used as an alternative to chemical N fertilizers (Kumar et al. 2012).

In a study by Chettri et al. (2017), it was found that soil pH, EC and bulk density decreased when vermicompost was added in rice field. Total N and available P were found maximum in vermicompost and chemical fertilizer amended plots. The results indicated that combined application of organic and chemical fertilizer can improve soil health.

Javier et al. (2004) used different types of organic material, chemical fertilizer and commercial organic fertilizer to determine the nutrient dynamics of rice cultivated soil. The study showed that soil N was maximum in chemical fertilizer plot. The N content of the soil followed a decreasing trend from 14 days after transplantation to

28 days after transplantation and then stabilized at the later stage. The maximum N content was recorded in chemical fertilizer applied plot. However, application of chicken manure and rice straw increased available P and K over chemical fertilizer applied plot throughout the crop growing stages.

Sarwar et al. (2008) found out that compost application in rice field significantly reduced the soil pH compared to chemical fertilizer treatment or no fertilizer treatment. This could be due to the release of organic acid from mineralization of organic materials. Amendment of compost along with chemical fertilizer improved the soil organic matter content (0.98 %). It was recommended that farmer should adopt the method of compost application in order to sustained the fertility and productivity of soil. The application of green manure in rice cropping resulted in maximum soil N, P and K contents followed by poultry manure. Application of green manure reduced the loss of N upon flooding (Alagappan and Venkitaswamy 2016).

3. MATERIALS AND METHODS

3.1. Study site

The experiment was conducted at the experimental plots of Rice Research Station, Wangbal situated in the Thoubal district of Manipur, India. The rice research station was set up under the State Agriculture Department. The site lies between 24°36'50"N to 24°36'55"N latitude and 94°1'10"E to 94°1'25"E longitude. The study area experienced a sub-tropical climate, with an altitude of 790 m above m.s.l. and an annual rainfall of 1200 mm to 2700 mm. The geographical location of the experimental site is represented in Fig.1. The air temperature during the study period ranged from a minimum of 14.07⁰C to a maximum of 34.95⁰C.

3.2. Climatic conditions of the study area

The meteorological data of the study site were collected for five years starting from 2019 to 2023 from the Directorate of Environment and Climate Change, Manipur. The detail description is presented below:

3.2.1. Ambient air temperature

The five years monthly average air temperature is depicted in Fig 2. The average maximum air temperature during the five years were ranged between 20.9⁰C in January, 2022 to 32.06⁰C in August, 2023. In the five years, 2023 recorded the maximum average air temperature (28.4⁰C) and 2020 recorded the minimum (16.71⁰C).

The average minimum air temperature was ranged between 7.7⁰C (January) to 21.98⁰C (July); 8.68⁰C (December) to 22.29⁰C (August); 8.83⁰C (January) to 22.12⁰C (August); 8.81⁰C (February) to 21.79⁰C (August); 8.46⁰C (January) to 23.50⁰C (September) during 2019, 2020, 2021, 2022 and 2023, respectively. In 2019, the average maximum air temperature reached upto 30.76⁰C during the month of June, and in 2020, the month of September with 30.87⁰C become the hottest month. In 2021, the maximum temperature was recorded during the month of April

with 31.16⁰C. And, in 2022 and 2023, the temperature reached upto 31.83⁰C and 32.06⁰C during September and August, respectively.

While, the average minimum temperature reached upto 7.79⁰C in the year 2019 during January. In 2020, December had the lowest average air temperature with 8.68⁰C. But in 2021, the minimum temperature in December increased to 10.58⁰C and the coldest month was recorded in the month of January with 8.83⁰C. In 2022, the month of February with 8.81⁰C recorded to be the coldest month. In 2023, the minimum average air temperature was recorded during January (8.46⁰C).

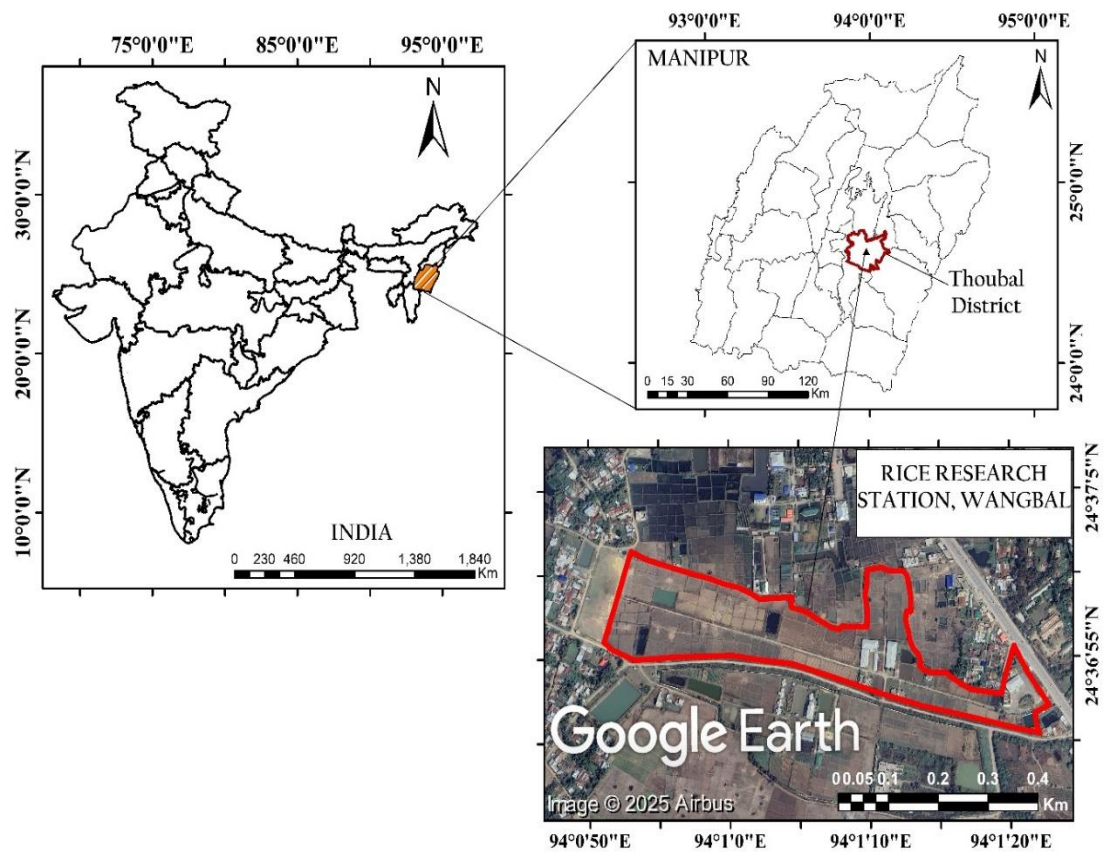


Fig.1: Map of the study area.

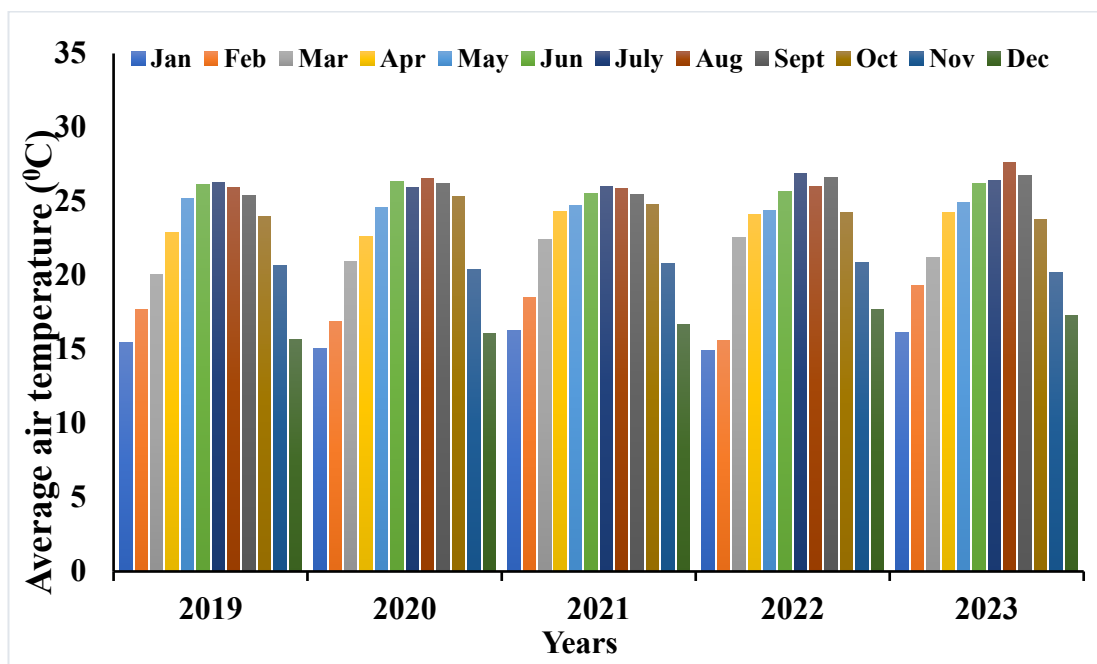


Fig.2: Average monthly temperature of Thoubal district for five years (2019 – 2023).

3.2.2. Total Rainfall

The rainfall pattern during the five years is depicted in Fig 3. In the five years, the highest total rainfall was recorded during the month of June, 2021 (266.8 mm). In 2019 and 2020, the maximum rainfall was recorded in the month of July with 148.2 mm and 191.4 mm of total rainfall, respectively. And in 2021, 2022 and 2023, the maximum rainfall was recorded in June with total rainfall of 266.8 mm, 214.6 mm, and 84.4 mm. In the five years, 2020 received the highest annual rainfall with a record of 1050.4 mm while the year 2023 recorded the lowest with 435.8 mm. Annual rainfall of 807.2 mm, 1005.8 mm and 832.8 mm was recorded during the year 2019, 2021, and 2022. During monsoon season (June to September), the rainfall was 517.8 mm, 591 mm, 711.4 mm, 488.2 mm, and 252 mm in the year 2019, 2020, 2021, 2022, and 2023, respectively. No rainfall was received during December 2020, and in 2023 there was no rainfall in the month of January and February.

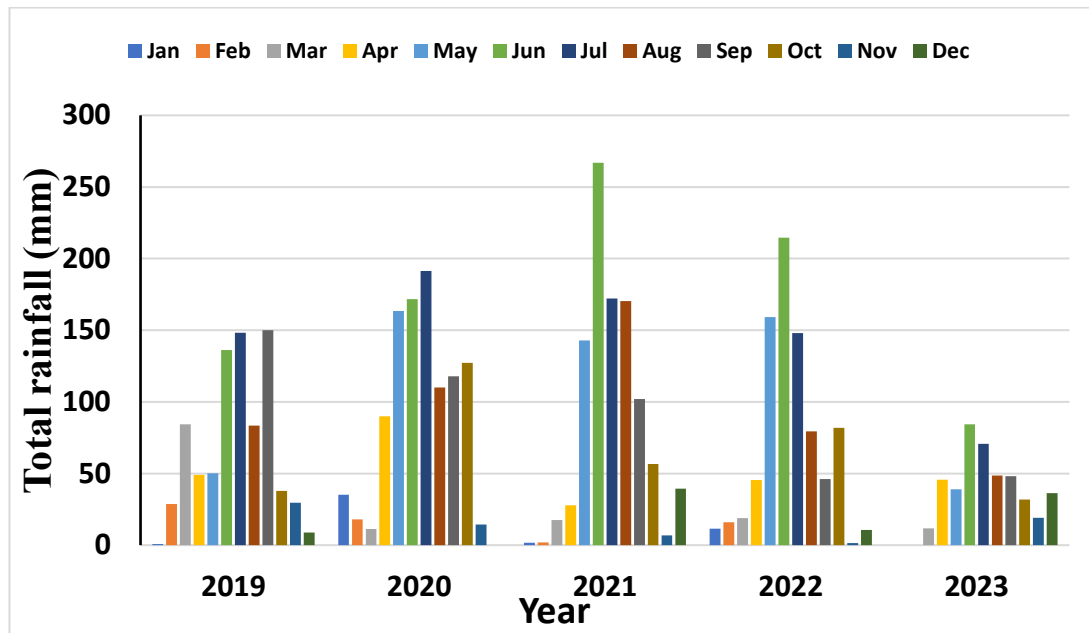


Fig.3: Monthly rainfall of Thoubal district for five years (2019 – 2023).

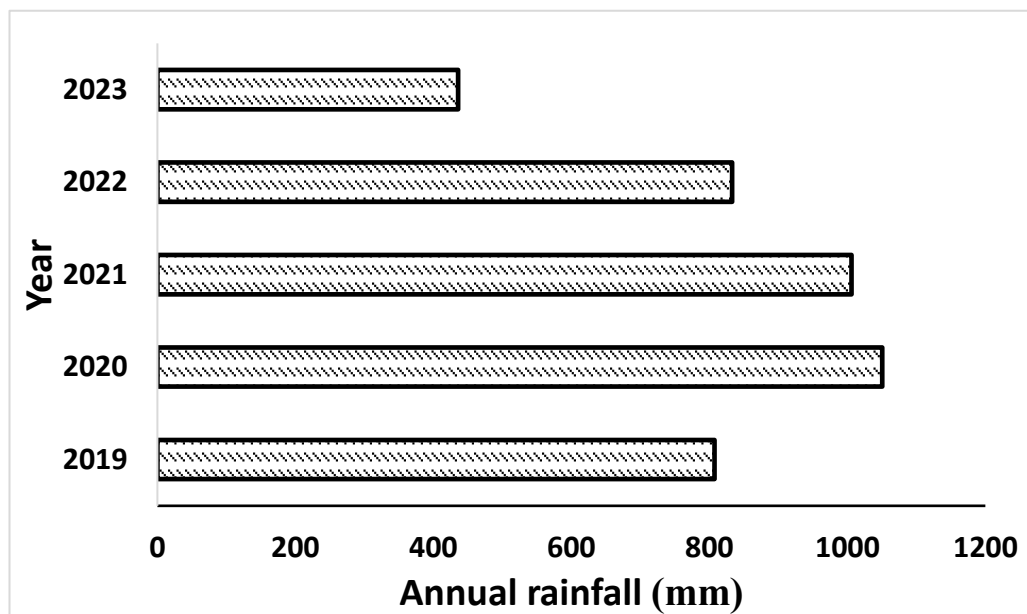


Fig.4: Total annual rainfall of Thoubal district for five years (2019 – 2023).

3.3. Types of compost

Three different composts were selected for the study *viz.* municipal solid waste (MSW) compost, vermicompost and *phumdi* compost. The MSW compost was made from the organic components of MSW. They were the compost derived from the organic source of municipal solid waste (MSW). The compost was collected from the Solid Waste Management Plant, Lamdeng Khunnou which is located in Imphal West district of Manipur. The Imphal Municipal Council has established this facility under the Jawaharlal Nehru National Urban Renewal Mission. Vermicompost was made from straw and cow manure by pit composting method. It was collected from a small-scale vermicompost production farm located in the Thoubal district of Manipur. *Phumdi* compost is a compost made from *phumdi* by pile composting method, a heterogenous mass of aquatic vegetations and organic debris. *Phumdi* is found in the Loktak lake of Manipur, a Ramsar site. *Phumdi* compost was also collected from a local production center. The initial total N content was analyzed using Kjeldahls digestion method (Anderson and Ingram, 1993), available P by Bray's method (Bray and Kurtz 1945) and available K by using flame photometer.

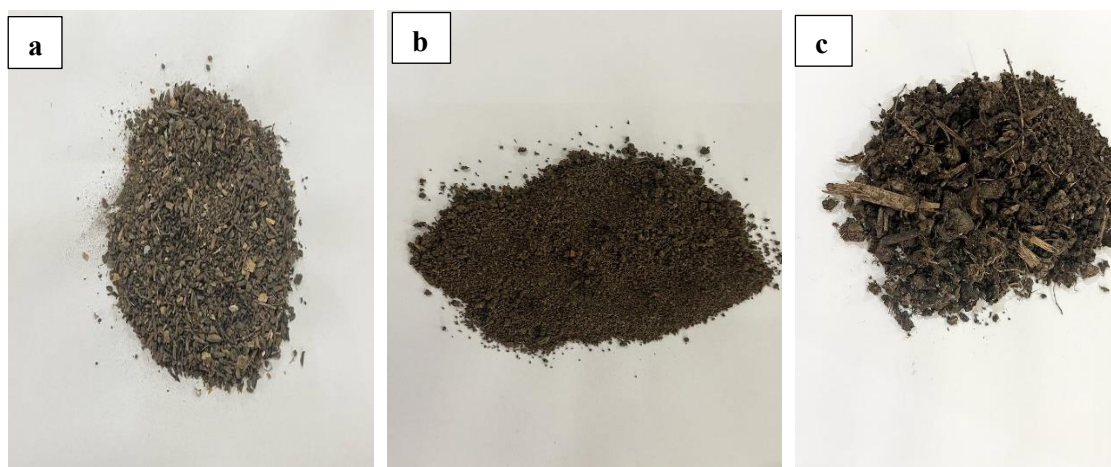


Plate 1: a) Municipal solid waste compost, b) Vermicompost, c) Phumdi compost



Plate 2: Pile of MSW compost at Lamdeng Khunou



Plate 3: Vermicompost production



Plate 4: Pile of *phumdi*

3.4. Selection of rice variety

The rice variety RC Maniphou 12 (RCM 13) was selected for the study. The variety has a short lifespan which usually takes 95-105 days to mature. The variety was produced by cross-breeding of two local varieties Akhanphou and Leimaphou. The variety has low amylose content which is desired by the people of north eastern hill region (ICAR, 2012). The seed of the rice was procured from the Indian Council of Agriculture and Research Center, Imphal. Viable seeds were selected, soaked in water for 24 hrs and incubated for another 24 hrs before sowing into the field. Sowing of the seed and transplanting of the nursery seedlings were done in separate plots.



Plate 5: Ploughing and puddling of field for sowing



Plate 6: Rice seed after soaking for 24 hrs

3.5. Experimental design and treatment

Twenty-one days old seedlings were transplanted with one seedling per hill in $2\text{ m} \times 2\text{ m}$ size experimental plots maintaining a plant spacing of $15\text{ cm} \times 20\text{ cm}$. The experimental plots were thoroughly ploughed, puddled and remained flooded for a few weeks before transplanting the seedlings. The plots were separated from each other by a distance of 1 m by levees. The experiment was carried out for two consecutively years 2022 and 2023 during the kharif cropping season.

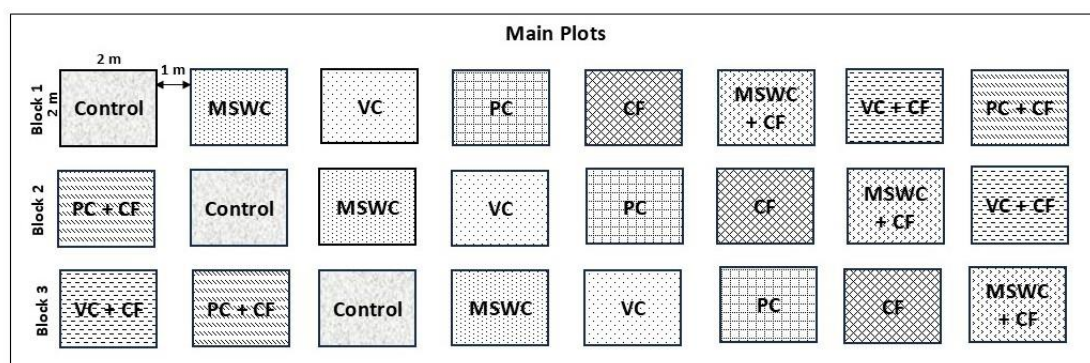


Fig.5: Randomized block design of the experimental plot.

The experiment was laid out in a randomized block design method with eight treatments and three replicates totaling to 24 plots (Fig 6). The eight treatments comprise of (i) control (no fertilizer); (ii) municipal solid waste compost at the rate 3.7 t ha^{-1} (MSWC, 100%); (iii) vermicompost at 3.5 t ha^{-1} (VC, 100%); (iv) *phumdi* compost at 3.0 t ha^{-1} (PC 100%) (v) chemical fertilizer (CF, 100%); (vi) municipal solid waste compost plus chemical fertilizer in the ratio 1:1 *i.e.* 1.85 t ha^{-1} MSWC + 0.06 t ha^{-1} CF (MSWC+CF); (vii) vermicompost plus chemical fertilizer in the ratio 1:1 *i.e.* 1.76 t ha^{-1} VC + 0.06 t ha^{-1} CF (VC+CF); (viii) *phumdi* compost plus chemical fertilizer in the ratio 1:1 *i.e.* 1.5 t ha^{-1} PC + 0.06 t ha^{-1} CF (PC+CF). The application rates of composts and chemical fertilizer were based on the total N-content of the composts and urea by fulfilling the recommended dose of N (60 kg ha^{-1}) as per the Department of Agriculture, Manipur. The composts and urea were supplied in three split doses *i.e.* 40% at the basal stage before transplanting, another 40% at active tillering and 20% at the panicle initiation stage of rice growth. Single

super phosphate (40 kg ha^{-1}) and muriate of potash (40 kg ha^{-1}) were incorporated 60% at the basal and remaining 40% at the tillering stage. The cultivation was done in rainfed condition with no artificial irrigation, and weeding was done manually whenever required.



Plate 7: Ploughing of the experimental field



Plate 8: Preparation of experimental plot



Plate 9: Preparation of levees

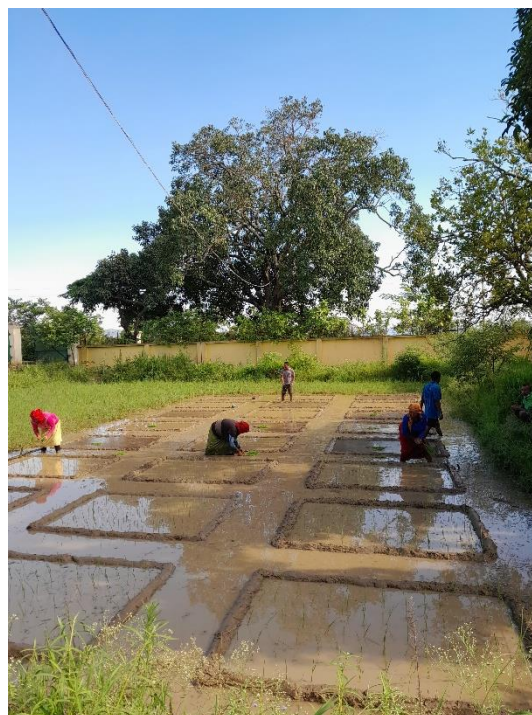


Plate 10: Transplanting of rice seedlings

3.6. Measurement of plant growth and its characteristics

Plant height was recorded at 30 days interval starting from the day of transplantation *i.e.* on 30, 60 and 90 days after transplantation (DAT). From each plot 30 rice plants were selected randomly and marked for measuring plant height. Plant height was recorded from the base of the stem upto the longest left. Rice hills grown at the border of the plots were excluded from the selection. Tiller number per plant (TNPP) and effective tiller number per plant (ETNPP) were also recorded from the 30 selected rice hills at the maturity.

3.7. Measurement of dry matter, yield and yield components

Total dry matter at maturity stage was determined by cutting three random samples from each plot at ground level and weighting it after drying for 48-72 h in an air oven at 70⁰ C until constant weight (Kadoglidou et al. 2019). At the time of harvesting, yield components including panicle length (PL), spikelets number per panicle (SNPP), number of filled spikelets per panicle (FSPP), number of unfilled spikelets per panicle (USPP), percentage of filled spikelets per panicle (PFSPP) and 1000

grain weight were determined from the selected 30 rice hills within each plot. Rice yield and straw yield were determined from the total area of the plot. Rice crop was reaped just above the ground and dried in the sun for each plot. Threshing of rice was done separately for each plot manually.

The harvest index (HI) was calculated by dividing the economic yield by biological yield (Yoshida, 1981)

$$HI = \frac{\text{Economic yield}}{\text{Biological yield}}$$

where, economic yield is the total grain weight and biological yield is the total grain and straw weight.

3.8. N uptake, Nitrogen use efficiency (NUE) and agronomic nitrogen efficiency (ANE)

The plant N uptake (kg N ha^{-1}) was calculated by multiplying the total dry biomass weight with plant N concentration (Wang et al. 2023). NUE was estimated as the difference between N uptake in the fertilized plot and N uptake in the unfertilized plot divided by the total nitrogen applied.

$$\text{NUE (\%)} = \frac{\text{Plant N uptake in fertilized plot} - \text{Plant N uptake in unfertilized plot}}{\text{Total N applied}} \times 100$$

Agronomic nitrogen efficiency was calculated by subtracting the grain yield in unfertilized plot by grain yield in N fertilizer applied pot and divided by total amount of N applied.

$$\text{ANE (kg grain kg}^{-1} \text{ N applied)} = \frac{\text{Grain yield in N fertilizer applied plot} - \text{Grain yield in unfertilized plot}}{\text{N applied}}$$



Plate 11: a)



Plate 11: b)



Plate 11: c)

Plate 11 a) to c): Early stages of rice growth



Plate 12: Active tillering stage of rice growth



Plate 13: Panicle initiation stage of rice growth



Plate 14: a)



Plate 14: b)

Plate 14 a) and b): Flowering stage of rice growth



Plate 15: Grain filling stage of rice field



Plate 16: Maturity stage of rice growth



Plate 17: Sun drying of rice crop after reaping



Plate 19: Measuring plant growth characteristics



Plate 20: Collection of plant samples for determination of dry matter



Plate 21: Oven drying of plant biomass



Plate 22: Weighting the above ground plant biomass after oven dried



Plate 23: Measuring 1000 grain weight



Plate 24: Measuring panicle length



Plate 25: a)



Plate 25: b)



Plate 25: c)

Plate 25 a) to c): Counting seeds for determining yield parameters

3.9. Gas sample collection and analysis

The gas samples for measuring CH₄, N₂O and CO₂ flux were collected by using the close chamber technique (Hutchinson and Moiser, 1981). Circular aluminum channels supported by aluminum base were inserted into the soil and permanently fixed in the experimental plots before transplanting the seedlings. Cylindrical chamber of 46 cm × 60 cm (diameter × height) was placed in the channel. Each chamber covered four rice hills. The channels were filled with water during the gas sampling to create the system airtight. The gas flux was recorded in weekly interval starting from the day of transplantation (DAT) till one week after harvesting. Gas samples were drawn from the chambers at a time interval of 0, 15 and 30 mins, respectively, in a 15 mL airtight syringe fitted with a three-way stopcock. The sampling was carried out between 9 a.m. to 11 a.m. in a day.

The concentration of CH₄, N₂O and CO₂ were estimated by Thermo Fisher Trace 1110 Gas Chromatograph fitted with Flame Ionised Detector (FID) and Porapak Q column for CH₄ and CO₂ and electron-capture detector (ECD) for N₂O. The column, injector and detector temperature were maintained at a required temperature. Nitrogen gas, hydrogen and zero air were used as carrier gas, fuel gas and supporting gas, respectively.

The CH₄ flux was estimated by following the given equation below (Debnath et al. 1996):

$$F = [(C_t - C_0) / t] \times H \times 42.857 \text{ mg m}^{-2} \text{ hr}^{-1}$$

Where, F = flux of CH₄;

C₀ = initial concentration of CH₄ (ppmV);

C_t = final concentration of CH₄ (ppmV);

t = time (min);

H = height of head space (m)

The N₂O flux was estimated by following the given equation below (Pathak et al. 2013):

$$F = [(C_t - C_0) / t] \times H \times 44/22.4 \mu\text{g m}^{-2} \text{ hr}^{-1}$$

Where, F = flux of N₂O;

C₀ = initial concentration of N₂O (ppmV);

C_t = final concentration of N₂O (ppmV);

t = time (min);

H = height of head space (m)

The CO₂ flux was estimated by following the given equation below (Khoiyangbam, 2008):

$$F = [(C_t - C_0 / t)] \times H \times 2.828 \text{ g m}^{-2} \text{ d}^{-1}$$

Where, F = flux of CO₂;

C₀ = initial concentration of CO₂ (ppmV);

C_t = final concentration of CO₂ (ppmV);

t = time (min);

H = height of head space (m).

Seasonal cumulative emission of CH₄, N₂O or CO₂ for the whole cropping season was estimated by following the given equation below (Ma et al. 2009):

$$\text{Cumulative seasonal CH}_4, \text{N}_2\text{O, or CO}_2 \text{ emission} = \sum_{i=0}^n Fi \times Di$$

Where, Fi = flux of CH₄ or N₂O or CO₂ in the ith sampling interval;

Di = number of days;

n = sampling intervals

The estimation of emission factor (EF) of CH₄ and N₂O for different treatments were determined by following the formula given below (Sun et al. 2020):

$$EF_{CH_4} = \frac{SCH_4}{D}$$

Where, EF_{CH_4} = CH₄ emission factor for each treatment (kg ha⁻¹ d⁻¹);

SCH_4 = seasonal cumulative emission of CH₄ (kg ha⁻¹);

D = rice cultivation period (d)

$$EF_{N_2O} = \frac{SNO_2 \text{ fertilized} - SNO_2 \text{ unfertilized}}{N \text{ input}} \times \frac{28}{44}$$

Where, EF_{N_2O} = N₂O emission factor for each fertilized treatment (kg N₂O-N (kg N)⁻¹);

$S_{N_2O \text{ fertilized}}$ = seasonal cumulative N₂O emissions from fertilized treatments (kg N₂O ha⁻¹);

$S_{N_2O \text{ unfertilized}}$ = seasonal cumulative N₂O emissions from unfertilized treatment (kg N₂O ha⁻¹);

N_{input} = total N input.



Plate 26: a)



Plate 26: b)



Plate 26: c)



Plate 26: d)

Plate 26 a) to d): Collection of gas samples



Plate 27: Thermo Fisher Trace 1110 Gas Chromatograph

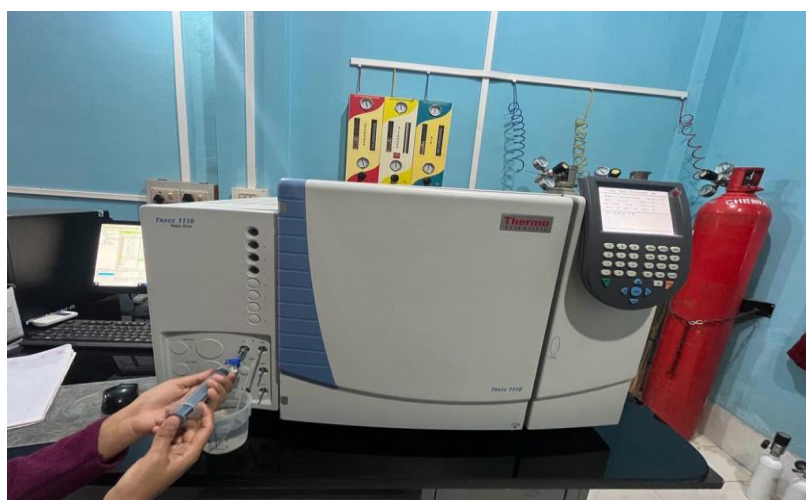


Plate 28: a)

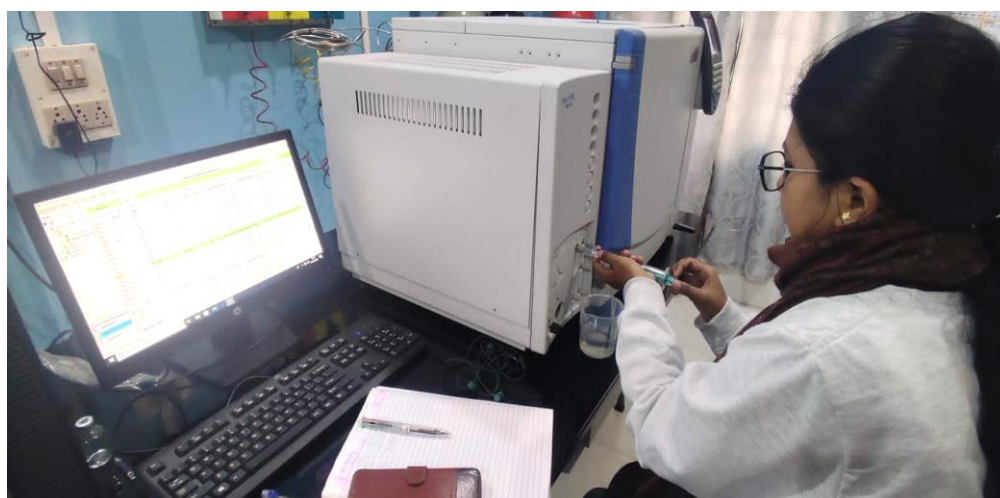


Plate 28: b)

Plate 28 a) and b): Analysis of gas samples

3.10. Global warming potential (GWP), greenhouse gas intensity (GHGI), carbon equivalent emission (CEE) and carbon efficiency ratio (CER)

GWP is defined as the ability of GHG to trap heat energy relative to CO₂. CH₄ and N₂O, respectively, has 27 and 273 times higher GWP than CO₂ over a 100 years time horizon (IPCC, 2021). GWP of the various treatments were calculated as followed:

$$\text{GWP (kg CO}_2\text{ equivalent ha}^{-1}\text{)} = 27 \times \text{CH}_4\text{ (kg ha}^{-1}\text{)} + 273 \times \text{N}_2\text{O (kg ha}^{-1}\text{)} + \text{CO}_2\text{ (kg ha}^{-1}\text{)}$$

The GHGI is defined as the total amount of GHG emitted per unit grain yield and was determined as followed:

$$\text{GHGI} = \frac{\text{Total GHG emissions}}{\text{Grain yield}} \text{ (kg CO}_2\text{ eq.t}^{-1}\text{ of grain yield)}$$

CEE and CER were estimated by using the following equations (Bhatia et al. 2005):

$$\text{CEE} = \frac{\text{GWP} \times 12}{44}$$

$$\text{CER} = \frac{\text{Grain yield (in terms of C) of rice}}{\text{CEE}}$$

Analysis of C of rice was done by using the dry ashing method (Campbell and Plank 1998).

3.11. Soil sampling and analysis

Soil samples were collected from the experimental field before the initiation of experiment to quantify the initial properties of the soil. Soil samples were also collected at four different stages of rice growth namely panicle initiation stage, active tillering stage, flowering stage and post-harvesting stage. The samples were collected randomly from three points of each plot at 5-15 cm depth. Pebbles, root fragments, stems were removed and air dried. The dry soil samples were crushed and sieved through a 2 mm diameter wire mesh. The following soil physico-chemical parameters were analyzed

3.11.1 Soil pH and EC

The soil pH and conductivity were measured with soil:water ratio of 1:5 using a portable environmental probe (Hanna, Model-HI98194).

3.11.2 Soil bulk density

Soil bulk density was determined by core sampler method described by Baker et al. 1986. It was calculated by the following formula:

$$\text{Soil bulk density (g cm}^{-1}\text{)} = \frac{\text{Weight of soil (g)}}{\text{Volume of solids and pore space (cm}^{-1}\text{)}}$$

3.11.3. Soil texture

Soil texture was measured by hydrometer method.

3.11.4. Total nitrogen (N) content

Soil total N was estimated by Kjeldahl's digestion method (Anderson and Ingram, 1993). The formula for estimating soil total N is given below:

$$\text{Total N in soil (\%)} = [(T_1 - T_2) \times N \times \text{At. Weight of nitrogen (14)} \times 100] / S \times 100$$

Where, T_1 = volume of titrant used against sample (ml);

T_2 = volume of titrant for blank (ml);

S = weight of sample (g).

3.11.5. Available phosphorus (P) and potassium (K)

Soil available P by determined by Bray's method using spectrophotometer at 820 nm (Bray and Kurtz 1945) and available K by ammonium acetate extraction method using flame photometer.

3.11.6. Soil organic carbon (SOC) and soil C stock

SOC was analyzed by Walkley and Black's titration method, SOC stock was computed by using the formula of Bharali et al. (2018):

$$\text{Soil C stock (Mg C ha}^{-1}\text{)} = \text{SOC} \times \text{bulk density} \times \text{depth} \times 100$$

Where, SOC = soil organic carbon in %;

BD = bulk density in Mg m^{-3} ;

d = depth of soil *i.e.* 0.15 m

$$\text{C sequestration (t ha}^{-1}\text{)} = \text{Final SOC stock (t ha}^{-1}\text{)} - \text{Initial SOC stock (t ha}^{-1}\text{)}$$



Plate 29: Air drying of soil samples



Plate 30: Crushing of soil sample



Plate 31: Sieving of the crushed soil



Plate 32: Soil samples preparation for chemical analysis



Plate 33: Filtration of soil solution



Plate 34: Preparation of standard solutions for available P



Plate 35: Standard curve for available



Plate 37: Sample analysis for the determination of available K



Plate 36: Flame photometer



Plate 38: Determination of organic C

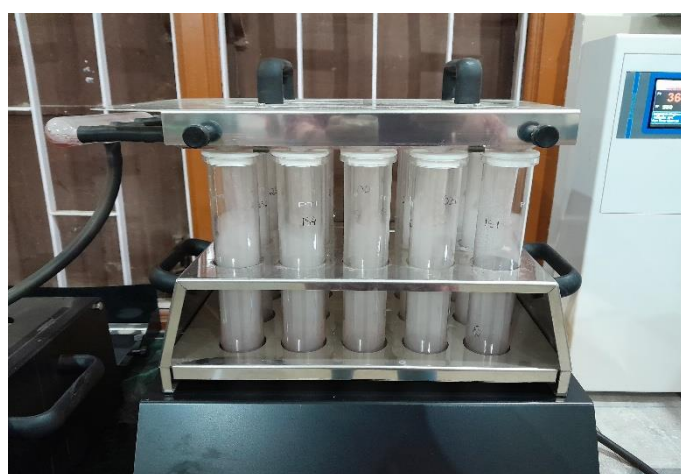


Plate 39: Digestion of soil samples for total N analysis



Plate 40: Distillation of soil sample for total N analysis



Plate 41: Sample after *V/S* before titration for determining total N

3.12. Statistical analysis

All the data obtained were statistically analyzed using SPSS Statistics 25.0. The data were subjected to one-way analysis of variance (ANOVA) and univariate analysis, followed by Tukey's HSD post-hoc test to determine the significant variations at 0.05 probability level. Pearsons's correlation coefficient and principal component analysis (PCA) were performed. Figures were drawn using OriginPro.



Plate 42: Experimental plots

4. RESULTS AND DISCUSSION

4.1. Initial quality of compost

The initial qualities of the three composts are presented in Table 1. The municipal solid waste (MSW) compost recorded a pH of 7.20 ± 0.05 , vermicompost 7.10 ± 0.4 , and *phumdi* compost 6.20 ± 0.05 . Vermicompost recorded the maximum organic C with $18.00 \pm 2.46\%$ and MSW compost recorded the minimum with $7.40 \pm 0.92\%$. The TN was maximum in *phumdi* compost with 2.00 ± 1.30 while minimum in MSW compost with $1.60 \pm 0.70\%$. Among the three composts, *phumdi* compost recorded the maximum AK ($1.05 \pm 0.86\%$) whereas vermicompost recorded the minimum ($0.77 \pm 1.12\%$). However, vermicompost has the maximum AP concentration with 0.68% and *phumdi* compost has the minimum with 0.40% . The C:N ratio of the three composts was low with a record of 4.62 in municipal solid waste compost, 8.26 in VC, and 20.58 in *phumdi* compost.

Table 1: Quality of three different composts.

Parameters	Municipal solid waste compost	Vermicompost	Phumdi compost
pH	7.20 ± 0.05	7.10 ± 0.4	6.20 ± 0.05
Organic carbon (%)	7.40 ± 0.92	18.0 ± 2.46	16.52 ± 3.05
TN (%)	1.60 ± 0.7	1.7 ± 0.05	2.00 ± 1.30
AP (%)	0.56 ± 0.18	0.68 ± 0.07	0.40 ± 0.02
AK (%)	0.89 ± 1.20	0.77 ± 1.12	1.05 ± 0.86
C/N ratio	4.62	10.58	8.26

Results are presented as mean $\pm$ standard deviation (SD)

4.2. Initial soil characteristic

The soil of the experimental site has a clayed loam texture with 33% sand, 31% silt, 36% clay, and typically inceptisols (USDA, 2022). The physico-chemical properties of the soil (0 – 15 cm) before the beginning of the experiment were analyzed. The pH of the soil is slightly acidic with value 6.2 and bulk density of 1.12 g cm^{-3} . The total

nitrogen content was found to be 0.35% and the organic carbon is low (0.62%). The concentration of available P and K was 0.04 ppm and 126.93 kg ha⁻¹ respectively.

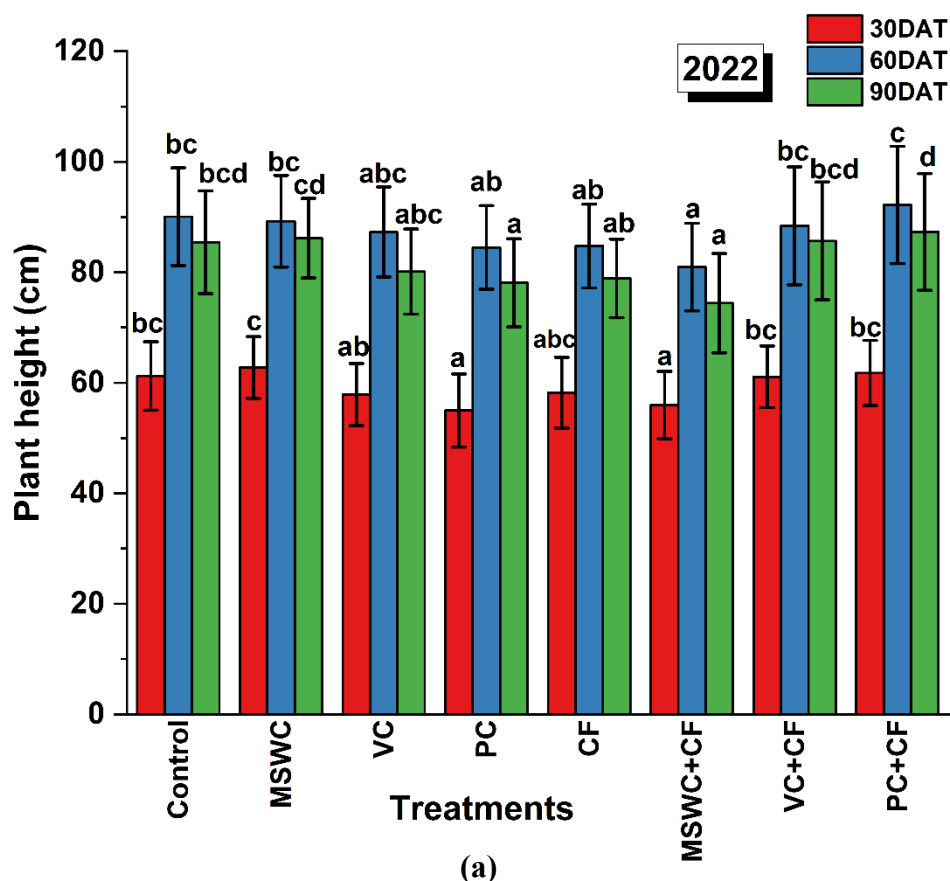
4.3. Plant growth and its characteristics under different fertilizer treatments

Plant height

Plant height of rice was significantly affected by different fertilizer treatments ($p < 0.05$) at various growth stages. There was an increasing trend of plant height from 30DAT to 60DAT, and then it decreased at the maturity stage. In both years, the plant height was maximum at 60 DAT in all the treatments and lowest at 30 DAT (Fig.6 a and b). The split application of fertilizer at the crop developing stages provides the required nutrients for plant metabolism, resulting in higher growth rate of the rice plant. And the decline of plant height at the maturity stage was due to the senescence of the crop. During the first year, PC treatment showed minimum plant height at 30DAT with 54.98 cm, but at 60DAT and 90DAT the plant height was minimum in MSWC+CF treatment with 81.0 cm and 74.4 cm, respectively (Fig.6 a). At the same time, the maximum plant height was recorded in PC+CF treatment in all the three stages with 61.77 ± 5.91 cm, 92.20 ± 10.61 cm and 87.31 ± 10.57 cm at 30DAT, 60DAT, and 90DAT, respectively. The result of the study observed that at 60DAT, the plant height in PC+CF treatment was 2.36% and 8.77% higher when compared with control and CF treatments, respectively, in the first year. The variation in plant height might be attributed by the variation in available nutrients caused by different nutrient source.

The plant height during the second year ranged from 55.12 cm to 64.54 cm at 30DAT, 85.13 cm to 94.90 cm at 60DAT and 82.55 cm to 89.00 cm at 90DAT. At 30DAT, 60DAT and 90DAT PC+CF treatment showed the maximum plant height with 64.54 ± 6.04 cm, 94.90 ± 7.84 cm and 89.00 ± 7.96 cm, respectively. And the minimum plant height was found in VC treatment (55.12 ± 5.05 cm), control treatment (85.1 ± 8.01 cm) and MSWC+CF (82.6 ± 7.85 cm) treatment at 30DAT, 60DAT and 90DAT, respectively. And there was an increase of 11.52% and 5.94% in the PC+CF treatment relative to control and CF treatments, respectively, in the second year, at 60DAT. Overall, among the treatments throughout the two-cropping season, the combined application of *phumdi* compost and chemical fertilizer at 1:1 ratio recorded maximum

plant height with average value of 81.62 ± 1.69 cm and the sole application of *phumdi* compost at the rate 3 t ha^{-1} to make 60 kg N ha^{-1} recorded the minimum with 73.80 ± 1.81 cm. Plant height is one of the critical factors that determine the yield and productivity of rice. The significant increase in plant height due to the application of combined *phumdi* compost and chemical fertilizer treatment might be attributed by the supply of essential nutrients that improve cell division and elongation. Increase in growth characteristics due to the integrated treatment of organic and chemical fertilizer was also reported by Hossain et al. (2011) and Mahanta et al. (2021). The plant height followed an increasing trend from the early stages of rice growth, peaked during flowering and decreased slightly at maturity. The maximum plant height was found at 60DAT. Correlation analysis showed that the plant height of rice was significantly related to TNPP ($r = 0.81$, $p < 0.01$), ETNPP ($r = 0.81$, $p < 0.01$), spikelets number per panicle ($r = 0.74$, $p < 0.05$), filled spikelets number per panicle ($r = 0.67$, $p < 0.05$), straw yield ($r = 0.88$, $p < 0.01$), and dry matter ($r = 0.76$, $p < 0.05$) (Fig.38).



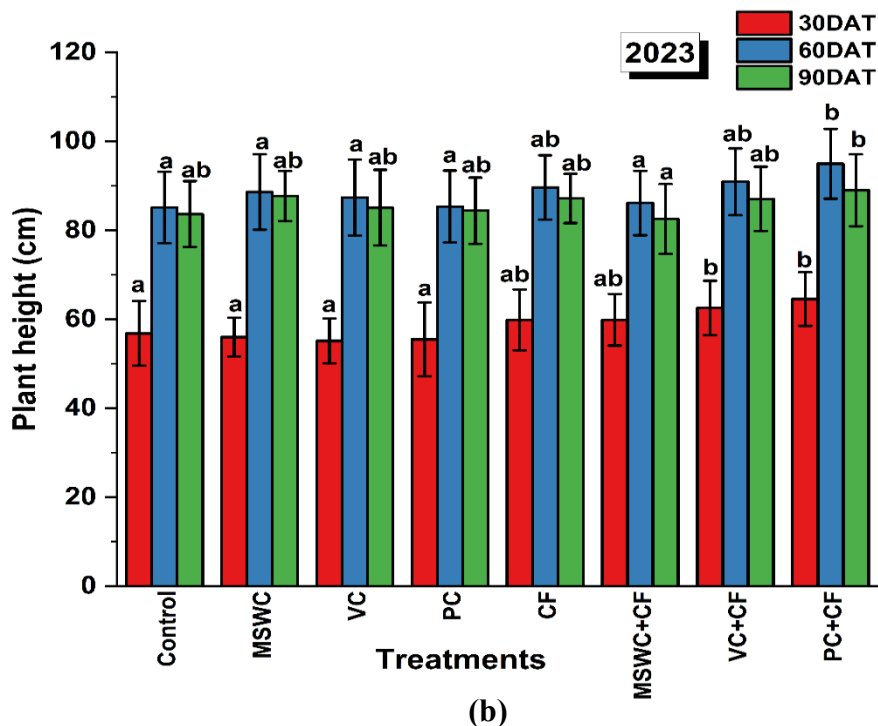


Fig.6: Plant height of rice at three different sampling day of (a) 2022 and (b) 2023. The bars with same letters at each sampling time are not significantly different in Tukey's HSD test ($p < 0.05$).

Tiller number per plant (TNPP)

TNPP in rice was significantly affected by different treatments over the two years ($p < 0.05$, Table 2), but the interaction between the treatments and years was not significant. In the first year, minimum TNPP was recorded in the control treatment with 3.99 ± 0.29 ($p < 0.05$), and the maximum was recorded in PC+CF with 4.90 ± 0.13 , as shown in Table 4. The TNPP in CF treatment (4.66 ± 0.12) was higher than all the other treatments, except PC+CF. The results showed 22.58% and 5.05% increased of TNPP in PC+CF treatment compared to the control and CF treatments, respectively. Again, in the second year, maximum TNPP was found in PC+CF treatment (5.16 ± 0.18), which is in line with the previous year's data. This shows that the integrated *phumdi* compost and chemical fertilizer fulfill the nutrient requirements of plants for the growth of tillers. But the minimum TNPP was recorded in PC treatment with 4.49 ± 0.25 . Among the fertilizer treatments, the TNPP during the second year was in the increasing order of PC treatment (4.49 ± 0.25) < MSWC+CF (4.59 ± 0.11) < VC (4.65 ± 0.30) < VC+CF (4.67 ± 0.28) < MSWC (4.97 ± 0.19) < CF (5.01 ± 0.24) <

PC+CF (5.16 ± 0.18). The total N content in *phumdi* compost was higher than vermicompost and MSW compost, but PC treatment recorded minimum TNPP, however, the combination of *phumdi* with chemical fertilizer gave a synergistic effect, which resulted in maximum production of TNPP. Furthermore, the study found that there was a significant increase in TNPP in all the treatments in the second year compared to the first year.

In addition to this, the average cumulative TNPP data of all the treatments shows that the PC+CF treatment shows the maximum production (5.03 ± 0.23) with a slight margin of 3.99% as compared to the CF treatment (4.83 ± 0.25). The result obtained in the study is in line with Hemalatha et al. (2000) and Ghosh et al. (2019), who reported increased growth characteristics due to the combined treatment of compost and chemical fertilizers. Hasanuzzaman et al. (2010) and Siavoshi et al. (2013) also reported an increase in tiller number per plant through the application of integrated fertilizers. However, the TNPP in MSWC+CF treatment and VC+CF treatment were lower than the sole application of chemical fertilizer. This could be either that the amount of nutrient applied could not meet the desired level for plant development or the nutrient released from MSW compost and vermicompost was slow. After PC+CF and CF treatments, MSWC treatment recorded higher TNPP of 4.79 ± 0.28 . This might be due to the low C:N ratio of MSW which decomposed and mineralized the organic matter easily (Sathiyabama et al. 2021). TNPP was found to be correlated significantly with ETNPP ($r = 0.88$, $p < 0.01$), spikelets number per panicle ($r = 0.64$, $p < 0.05$), filled spikelets number per panicle ($r = 0.68$, $p < 0.05$), straw yield ($r = 0.69$, $p < 0.05$), plant height ($r = 0.81$, $p < 0.05$) and dry matter ($r = 0.79$, $p < 0.05$) (Fig.38).

Table 2: Two-way ANOVA table for TNPP.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	5.577	15	0.372	6.360	0.000
Intercept	1025.557	1	1025.557	17543.148	0.000
Treatment	2.536	7	0.362	6.197	0.000
Year	2.158	1	2.158	36.910	0.000
Treatment*Year	0.884	7	0.126	2.159	0.065
Error	1.871	32	0.58	-	-
Total	1033.005	48	-	-	-

Effective tiller number per panicle (ETNPP)

During the first year, the application of CF treatment produced maximum ETNPP with a value of 4.48 ± 0.22 , while the minimum ETNPP was recorded in the MSWC+CF treatment with 3.48 ± 0.33 , which was even lower than the control treatment. It was also found that the value of ETNPP in PC treatment (3.97 ± 0.27) was on par with the control treatment (3.96 ± 0.37). However, the application of different fertilizer treatments showed no significant variation in ETNPP of rice in the first year ($p < 0.05$, Table 4). In the second year, the ETNPP was the minimum in VC treatment (4.28 ± 0.30) and the maximum in PC+CF treatment (5.00 ± 0.20). The application of chemical fertilizer alone produced more ETNPP than VC treatment (4.28 ± 0.30), MSWC+CF treatment (4.30 ± 0.32), PC treatment (4.38 ± 0.24) and VC+CF treatment (4.43 ± 0.36) during the second year. Marlina et al. (2015) stated that the production of ETNPP is stimulated by the availability of macronutrients.

The average ETNPP of the two years was recorded maximum in the *phumdi* compost and chemical fertilizer integrated treatment (4.70 ± 0.47), however, the result was not statistically increased from other treatments except MSWC+CF treatment. Compared to control and CF treatment respectively, the application of *phumdi* compost with chemical fertilizer produced 8.04% and 4.91% higher ETNPP. It was also found that the MSWC treatment recorded higher ETNPP with 4.57 ± 0.28 , which was followed by the CF treatment with 4.48 ± 0.32 . Municipal solid waste compost which is mature and made from separately collected organic materials contained high organic matter and improve soil fertility (Hargreaves et al. 2008), which in turn deliver the required nutrients to the plant. Other than PC+CF and MSWC treatments, higher ETNPP was recorded in 100% application of N through chemical fertilizer alone. It might be due to the supply of nutrients in the plant available form. The availability of nutrients stimulates the development of ETNPP. According to Chen (2006), the application of chemical fertilizer has advantages over the application of compost alone, as nutrients in chemical fertilizers are available in soluble form which can be easily used for plant growth. Sowmyalatha (2010) also reported higher ETNPP due to the application of chemical fertilizer. And, over the two-year average data, there was a significant difference between the treatments and the two years, but their interaction showed no

effect ($p < 0.05$, Table 3). A significant positive correlation of ETNPP was found with plant height ($r = 0.81$, $p < 0.01$) and straw yield ($r = 0.61$, $p < 0.05$) (Fig.38).

Table 3: Two-way ANOVA table for ETNPP.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	5.837	15	0.389	3.130	0.003
Intercept	899.928	1	899.928	7239.857	0.000
Treatment	2.777	7	0.397	3.191	0.011
Year	2.188	1	2.188	17.600	0.000
Treatment*Year	0.872	7	0.125	1.002	0.448
Error	3.978	32	0.124	-	-
Total	909.742	48	-	-	-

Table 4: Tiller number and effective tiller number per plant found during the two

Treatment	TNPP			ETNPP		
	2022	2023	Average	2022	2023	Average
Control	3.99±0.29a	5.11±0.23ab	4.55±0.65ab	3.96±0.37a	4.74±0.36a	4.35±0.54a
MSWC	4.61±0.25ab	4.97±0.19ab	4.79±0.28bc	4.44±0.18a	4.70±0.34a	4.57±0.28b
VC	4.22±0.28ab	4.65±0.30ab	4.44±0.35ab	4.08±0.40a	4.28±0.30a	4.18±0.33a
PC	4.11±0.23a	4.49±0.25a	4.30±0.29a	3.97±0.27a	4.38±0.24a	4.18±0.32a
CF	4.66±0.12ab	5.01±0.24ab	4.83±0.25bc	4.48±0.22a	4.48±0.46a	4.48±0.32a
MSWC+CF	4.26±0.23ab	4.59±0.11ab	4.42±0.24ab	3.48±0.33a	4.30±0.32a	3.89±0.53a
VC+CF	4.48±0.29ab	4.67±0.28ab	4.58±0.27abc	4.09±0.53a	4.43±0.36a	4.26±0.44a
PC+CF	4.90±0.24b	5.16±0.18b	5.03±0.23c	4.39±0.47a	5.00±0.20a	4.70±0.47b

years.

Results are presented as mean±SD

4.4. Yield characteristics under different fertilizer treatments

Panicle length

As illustrated in figure 7 a, the application of *phumdi* compost with chemical fertilizer recorded maximum panicle length with 18.43±1.33 cm in the first year. This was followed by MSWC+CF treatment and VC+CF treatments having panicle length of 18.10±1.47 cm and 18.09±1.14 cm. The result of the study indicates that combining compost with chemical fertilizer could meet the desired quantity of nutrients for

panicle elongation. The minimum panicle was recorded in the control (16.20 ± 1.42 cm); however, among the fertilizer treatments, the sole application of *phumdi* compost, PC treatment had the minimum panicle length with 6.90 ± 0.33 cm. Compared to the CF treatment, panicle length in the PC treatment was slightly decreased by a margin of 1.9%, which means that the difference was not significant ($p < 0.05$). And the maximum panicle length in PC+CF was 9.05% increased relative to the sole application of chemical fertilizer. Panicle length is an important trait in rice production since it reflects the ability to bear rice grain.

Furthermore, the longest panicle length in the second year was congruent with first-year data, where PC+CF recorded the longest with the value of 20.81 ± 0.51 cm (Fig.7 b). The panicle length in the control treatment (18.87 ± 0.65 cm) was similar with the sole applications of chemical fertilizer (18.84 ± 0.56 cm). And the VC treatment (17.77 ± 0.37) exhibit the minimum panicle length, which was 6.19% lower than the control treatment in the second year. However, in the average data of two years, increase in panicle length was recorded in all the treatments as compared to the control. The application of different fertilizers had a significant effect on panicle length, where the application of combined chemical fertilizer and compost treatments resulted in higher panicle length compared to the sole compost application. The average panicle length found during the two-years study was in the following order control (17.53 ± 1.16) < VC treatment (17.75 ± 0.98) < CF treatment (17.87 ± 1.14) < PC treatment (17.94 ± 1.51) < MSWC treatment (18.34 ± 1.16) < VC+CF treatment (18.59 ± 0.96) < MSWC+CF treatment (18.88 ± 1.37) < PC+CF treatment (19.62 ± 1.58) (Table 5). There was a significant increase in panicle length in the second year compared to the first year, but the interaction between the treatments and years did not show significant differences ($p < 0.05$, Table 6). Overall, the yield characteristic panicle length in PC+CF treatment was increased by 9.7% from the sole application of chemical fertilizer.

During the two years of study, panicle length was found to be significantly correlated with important yield traits spikelets number per panicle ($r = 0.87$, $p < 0.01$), filled spikelets number per panicle ($r = 0.94$, $p < 0.01$), 1000 grain weight ($r = 0.94$, $p < 0.01$), and grain yield ($r = 0.92$, $p < 0.01$) (Fig.38) which justifies the influence of panicle length in achieving higher grain yield. Moreover, the study revealed that there

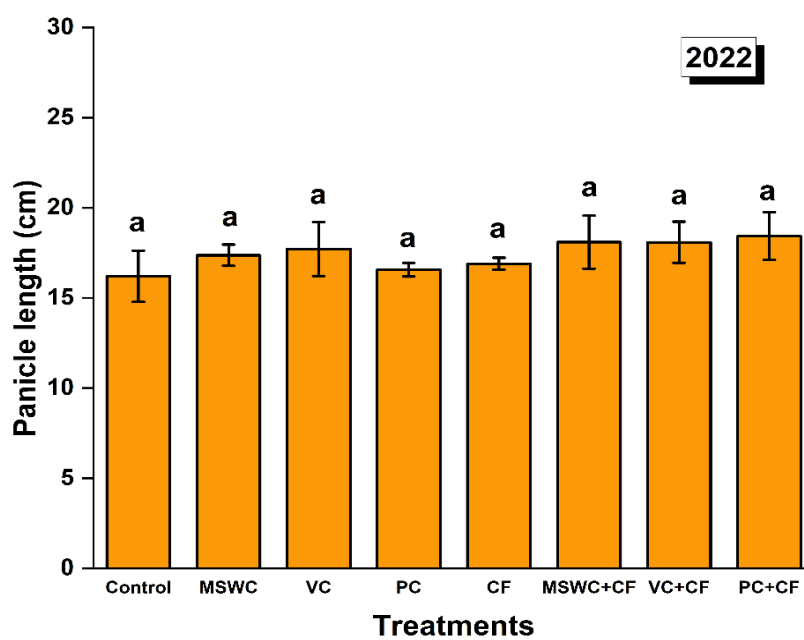
was a significant positive correlation between panicle length and dry matter accumulation ($r = 0.81$, $r < 0.01$), plant N uptake ($r = 0.86$, $p < 0.01$), and soil total N concentration ($r = 0.80$, $p < 0.01$). It can reveal that higher N content in soil enhanced utilization of nutrient, especially N by plants, resulting in higher dry matter accumulation which in turn increased the rice panicle length. A similar strong positive correlation of panicle length with N uptake was reported by Troza et al. (2021). The results were also supported by the findings of Kamiji et al. (2011) and Hu et al. (2024) who reported that the dry matter accumulation and N accumulation during panicle development were the result of obtaining larger panicles. Also, the N availability in plants controls the release of functional genes of panicle development which in turn regulate spikelets per panicle (Ding et al. 2016).

Table 5: Variation in panicle length of rice under different fertilizer treatments, recorded during the two years of study.

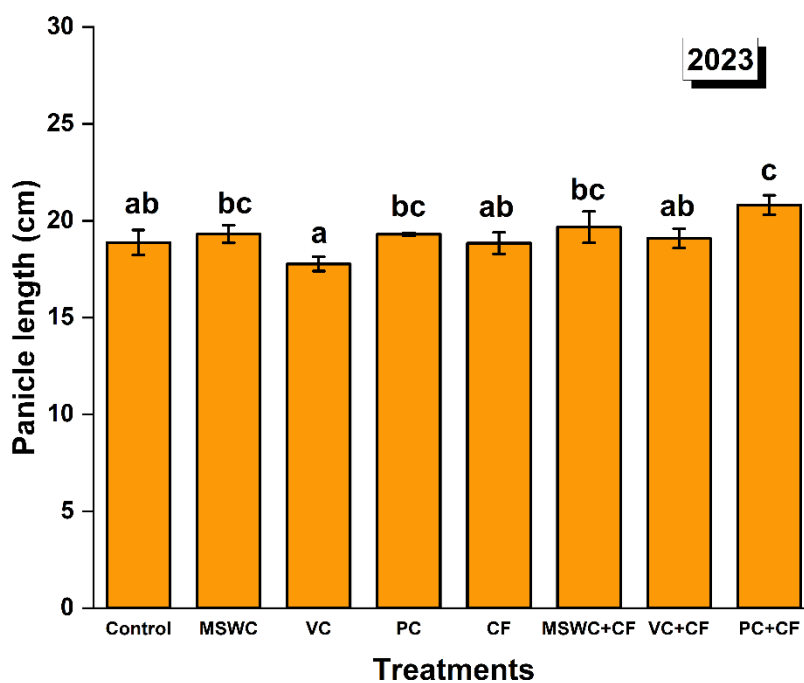
Treatment	Panicle length		
	2022	2023	Average
Control	16.20±1.42	18.87±0.65	17.53±1.76
MSWC	17.37±0.59	19.31±0.46	18.34±1.16
VC	17.72±1.50	17.77±0.37	17.75±0.98
PC	16.57±0.38	19.30±0.08	17.94±1.51
CF	16.90±0.33	18.84±0.56	17.87±1.14
MSWC+CF	18.10±1.47	19.67±0.81	18.88±1.37
VC+CF	18.09±1.14	19.09±0.50	18.59±0.96
PC+CF	18.43±1.33	20.81±0.51	19.62±1.58

Table 6: Two-way ANOVA table for panicle length.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	67.210	15	4.481	5.743	0.000
Intercept	16107.677	1	16107.677	20644.582	0.000
Treatment	20.242	7	2.892	3.706	0.005
Year	38.342	1	38.342	49.141	0.000
Treatment*Year	8.626	7	1.232	1.579	0.177
Error	24.968	32	0.780	-	-
Total	16199.854	48	-	-	-



(a)



(b)

Fig.7: Panicle length of rice under different fertilizer treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Spikelets number per panicle

It was observed that there was a significant difference in spikelets number per panicle among the different fertilizer treatments, between the two years and their interaction ($p < 0.05$, Table 8). During the first year, the treatment PC+CF (99.45 ± 3.32) and VC+CF (99.23 ± 5.61) significantly increased the spikelets number per panicle, with PC+CF attaining the maximum spikelet number per panicle (Fig.8 a). While the sole application of *phumdi* compost attained the minimum spikelets number per panicle (76.54 ± 4.37), which was 29.93% decreased compared to the highest spikelets number in the PC+CF treatment. However, the value of spikelets number per panicle in PC treatment was at par with CF treatment (78.58 ± 4.11). Interestingly, significantly higher spikelets number per panicle was observed in the application of municipal solid waste compost alone at the rate of 3.7 t ha^{-1} compared to the CF treatment and MSWC+CF treatment. The result is supported by the findings of Siavoshi et al. (2011), where the application of 2 t ha^{-1} of organic fertilizer resulted in higher spikelet numbers per panicle than the chemical fertilizer combined with organic fertilizer. However, in the second year, the treatments CF and MSWC+CF produce more spikelets per panicle than the MSWC treatment. The study further found that the spikelets number per panicle was greatly increased during the second year, irrespective of the fertilizer treatments. Again, the integrated treatment of *phumdi* compost and chemical fertilizer had the maximum spikelets number (Fig.8 b) in the second year, recording a value of 135.39 ± 8.64 . This indicates that the application of *phumdi* compost with chemical fertilizer was found to be more effective in increasing spikelets number per panicle. The availability of nutrients from the combined application of composts and chemical fertilizer triggers the plant to absorb the essential nutrients, which helps in the formation of spikelets. Whereas, the control treatment (96.07 ± 7.56) recorded the minimum. And among the fertilizer application plots, still the PC treatment recorded the minimum spikelet number per panicle in the second year where it decreased by 7.69% compared to the sole application of chemical fertilizer. However, the difference between the two was not significant.

Additionally, when taking average of the two years, the spikelets number per panicle was found in the order of control treatment (88.87 ± 9.92) < PC treatment (89.45 ± 14.92)

< CF treatment (94.41 ± 18.41) < MSWC+CF (98.43 ± 16.80) < VC treatment (98.80 ± 14.74) < MSWC treatment (99.41 ± 12.55) < VC+CF treatment (105.36 ± 8.86) < PC+CF treatment (117.42 ± 20.53) (Table 7). There was an increment of 24.37%, 11.59% and 4.25% spikelets number per panicle in PC+CF, VC+CF and MSWC+CF treatments compared to CF treatment. A similar result of higher spikelets per panicle due to the substitution of 50% N chemical fertilizer with organic fertilizer was reported by Moe et al. (2019). Iqbal et al. (2020) and Kakar et al. (2020) also reported that application of organic fertilizer and chemical fertilizer resulted in higher spikelets number per panicle. Compost application releases nutrients slowly and steadily, which ensures plants receive sufficient nutrients during the critical stage of spikelet differentiation and panicle development, resulting in higher spikelet numbers per panicle (Sathiyabama et al. 2021). Moreover, the integrated application of compost with chemical fertilizer could not only enhance rice yield characteristics but also help in reducing the use of chemical fertilizers, which may cause adverse environmental degradation.

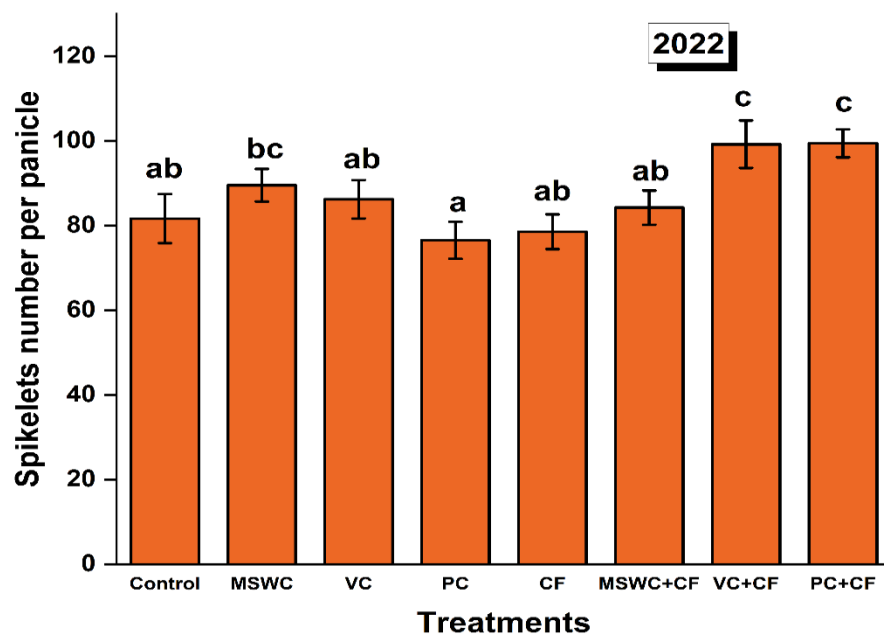
The spikelet numbers per panicle showed linear relationship with filled spikelet numbers per panicle ($r = 0.95$, $p < 0.01$), 1000 grain weight ($r = 0.82$, $p < 0.01$), straw yield ($r = 0.70$, $p < 0.05$), grain yield ($r = 0.90$, $p < 0.01$), CER ($r = 0.70$, $p < 0.05$), plant height ($r = 0.74$, $p < 0.05$), dry matter ($r = 0.88$, $p < 0.01$), plant N uptake ($r = 0.76$, $p < 0.05$), total N ($r = 0.68$, $p < 0.05$) and available K ($r = 0.68$, $p < 0.05$) (Fig.38). The positive correlation of N uptake and spikelet numbers per panicle showed that applying compost with chemical fertilizer improved root development and nutrient uptake, producing higher spikelets per panicle. The result was similar to the findings of Troza et al. (2021). The growth and development of plants are mainly determined by the type and amount of nutrients available in the soil (Morgan and Connolly, 2013). Wada et al. (1986) reported that the amount of N absorbed by the plant at the late stage of panicle initiation determined the spikelet numbers of panicle in rice.

Table 7: Variation in spikelets number per panicle under different fertilizer treatments, recorded during the two years of study.

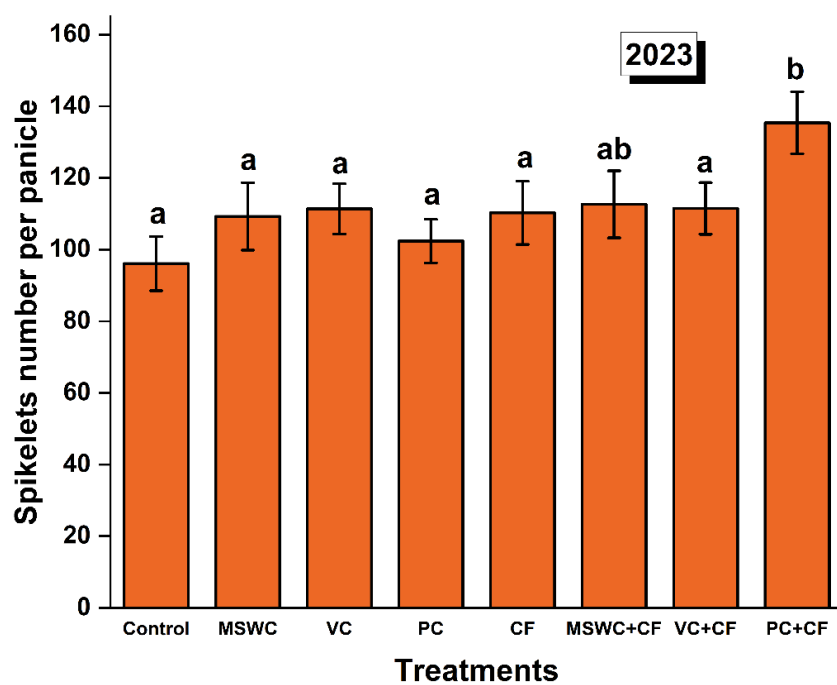
Treatment	Spikelets number per panicle		
	2022	2023	Average
Control	81.67±5.78	96.07±7.56	88.87±9.92
MSWC	89.56±3.85	109.26±9.39	99.41±12.55
VC	86.24±4.54	111.37±7.01	98.80±14.74
PC	76.54±4.37	102.37±6.09	89.45±14.92
CF	78.58±4.11	110.25±8.84	94.41±18.41
MSWC+CF	84.26±4.04	112.61±9.35	98.43±16.80
VC+CF	99.23±5.61	111.49±7.23	105.36±8.86
PC+CF	99.45±3.32	135.39±8.64	117.42±20.53

Table 8: Two-way ANOVA table for spikelets number per panicle.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	11285.300	15	752.253	17.471	0.000
Intercept	470685.630	1	470685.630	10930.142	0.000
Treatment	3570.697	7	510.100	11.845	0.000
Year	7004.950	1	7004.950	162.667	0.000
Treatment*Year	709.652	7	101.379	2.354	0.047
Error	1378.019	32	43.063	-	-
Total	483348.948	48	-	-	-



(a)



(b)

Fig.8: Spikelets number per panicle of rice under different treatments during

(a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Filled spikelets number per plant

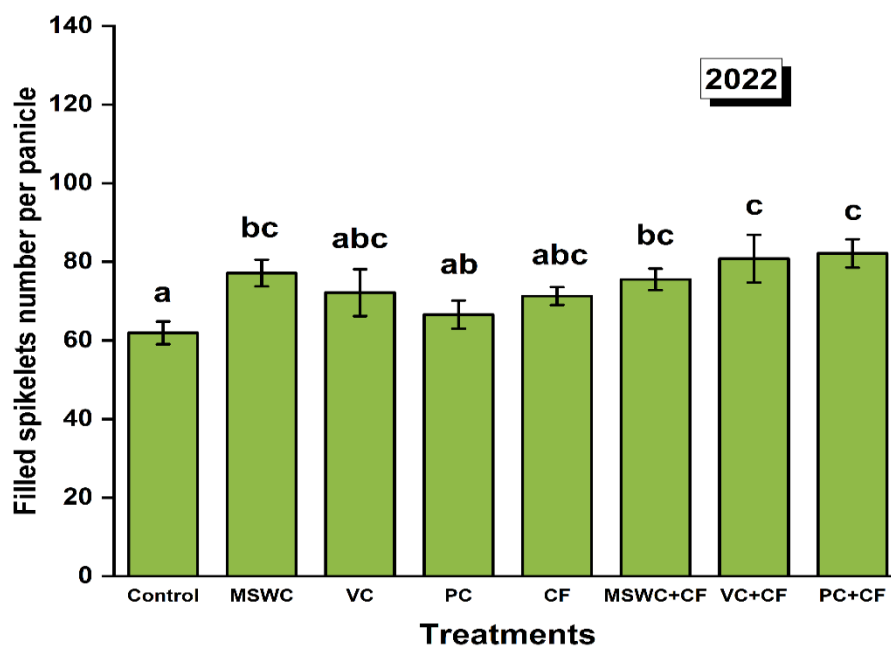
The filled spikelets number per plant was found in the range of 61.92 to 82.16 and 87.86 to 123.84 in the first and second year, respectively. In the two years, the study observed that the filled spikelets number per plant was significantly varied between the treatments ($p < 0.05$, Table 10). The maximum filled spikelets number per panicle was recorded in PC+CF treatment with a value of 82.16 ± 3.60 and 123.84 ± 8.73 in the first and second years, respectively. At the same time, the minimum was observed in the control treatment with 61.92 ± 2.88 and 87.86 ± 6.38 in the first year and second year, respectively (Fig.9 a and b). It was quite evident that the minimum result found in the control could be due to the low availability of required nutrients for plant development. Among the fertilizer treatment plots, the minimum 66.57 ± 3.59 of filled spikelets number per panicle was recorded in PC treatment in the first year and 91.50 ± 6.26 in VC treatment in the second year.

There was a significant increase in the number of filled spikelets per plant in the second year compared to the first year ($p < 0.05$). However, the interaction between the treatments and years showed no effect on the number of filled spikelets per plant. The average filled spikelets per plant in the two years was in the order of control (74.89 ± 14.88) < PC treatment (79.21 ± 14.97) < VC treatment (81.83 ± 11.90) < CF treatment (84.29 ± 15.25) < MSWC+CF treatment (87.86 ± 15.79) < MSWC treatment (88.11 ± 14.51) < VC+CF treatment (90.25 ± 12.21) < PC+CF treatment (103.00 ± 23.59) (Table 9). From the result, it was observed that the integrated treatment of composts with chemical fertilizer resulted in higher filled spikelets per panicle than the CF treatment. And it was increased by 22.19%, 7.07%, and 4.23%, respectively in PC+CF, VC+CF, and MSWC+CF treatments. And the sole application of municipal solid waste compost also increased filled spikelets number slightly over the CF treatment and its integrated treatment with chemical fertilizer, *i.e.* MSWC+CF treatment. Although the CF treatment produced higher filled spikelet number per panicle than VC and PC treatments, there was no significant difference between the

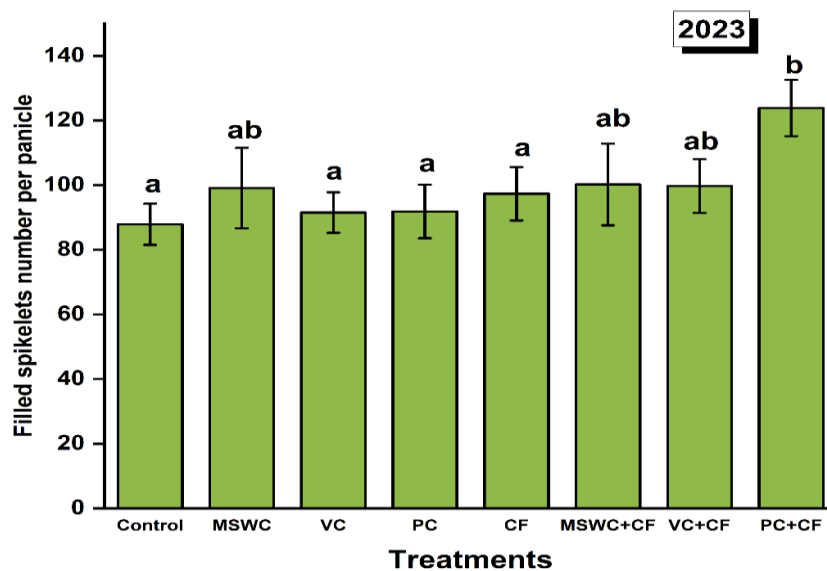
treatments. The number of filled spikelets per panicle is more critical in determining the rice yield rather than the total spikelets number of spikelets per panicle. Application of organic fertilizer has been known for its better performance in crop production by improving the soil physical, chemical, and biological properties (Sitepu et al. 2017; Hammed et al. 2019). Iqbal et al. (2020) stated that applying organic fertilizer produces growth-regulating substances that help better grain filling. Higher production of filled spikelets number per panicle due to the application of vermicompost integrated with chemical fertilizer was reported by Kundu and Brahmachari (2012). The correlation results of the study also revealed that filled spikelets number per panicle was significantly influenced by plant dry matter ($r = 0.91$, $p < 0.01$), plant N uptake ($r = 0.86$, $p < 0.01$), soil total N ($r = 0.80$, $p < 0.01$), and available K ($r = 0.74$, $p < 0.05$) (Fig.38). When plants take up N, it activates and regulates the expression of specific nitrate and ammonium transporters in their root cells. This process boosts the plant's capacity to absorb N efficiently while improving the uptake of other essential nutrients (Muratore et al. 2021), ultimately resulting in greater plant development.

Table 9: Variation in filled spikelets number per panicle under different fertilizer treatments, recorded during the two years of study.

Treatment	Filled spikelets number per panicle		
	2022	2023	Average
Control	61.92±2.88	87.86±6.38	74.89±14.88
MSWC	77.15±3.38	99.07±12.46	88.11±14.51
VC	72.16±5.96	91.50±6.26	81.83±11.9
PC	66.57±3.59	91.84±8.28	79.21±14.97
CF	71.28±2.28	97.31±8.23	84.29±15.25
MSWC+CF	75.53±2.73	100.20±12.65	87.86±15.79
VC+CF	80.81±6.04	99.69±8.33	90.25±12.21
PC+CF	82.16±3.60	123.84±8.73	103.00±23.59



(a)



(b)

Fig.9: Filled spikelets number per panicle under different treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 10: Two-way ANOVA table for the number of filled spikelets number per panicle.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	11345.385	15	756.359	14.971	0.000
Intercept	356532.772	1	356532.772	7057.264	0.000
Treatment	3027.320	7	432.474	8.560	0.000
Year	7781.710	1	7781.710	154.032	0.000
Treatment*Year	536.355	7	76.622	1.517	0.197
Error	1616.639	32	50.520	-	-
Total	369494.797	48	-	-	-

Unfilled spikelets number per plant

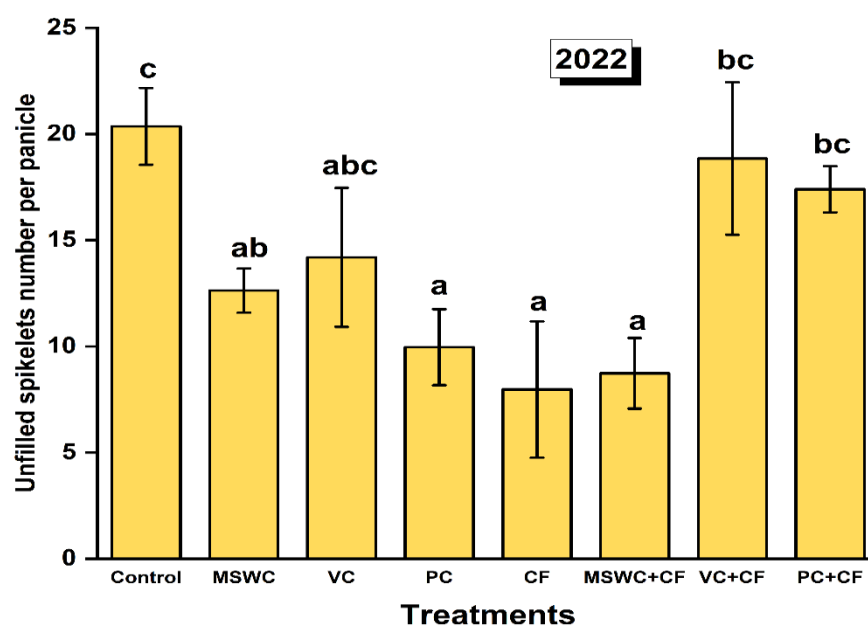
The unfilled spikelets number per plant was significantly affected by application of different fertilizer treatments ($p < 0.05$, Table 12). As shown in the Fig.10 a and b, compared to the control, all the treatments decreased the unfilled spikelets number per panicle. The minimum unfilled spikelet number per plant was observed in the CF treatment with 7.97 ± 3.21 in the first year, which was 60.85% decreased from the control (20.36 ± 1.81). It was followed by MSWC+CF treatment (8.73 ± 1.66) and PC treatment (9.96 ± 1.79) with 57.12% and 51.08% decreased. Among the fertilizer treatments, VC+CF recorded maximum unfilled spikelets having 18.85 ± 3.59 value which was 7.41% decreased compared to the control treatment. However, in the second year, the application of chemical fertilizer alone increased the unfilled spikelets number. The VC treatment (8.29 ± 2.91) produced the minimum unfilled spikelets number in the second year, which was followed by MSWC treatment (10.27 ± 2.61), PC treatment (10.73 ± 3.77), PC+CF treatment (11.67 ± 2.65), VC+CF treatment (12.42 ± 5.36), and then MSWC+CF treatment (12.54 ± 2.04). While the CF treatment recorded the maximum unfilled spikelets number per plant with 13.19 ± 3.74 , among the fertilized plots. There was a decrease in unfilled spikelets number in all the treatments except PC, CF and MSWC+CF treatments in the second year, however, the decline was not significant. Luong and Heong (2005) and Siavoshi et al. (2011) reported a similar result of higher unfilled spikelets in the chemical fertilizer treated plot. Although the unfilled spikelets number per plant in PC treatment was slightly increased in the second year, the treatment had the least unfilled spikelets number per

plant when taking average over the two years data (Table 11). And the maximum unfilled spikelets number was recorded in the control. Similar result was observed by Hossain et al. (2011). This study found that the interaction between the different fertilizer treatments and years had a significant effect on unfilled spikelets number per plant ($p < 0.05$, Table 12).

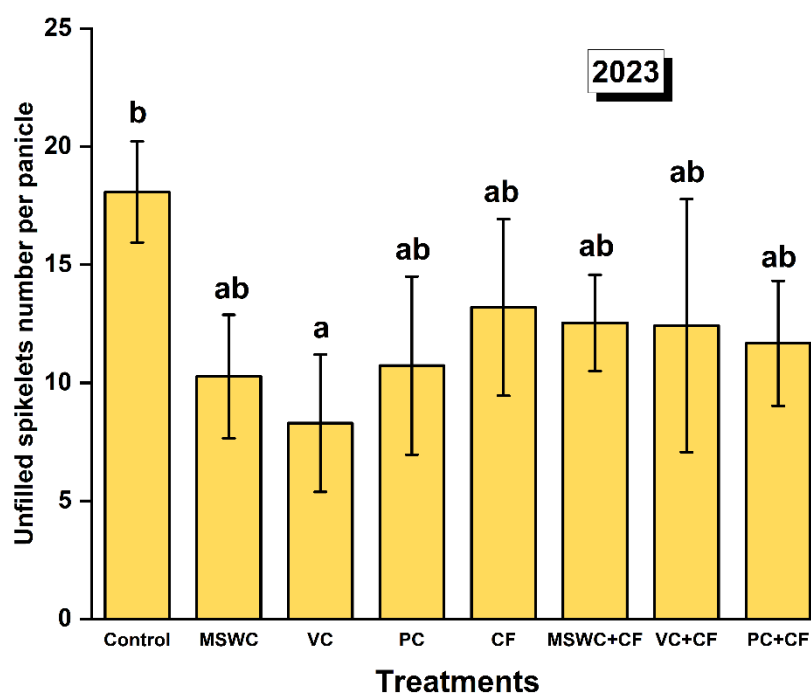
A strong negative correlation was observed between the unfilled spikelets number per panicle and percentage of filled spikelet number per panicle ($r = -0.92$, $p < 0.01$), harvest index ($r = -0.72$, $p < 0.05$), soil organic carbon ($r = -0.83$, $p < 0.01$), and pH of soil ($r = -0.77$, $p < 0.05$). And a moderate negative correlation with available K ($r = -0.52$, $p < 0.05$) (Fig.38). The result could imply that a lower organic carbon limits the plant's essential nutrient availability and affects the grain filling. Soil organic carbon is a component of soil organic matter, and it plays an important role in soil nutrient availability. Soil organic matter stores macro and micro nutrients in the plant-available form. It also determined the fertility of the soil (Gerke 2022).

Table 11: Variation in unfilled spikelets number per panicle under different fertilizer treatments, recorded during the two years of study.

Treatment	Unfilled spikelets number per panicle		
	2022	2023	Average
Control	20.36±1.81	18.08±2.14	19.22±2.17
MSWC	12.63±1.04	10.27±2.61	11.45±2.20
VC	14.19±3.27	8.29±2.91	11.24±4.25
PC	9.96±1.79	10.73±3.77	10.34±2.67
CF	7.97±3.21	13.19±3.74	10.58±4.23
MSWC+CF	8.73±1.66	12.54±2.04	10.63±2.67
VC+CF	18.85±3.59	12.42±5.36	15.63±5.39
PC+CF	17.40±1.09	11.67±2.65	14.50±3.62



(a)



(b)

Fig.10: Unfilled spikelets number per panicle under different treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 12: Two-way ANOVA table for unfilled spikelets number per panicle.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected					
Model	674.894	15	44.993	5.383	0.000
Intercept	8060.446	1	8060.446	964.398	0.000
Treatment	431.782	7	61.683	7.380	0.000
Year	31.179	1	31.179	3.730	0.062
Treatment*Year	211.932	7	30.276	3.622	0.006
Error	267.456	32	8.358	-	-
Total	9002.796	48	-	-	-

Percentage of filled spikelet number per panicle

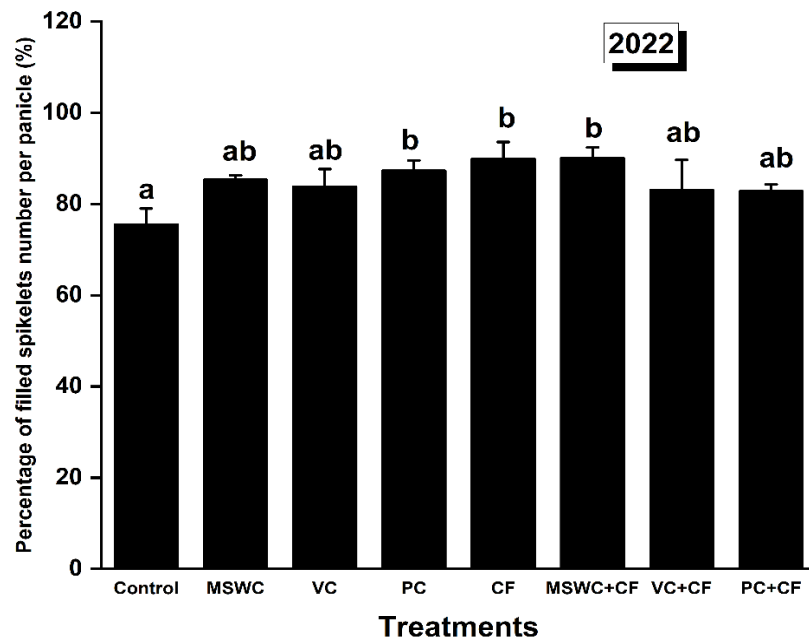
A significant difference in the percentage of filled spikelet number per panicle was recorded under different fertilizer treatments ($p < 0.05$, Table 14). The results pertaining to the percentage of filled spikelet number per panicle are given in Table 13. In the two-year average data, the maximum percentage of filled spikelet number per plant of $90.31 \pm 2.93\%$ was recorded in the CF treatment, however, the increase was not significant from the combined application of chemical fertilizer and composts. The MSWC+CF, VC+CF, and PC+CF treatments recorded $89.31 \pm 2.02\%$, $86.89 \pm 6.25\%$, and $86.19 \pm 4.49\%$ of filled spikelet number per panicle. It increased the percentage by 12.58%, 9.52%, and 8.64%, respectively, compared to the control treatment. Further, the study observed that percentage of filled spikelet number per plant was significantly increased in the second year except MSWC+CF treatment ($p < 0.05$). The maximum percentage of filled spikelet number per plant was found in MSWC+CF treatment ($90.04 \pm 2.36\%$) in the first year, while the lowest was in the control treatment ($75.50 \pm 3.49\%$). However, in the second year, the highest percentage of filled spikelet number per panicle of $91.43 \pm 1.74\%$ was recorded in VC treatment, but the lowest was still found in the control treatment with the percentage of $83.16 \pm 1.57\%$. And between the fertilizer treatment plots PC+CF treatment and MSWC+CF treatments recorded

minimum percentage of filled spikelet number per panicle with $82.80 \pm 1.45\%$ and $88.58 \pm 1.76\%$, during the first and second year, respectively.

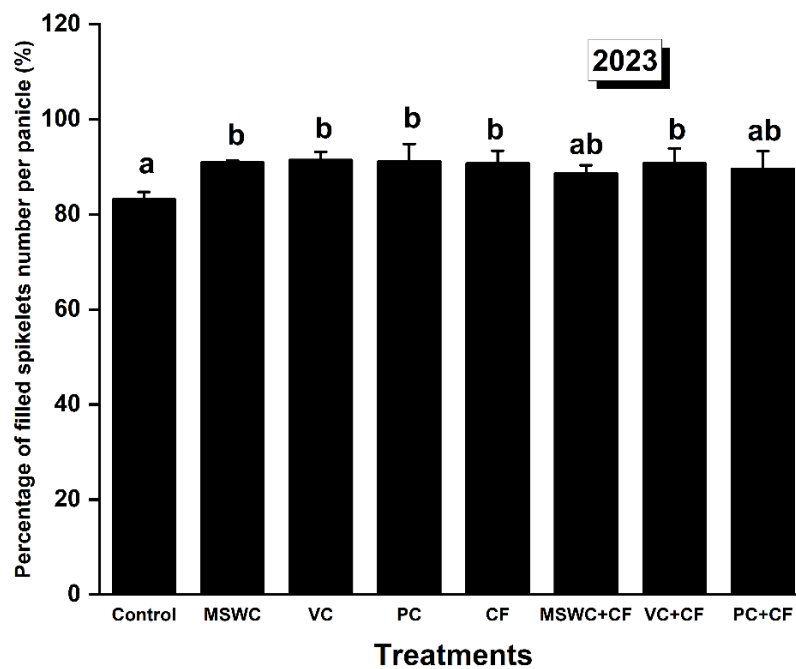
The percentage of filled spikelet number per panicle was found to be positively correlated with HI ($r = 0.88$, $p < 0.01$), available K ($r = 0.72$, $p < 0.05$), available P ($r = 0.68$, $p < 0.05$), total N ($r = 0.67$, $p < 0.05$), and SOC ($r = 0.90$, $p < 0.05$). And moderately correlated negatively with straw yield ($r = -0.56$, $p < 0.05$) (Fig.38).

Table 13: Variation in percentage of filled spikelets number per panicle under different fertilizer treatments, recorded during the two years of study.

Treatment	Percentage of filled spikelets number per panicle (%)		
	2022	2023	Average
Control	75.50 ± 3.49	83.16 ± 1.57	79.33 ± 4.84
MSWC	85.30 ± 0.99	90.91 ± 0.43	88.11 ± 3.14
VC	83.83 ± 3.83	91.43 ± 1.74	87.63 ± 4.94
PC	87.28 ± 2.28	91.12 ± 3.70	89.20 ± 3.46
CF	89.89 ± 3.72	90.72 ± 2.68	90.31 ± 2.93
MSWC+CF	90.04 ± 2.36	88.58 ± 1.76	89.31 ± 2.02
VC+CF	83.05 ± 6.62	90.74 ± 3.12	86.89 ± 6.25
PC+CF	82.80 ± 1.45	89.59 ± 3.71	86.19 ± 4.49



(a)



(b)

Fig 11: Percentage of filled spikelets number per panicle under different treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 14: Two-way ANOVA table of percentage of filled spikelet number per panicle.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	898.340	15	59.889	6.311	0.000
Intercept	364369.772	1	364369.772	38393.959	0.000
Treatment	492.390	7	70.341	7.412	0.000
Year	278.710	1	278.710	29.368	0.000
Treatment*Year	127.240	7	18.177	1.915	0.100
Error	303.689	32	9.490	-	-
Total	365571.801	48	-	-	-

1000 grain weight

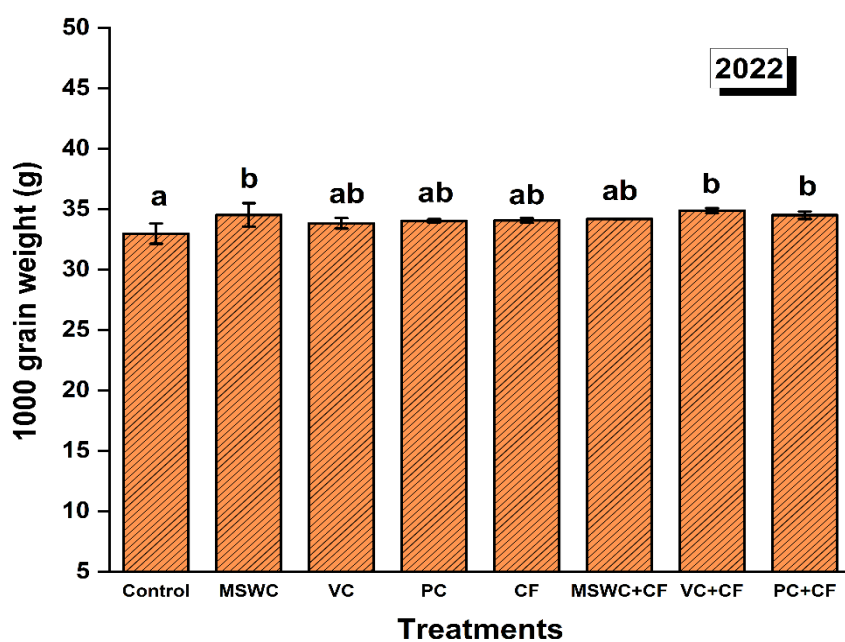
1000 grain weight was significantly affected by different fertilizer treatments and years, but the interaction between the two did not show significant variation ($p < 0.05$, Table 16). From the Fig.12 a, it was found that the application of vermicompost integrated with chemical fertilizer VC+CF treatment attained the maximum 1000-grain weight in the first year, having a weight of 34.89 ± 0.20 g. Whereas, the minimum 1000 grain weight was recorded in control with 32.99 ± 0.48 g, but among the fertilizer treatment plots, VC treatment obtained the minimum weight of 33.84 ± 0.43 g. Compared with the CF treatment, an increase in 1000 grain weight was recorded in MSWC+CF, MSWC, PC+CF, and VC+CF with 0.35%, 1.35%, 1.29%, and 2.40%, respectively, in the first year ($p < 0.05$). However, in the second year, the maximum 1000-grain weight was recorded in the PC+CF treatment (36.20 ± 0.34 g), followed by MSWC+CF treatment (35.58 ± 0.36) and VC+CF treatment (35.16 ± 0.58). While the minimum was recorded in VC treatment with 33.85 ± 0.50 g (Fig.12 b). The weight of 1000-grain in the control treatment was recorded as 34.67 ± 0.60 g. The integrated treatment of 50% municipal solid waste compost and 50% chemical fertilizer along with 20% of mustard oil cake and 30% poultry manure produced same level of 1000-grain weight compared with 100% application of chemical fertilizer (Sultana et al. 2021), which is in line with our study results.

When taking average of the two years' data, the co-application of composts and chemical fertilizers resulted in higher 1000-grain weight. The average weight of

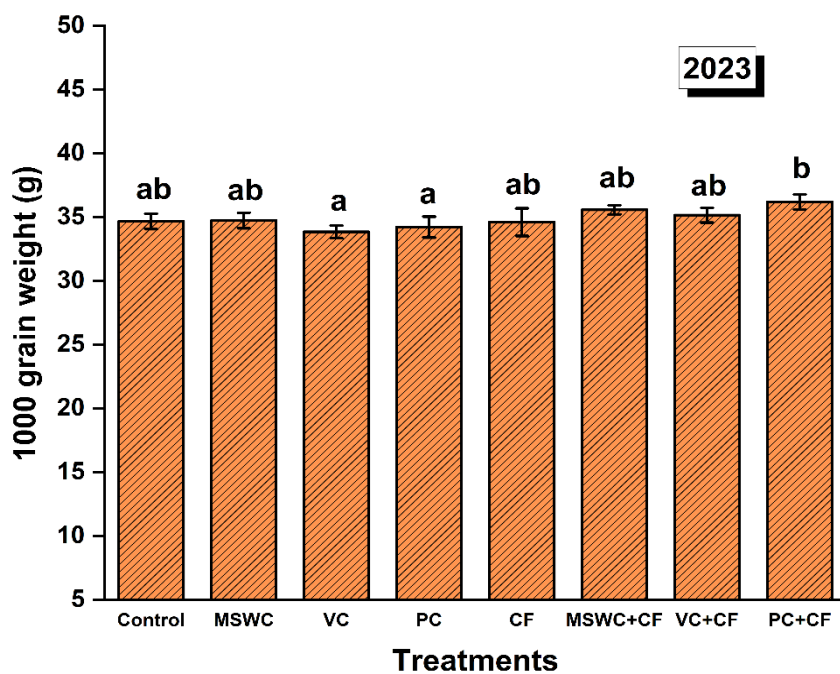
1000-grain was in the order of PC+CF treatment (35.36 ± 1.01) > VC+CF treatment (35.02 ± 0.41) > MSWC+CF treatment (34.88 ± 0.79) > MSWC treatment (34.63 ± 0.73) > CF treatment (34.34 ± 0.75) > PC treatment (34.13 ± 0.53) > VC treatment (33.84 ± 0.42) > control (33.83 ± 1.12) (Table 15). Similar result of increased 1000-grain weight due to the combined application of chemical fertilizer and organic fertilizer were reported by Yang et al. (2004), Hasanuzzaman et al. (2010), Kumar et al. (2014), Hindersah et al. (2022). Muhammad et al. (2008) found that application of composts and organic manure influence 1000-grain weight of rice. In the present study, the N content of *phumdi* compost is higher than municipal solid waste compost and vermicompost. Consequently, the 1000 grain weight was highest in the co-application of *phumdi* compost and chemical fertilizer. The 1000-grain weight of rice was found to be correlated positively with grain yield ($r = 0.91$, $p < 0.01$), and dry matter ($r = 0.84$, $p < 0.01$). Further, there was a strong positive correlation between 1000-grain weight and plant N uptake ($r = 0.80$, $p < 0.01$), available K ($r = 0.65$, $p < 0.05$), and total N ($r = 0.77$, $p < 0.05$) (Fig.38). A similar positive relationship between grain yield and 1000-grain weight was reported by Hoque et al. (2019). The nutrients N and K play a vital role in grain formation and grain filling as N boosts photo-assimilate production, and K improves the translocation of carbohydrates. It resulted in increased fertility of pollen, which in turn improved 1000 grain-weight of rice (Troza et al. 2021).

Table 15: Variation in 1000-grain weight under different fertilizer treatments, recorded during the two years of study.

Treatment	1000-grain weight (g)		
	2022	2023	Average
Control	32.99 ± 0.84	34.67 ± 0.60	33.83 ± 1.12
MSWC	34.53 ± 0.97	34.63 ± 0.61	34.63 ± 0.73
VC	33.84 ± 0.43	33.85 ± 0.50	33.84 ± 0.42
PC	34.04 ± 0.14	34.23 ± 0.82	34.13 ± 0.53
CF	34.07 ± 0.20	34.61 ± 1.08	34.34 ± 0.75
MSWC+CF	34.19 ± 0.02	35.58 ± 0.36	34.88 ± 0.79
VC+CF	34.89 ± 0.20	35.16 ± 0.58	35.02 ± 0.41
PC+CF	34.51 ± 0.31	36.20 ± 0.59	35.36 ± 1.01



(a)



(b)

Fig.12: 1000 grain weight of rice under different treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 16: Two-way ANOVA table of 1000-grain weight.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	25.316	15	1.688	4.716	0.000
Intercept	159727.316	1	159727.316	159727.316	0.000
Treatment	13.292	7	1.899	5.306	0.000
Year	6.675	1	6.675	18.652	0.000
Treatment*Year	5.349	7	0.764	2.135	0.068
Error	11.452	32	0.358	-	-
Total	57200.513	48	-	-	-

4.5. Grain yield

The grain yield found in the two years of study is shown in the Fig.13 a and b. There was a significant variation in grain yield under different treatments ($p < 0.05$, Table 17). It showed that the application of organic fertilizer, chemical fertilizer and their combinations influenced the production of grain yield of rice. In the first year, the grain yield was in the range of 3.17 to 5.37 t ha⁻¹. The maximum grain yield was recorded in PC+CF treatment. It was followed by VC+CF treatment and MSWC+CF treatment with 4.84±0.32 t ha⁻¹ and 4.53±0.18 t ha⁻¹, respectively. While the minimum grain yield was obtained in control treatment, however, among the fertilized plots, VC treatment (3.81±0.11 t ha⁻¹) had the minimum grain yield which was statistically at par with PC treatment (3.98±0.31 t ha⁻¹) and CF treatment (4.14±0.38 t ha⁻¹) (Fig.13 a). Similar to the first year, the maximum grain yield was still found in PC+CF treatment with 7.53±0.52 t ha⁻¹, which was then followed by VC+CF treatment (6.04±0.91) and MSWC+CF treatment (5.72±0.34), and the minimum in control with 3.70±0.48 t ha⁻¹ in the second year. The results of our study are in good agreement with the findings of Ali *et al* (2012), Sharma *et al.* (2013) and Mahmud *et al.* (2016), where integrated nutrient treatment produced higher rice grain.

Moreover, from the two-years average data, it was found that PC+CF treatment significantly increased the grain yield from the sole applications of chemical fertilizers and composts. *Phumdi* compost is a compost made from *phumdi*, a floating mass found in the Loktak lake of Manipur. The *phumdi* consists of a rich diversity of aquatic

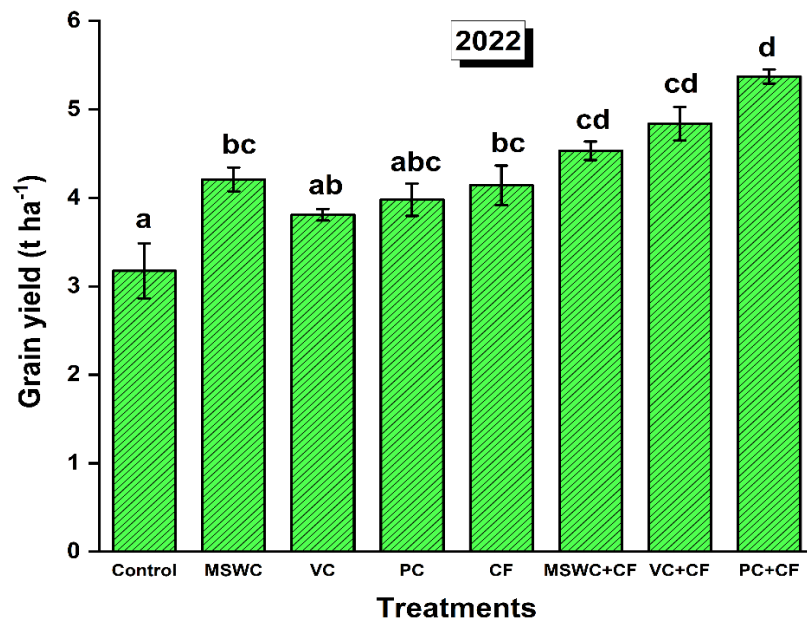
macrophytes, including *Phragmites karka*, *Hydrilla verticillata*, *Polygonum orientale*, etc, along with organic debris and mixture of soil. The utilization of *phumdi* compost not only improves agricultural productivity but also helps in managing the proliferation of *phumdi* that degrades the lake ecosystem. At the same time, the application of *phumdi* compost saved energy and transportation costs as it is easily available to the target farmers. The *phumdi* compost contained higher total N and available K compared to the other two compost which resulted in higher grain production in PC+CF treatment. Organic fertilizer containing higher total N content released more available N for plants (Eghball et al. 2002). The application of *phumdi* compost at the rate of 1.5 t ha⁻¹ along with 50% chemical fertilizer is proved to be beneficial for the growth and productivity of rice. Razavipour et al. (2018) reported a similar result where the rice grain yield was increased by 13.8% due to the application of compost made from the aquatic plant *Azolla* at 5% of soil weight. In the present study, PC+CF treatment produced 33.6% higher grain yield compared to CF treatment. Moreover, the improved yield traits found in the combined application of *phumdi* compost and chemical fertilizer help in achieving the maximum grain yield in the treatment. The statement is justified by the significant positive correlation of grain yield with panicle length ($r = 0.92$, $p < 0.01$), spikelets number per panicle ($r = 0.90$, $p < 0.01$), filled spikelets number per panicle ($r = 0.96$, $p < 0.01$), and 1000-grain weight (Fig.14). Myint et al. (2010) supported our result of such positive relationship between grain yield and yield components.

After PC+CF treatment, the conjunctive application of vermicompost and chemical fertilizer produced higher grain yield, which was followed by MSWC+CF treatment. The result showed that substitution of 50% N chemical fertilizer with compost resulted in higher grain yield compared to the CF treatment. This could also imply that balanced application of chemical fertilizer and compost improves the crop productivity. The result agrees with the findings of Kumar et al. (2014), Moe et al. (2019) and Urmi et al. (2022), where the integrated nutrient treatments give a positive effect on rice grain yield and yield attributes. Vermicompost contains nutrients in readily available forms, which could be taken up by plants for performing metabolic activities. Furthermore, the use of vermicompost as a soil amendment inhibits the

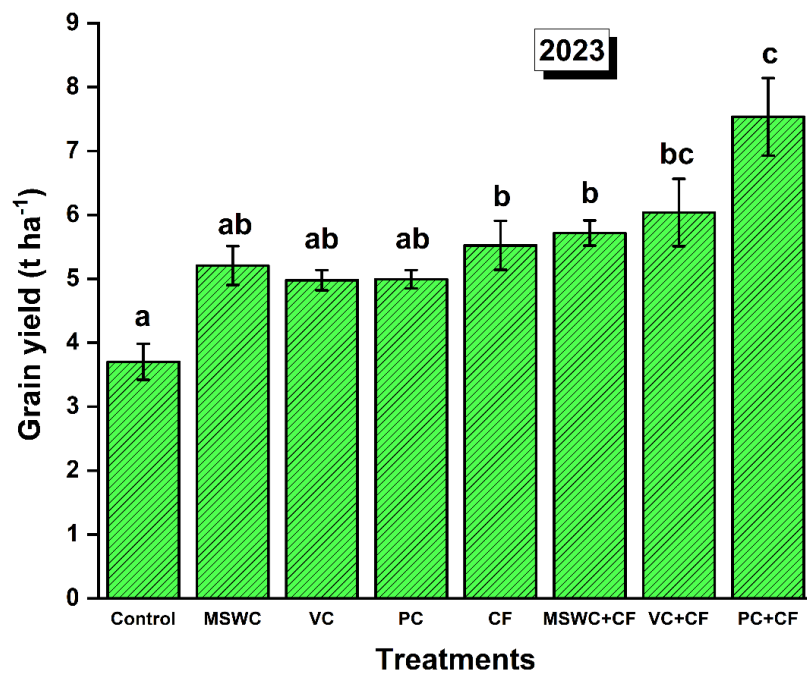
growth of plant fungi due to the presence of a diverse bacterial population, including *Bacillus* spp., *Enterobacter* spp., and *Pseudomonas* spp. *Streptomyces* (Vambe et al. 2023). It resulted in better performance of vermicompost as an organic fertilizer. Similar results of enhanced productivity of rice due to the application of 2.25 t ha⁻¹ of vermicompost with jeevamrutha were observed in the study of Mahanta et al. (2021). The application of vermicompost along with chemical fertilizer was found to be significantly increased grain yield as compare to the sole application of vermicompost or chemical fertilizer (BalajiNaik and Yakadari, 2004; Alam et al. 2022). Ranjitha et al. (2013) and Dekhana et al. (2014) reported that application of 50% vermicompost along with 50% chemical fertilizer produces the maximum grain yield of rice.

In the present study, the rice production in MSWC+CF treatment was 6.00% and 8.70% higher over the sole application of chemical fertilizer and municipal solid waste compost, respectively. Our findings are more or less similar to the results of Sultana et al. (2021) and Aktar et al. (2018), who reported higher grain yield using combined application of municipal solid waste compost and chemical fertilizer. And overall, the application of CF treatment reduced grain yield by 6.00%, 12.62% and 33.54% from MSWC+CF, VC+CF and PC+CF, respectively. Another reason of better performance of grain yield in the combined application of compost and chemical fertilizer could be due to the received of nutrients throughout the growing stages. N from chemical fertilizer is easily available to the plant in the early growth stage and the mineralization of compost supply nutrients at the later growth stage (Hidayatullah 2016)

The result also observed an increment of grain yield in second year in all the treatments ($p < 0.05$). This could be due to the residual effect of compost applied during the first year. Tran et al. (2012) reported a similar residual effect of compost in rice cultivation after one year of application. According to Badruzzaman et al. (2002), application of organic fertilizer had direct and residual effects on rice yield.



(a)

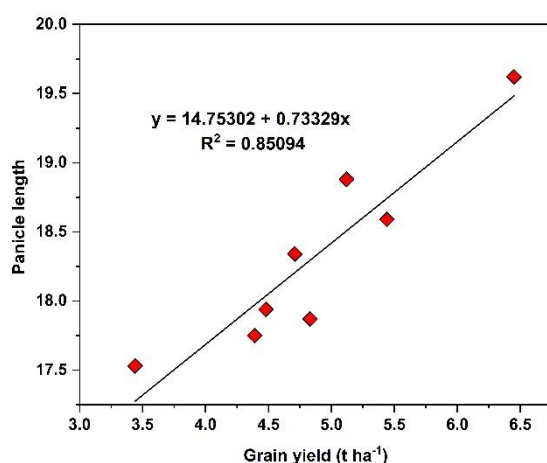


(b)

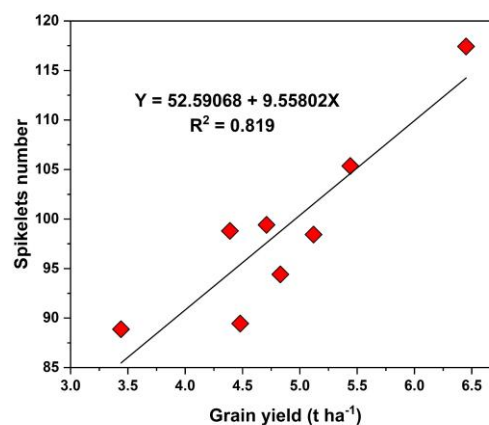
Fig.13: Grain yield of rice under different treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 17: Two-way ANOVA table of the grain yield of rice.

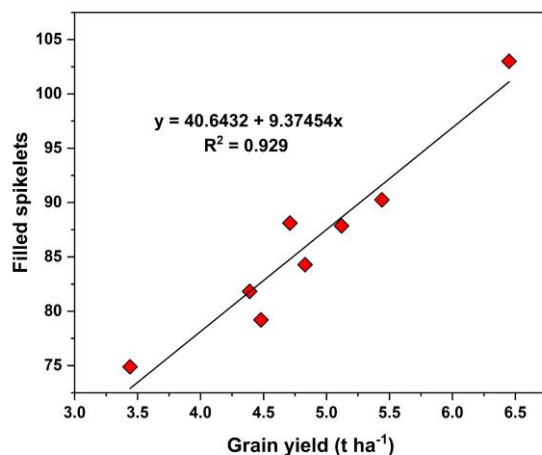
Source	Sum of Squares	df	Mean Square	F	Sig
Corrected					
Model	51.755	15	3.450	17.853	0.000
Intercept	1134.324	1	1134.324	5869.217	0.000
Treatment	32.072	7	4.582	23.707	0.000
Year	17.448	1	17.448	90.282	0.000
Treatment*Year	2.234	7	0.319	1.651	0.157
Error	6.185	32	0.193	-	-
Total	1192.264	48	-	-	-



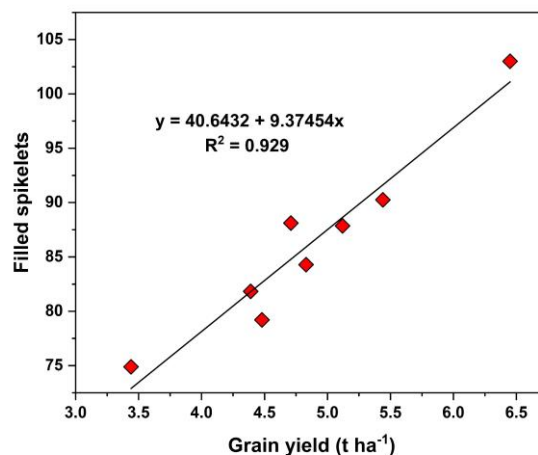
(a)



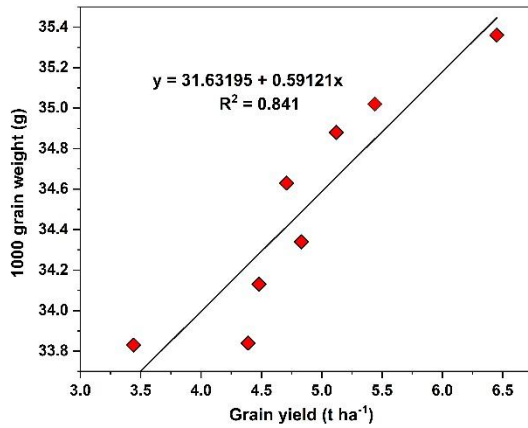
(b)



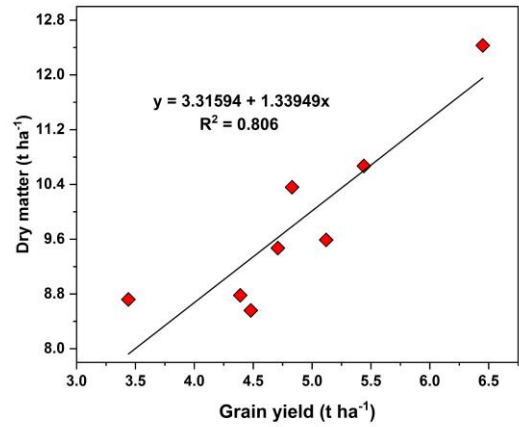
(c)



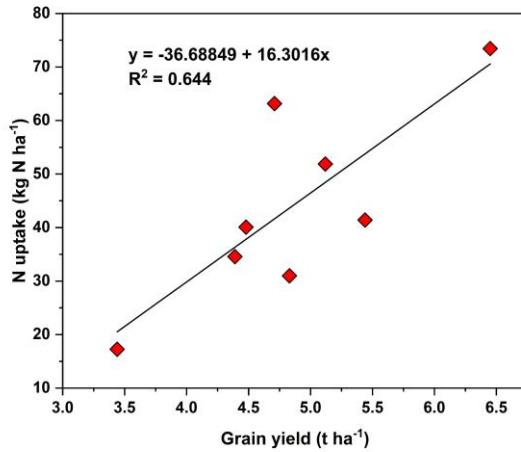
(d)



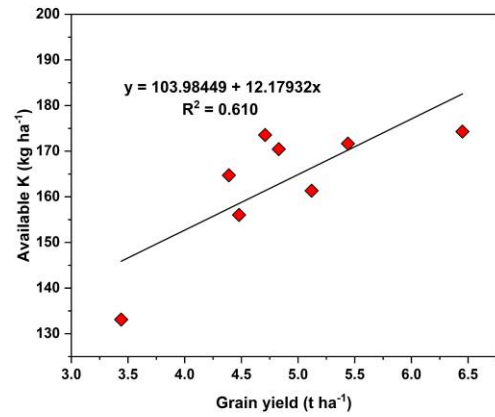
(e)



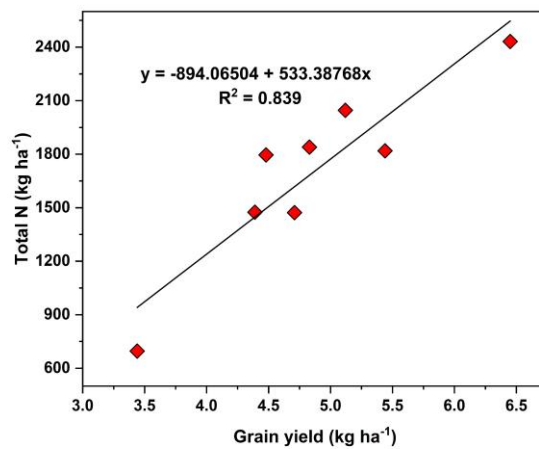
(f)



(g)



(h)



(i)

Fig.14: Relationship between grain yield and (a) panicle length; (b) spikelets number per panicle; (c) filled spikelets number per panicle; (d) harvest index; (e) 1000 grain weight; (f) dry matter; (g) plant N uptake; (h) available K; (i) total N.

4.6 Straw yield

During the two years of study, the application of different fertilizer treatments significantly impacts the straw yield, which was clearly demonstrated in Fig.15 a and b. In the first year, control treatment recorded maximum straw yield with $5.96 \pm 0.71 \text{ t ha}^{-1}$ of production. The treatment PC+CF produced similar straw production ($5.95 \pm 0.50 \text{ t ha}^{-1}$), which was followed by VC+CF treatment ($5.71 \pm 0.54 \text{ t ha}^{-1}$), MSWC ($5.51 \pm 0.18 \text{ t ha}^{-1}$), and MSWC+CF treatment ($4.85 \pm 0.22 \text{ t ha}^{-1}$), while the PC treatment recorded the minimum with $4.56 \pm 0.29 \text{ t ha}^{-1}$. Further, the study found out that the straw yield in CF treatment (4.78 ± 0.14) was at par with VC treatment (4.76 ± 0.20). Straw yield in PC+CF and control treatments was significantly increased by 24.47% and 24.68%, respectively, over the 100% N application from chemical fertilizer in the first year. The study noticed a significant increase in straw yield in the second year ($p < 0.05$, Table 19).

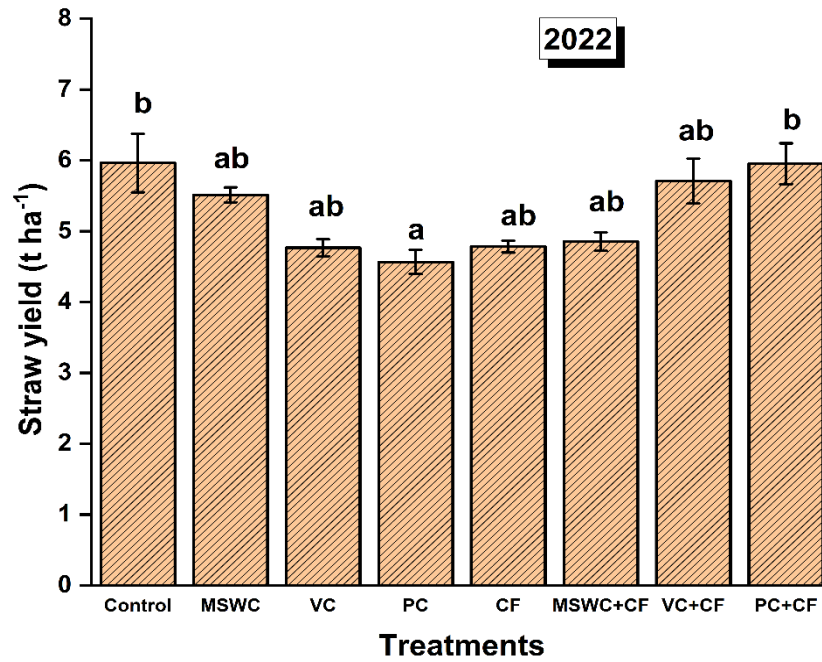
In the second year, maximum yield of $8.01 \pm 0.90 \text{ t ha}^{-1}$ was found in PC+CF treatment which was significantly higher than MSWC ($6.00 \pm 0.44 \text{ t ha}^{-1}$), VC (6.01 ± 0.48), PC (5.59 ± 0.17), and MSWC+CF (6.07 ± 0.50) by 31.96% to 43.29%. Although different fertilizer treatments and years distinctly showed variation in straw yield, the interaction between the two had no significant effect ($p < 0.05$, Table 19). In contrast to rice grain yield, the control produced more straw yield than CF treatment because the plant height in control was higher than CF treatment. The result is supported by the positive correlation of straw yield with plant height ($r = 0.88$, $p < 0.01$) in the present study (Fig.38). Sathiyabama et al. (2021) stated that straw yield is influenced by the growth characteristics of the crop, *i.e.* increase in plant height, tiller numbers, and dry matter production results in higher straw yield. In our study, the straw yield was also found to be positively correlated with dry matter ($r = 0.74$, $p < 0.05$).

Moreover, it was found out that the treatments PC+CF and VC+CF resulted in significantly higher straw yield production by 26.44% and 12.86% compared to the sole application of chemical fertilizer. The study is in good agreement with the findings of Khursheed et al. (2013), where the combined application of chemical fertilizer with vermicompost recorded 15.9% higher straw yield. The co-application

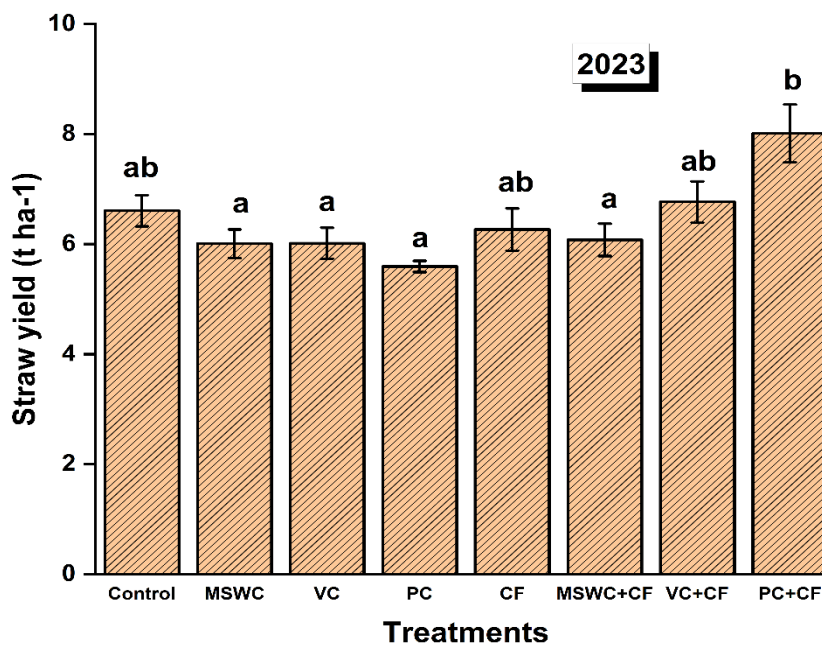
of organic and chemical fertilizers enhanced the vegetative growth of the plant that resulting in higher straw yield (Anisuzzaman et al. 2021). The enhancement in straw yield caused by the application of integrated fertilizers was also reported by Ahmad and Rahman (1991), Khan et al. (2007), and Haque et al. (2021). The supply of adequate nutrients from the integrated treatment of PC+CF and VC+CF during the plant developmental stages resulted in increased straw yield in the PC+CF and VC+CF treatments.

Table 18: Variation in straw yield under different fertilizer treatments, recorded during the two years of study.

Treatment	Straw Yield (t ha ⁻¹)		
	2022	2023	Average
Control	5.96±0.71	6.60±0.49	6.28±0.65
MSWC	5.51±0.18	6.00±0.44	5.76±0.40
VC	4.76±0.20	6.01±0.48	5.39±0.76
PC	4.56±0.29	5.59±0.17	5.08±0.60
CF	4.78±0.14	6.62±0.66	5.52±0.91
MSWC+CF	4.85±0.22	6.07±0.50	5.46±0.75
VC+CF	5.71±0.54	6.76±0.64	6.23±0.78
PC+CF	5.95±0.50	8.01±0.90	6.98±1.30



(a)



(b)

Fig.15: Straw yield of rice under different treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 19: Two-way ANOVA table of the straw yield of rice.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	34.629	15	2.309	9.333	0.000
Intercept	1637.653	1	1637.653	6620.792	0.000
Treatment	16.132	7	2.305	9.317	0.000
Year	15.997	1	15.997	64.673	0.000
Treatment*Year	2.499	7	0.357	1.444	0.223
Error	7.915	32	0.247	-	-
Total	1680.197	48	-	-	-

4.7. Harvest Index

The variation of HI in the first year and second year with the application of different fertilizer treatments is shown in Fig.16 a and b. In the first year, the maximum HI of 0.48 ± 0.008 was recorded in MSWC+CF treatment, followed by the PC+CF treatment with the value of 0.47 ± 0.024 . The HI in PC treatment obtained a similar result to CF treatment (0.46). While the control treatment produced the minimum value of 0.34 ± 0.020 . Among the fertilizer application treatments, MSWC recorded minimum HI in the first year. The maximum and minimum HI recorded in the second year are in line with the first year where MSWC+CF gave the maximum HI (0.48 ± 0.007) and control recorded the minimum (0.35 ± 0.017). In our study, the HI was found between the range of 0.34 to 0.48. HI can be defined as the ratio of economic yield to the total aboveground biomass. According to Hay (2008), the HI of intensively cultivated crop varieties generally varied between 0.40 to 0.60. The results of HI in all the treatments fall within the given range except the control. In the study, the application of different fertilizer treatments significantly affects the HI in rice ($p < 0.05$, Table 21). The higher HI value in PC+CF and MSWC+CF treatments indicates that it could supply the nutrients needed by plants for development, and the assimilates were translocated to the grain yield rather than the vegetative parts. According to Ju et al. (2009) and Yang and Zhang (2010), crop management systems determine the effectiveness of producing higher grain yield over the biological yield.

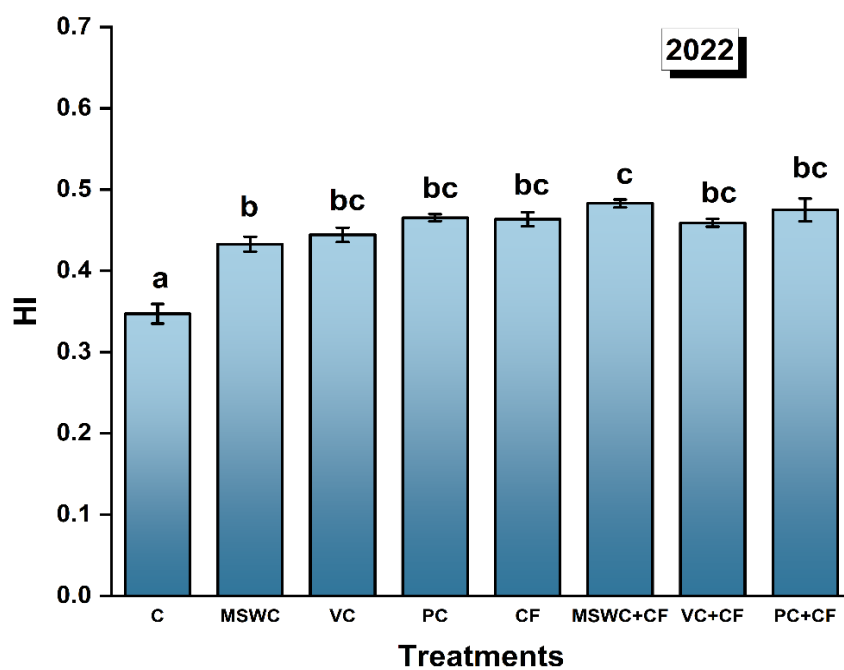
In the average of two years of data, MSWC+CF treatment had the highest HI with a value of 0.48 ± 0.007 (Table 20). This could be explained by the lower straw yield

production, which lowers the biological yield in the combined treatment of municipal solid waste compost and chemical fertilizer compared to other integrated treatments and sole application of chemical fertilizer. The maximum HI in MSWC+CF treatment was followed by PC+CF treatment with 0.47 ± 0.016 value. The development of plant growth and increased yield production is governed by the availability of nutrients which can be easily absorbed by the plant. The application of composts has the potential to enhance the overall properties of soil and improve the nutrient use efficiency (Rengel et al. 1999; Dhaliwal et al. 2019). The higher HI value in the combined use of organic and chemical fertilizer implies that the treatments could be able to provide nutrients to the plant which significantly increases economic yield. And the result of HI in VC+CF and PC treatments was at par with the CF treatment.

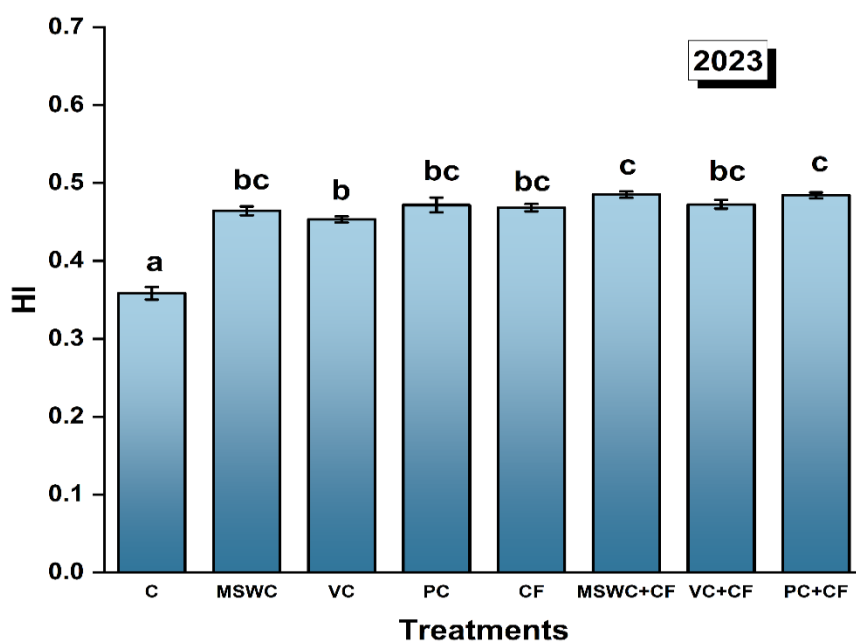
The correlation results of the study indicate that HI has a strong positive and linear relationship with available K ($r = 0.81$, $p < 0.01$), total N ($r = 0.92$, $p < 0.01$), and SOC ($r = 0.88$, $p < 0.01$) (Fig.38). It further observed moderate correlation between N uptake ($r = 0.63$, $p < 0.05$), available P ($r = 0.63$, $p < 0.05$). Such a positive correlation between HI and N, P, and K was also reported by Syamsiyah et al. (2023). A mature compost contains humic substance, a stable major component of organic matter which can significantly influence the nutrient availability and uptake by plants, thereby its application increases grain yield and HI of rice.

Table 20: Variation in HI number per panicle under different fertilizer treatments, recorded during the two years of study.

Treatment	HI		
	2022	2023	Average
Control	0.34 ± 0.020	0.35 ± 0.014	0.35 ± 0.017
MSWC	0.43 ± 0.015	0.46 ± 0.009	0.44 ± 0.020
VC	0.44 ± 0.015	0.45 ± 0.006	0.44 ± 0.011
PC	0.46 ± 0.007	0.47 ± 0.016	0.46 ± 0.011
CF	0.46 ± 0.015	0.46 ± 0.008	0.46 ± 0.011
MSWC+CF	0.48 ± 0.008	0.48 ± 0.007	0.48 ± 0.007
VC+CF	0.45 ± 0.008	0.47 ± 0.009	0.46 ± 0.011
PC+CF	0.47 ± 0.024	0.48 ± 0.006	0.47 ± 0.016



(a)



(b)

Fig.16: HI of rice under different treatments during (a) 2022 and (b) 2023. The bars with same letters are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 21: Two-way ANOVA table of HI.

Source	Sum of Squares	df	Mean Square	F	Sig
Corrected Model	0.076	15	0.005	29.040	0.000
Intercept	9.796	1	9.796	56015.826	0.000
Treatment	0.074	7	0.011	60.380	0.000
Year	0.001	1	0.001	8.102	0.008
Treatment*Year	0.001	7	0.000	0.691	0.679
Error	0.006	32	0.000	-	-
Total	9.878	48	-	-	-

4.8. N uptake, Nitrogen use efficiency (NUE) and agronomic nitrogen efficiency (ANE).

In the two years of study, maximum average dry matter was recorded in PC+CF treatment ($12.43 \pm 1.57 \text{ t ha}^{-1}$), followed by VC+CF treatment ($10.67 \pm 0.18 \text{ t ha}^{-1}$), while the lowest was recorded in PC treatment ($8.56 \pm 0.03 \text{ t ha}^{-1}$). MSWC+CF treatment produces less dry matter production than CF treatment with 8.02% reduction. At the same time, the sole application of composts MSWC ($9.47 \pm 0.35 \text{ t ha}^{-1}$), VC ($8.78 \pm 0.29 \text{ t ha}^{-1}$), and PC ($8.56 \pm 0.03 \text{ t ha}^{-1}$) treatments also recorded minimal dry matter production compared to the CF treatment ($10.36 \pm 2.02 \text{ t ha}^{-1}$). A mature compost contains humic substances, a stable major component of organic matter. The humic substances act as fertilizer, which significantly influences the nutrient availability and uptake by plants and regulates plant growth hormones (Atiyeh et al. 2002; Guo et al. 2019), thereby increasing biomass accumulation of the crop. A similar result of higher plant aboveground biomass due to the combined application of chemical fertilizer and compost was reported by Ghosh and Devi (2019). The dry matter production was found to be correlated positively with TNPP ($r = 0.79$, $p < 0.05$), panicle length ($r = 0.81$, $p < 0.01$), spikelets number per panicle ($r = 0.88$, $p < 0.01$), filled spikelets number per panicle ($r = 0.91$, $p < 0.01$), 1000-grain yield ($r = 0.84$, $p < 0.01$), straw yield ($r = 0.74$, $p < 0.05$), and grain yield ($r = 0.89$, $p < 0.01$) (Fig.38). This means that dry matter production is greatly determined by the growth and yield characteristics of the rice. Moreover, there was a positive relationship between dry matter and N uptake, available K, total N and SOC ($p < 0.05$). The development of plants needs N, P, and K for optimum growth. The addition of integrated fertilizers improved plant N uptake

and enhanced dry matter accumulation by promoting shoot growth and leaf expansion (Chen et al. 2017).

The present study observed that the plant N content and N uptake by plant biomass varied significantly due to different fertilizer treatments ($p < 0.05$). The maximum N content in plant was recorded in MSWC treatment with 6.67 ± 0.09 %, which was followed by PC+CF and MSWC+CF treatments with N content of 5.92 ± 0.19 % and 5.41 ± 0.36 %, respectively. The average N uptake by the plant varied from 17.26 to 73.44%. From the Table 22, it was found that the maximum N uptake resulted from PC+CF treatment, while CF treatment recorded minimum N uptake among the fertilizer application treatments. There was a significant increase of 137.05%, 67.39%, and 33.63% N uptake in PC+CF treatment, MSWC+CF treatment, and VC+CF treatment, respectively, over the 100% application of N by chemical fertilizer. The plant N uptake in the integrated fertilizer treatments was higher than their sole application, except MSWC+CF. The plants in the MSWC treatment had more N uptake capacity than the MSWC+CF treatment. This result could be attributed to the higher growth characteristics in the MSWC treatment. Ahmad et al. (2008) stated that the growth and yield potential of rice is significantly influence by the difference in nutrient absorption due to the application of different N source. The compost with low C:N ratio has the potential to release N faster in the soil (Kadoglidou et al. 2019).

NUE was also significantly influenced by the application of different fertilizer treatments. The average NUE under different fertilizer treatments varied significantly, ranging from 22.87 to 93.65% (Table 22). In the study, PC+CF treatment had the highest NUE (93.95%), which was followed by MSWC (76.49 ± 1.79), MSWC+CF (57.67 ± 0.56 %), and VC+CF (42.09 ± 1.61 %) treatments. CF treatment recorded the lowest NUE with a record of 22.87 ± 15.01 %. The treatments VC+CF and PC+CF improved the ANE by 29.45% and 146.15% over the sole compost application treatments VC and PC, respectively. It was clearly observed from the Table 22 that ANE was significantly affected by different treatments ($p < 0.05$). The maximum ANE was also occurred in PC+CF treatment with 50.25 ± 19.28 kg grain kg^{-1} N which was significantly higher than other treatments. And the lowest ANE was recorded in VC treatment with 15.91 ± 7.58 kg grain kg^{-1} N. ANE in PC+CF, VC+CF, and MSWC+CF treatments were 114.79%, 43.35%, and 20.90% higher than CF treatment.

Interestingly, a significant positive correlation was found between the N uptake by plants and grain yield ($r = 0.80$, $p < 0.01$). Since the grain yield was higher with the combined treatment of composts and chemical fertilizer, it can be concluded that applying composts alongside chemical fertilizer enhanced the nutrient availability and improved use efficiency by rice. Similar results of higher N uptake due to the application of integrated fertilizer was reported (Virdia and Mehta, 2009; Sathish et al. 2011) NUE refers to how effectively the rice crop utilizes the applied N fertilizer to produce biomass or yield. It is a critical index in crop production as it balances resource utilization while minimizing environmental loss. The results of our study suggested that the combined application of organic and chemical fertilizer treatment is more beneficial for achieving sustainable agriculture. Similarly, ANE in the PC+CF treatment, VC+CF treatment and MSWC+CF treatment were 116.12%, 43.35% and 20.90%, respectively, increased over the CF treatment. However, the MSWC, VC, and PC treatments recorded lower ANE compared to CF treatments. Even though the application of compost is beneficial to both plants and soil, our study demonstrated that their sole application could not supply the intrinsic amount of nutrients needed for optimal yield.

Table 22: The average data of dry matter production, plant N concentration, N uptake by plant, nitrogen use efficiency (NUE) and agronomic N efficiency (ANE) of rice under different fertilizer treatments over the two years.

Treatments	Dry matter (t ha ⁻¹)	Plant N concentration (%)	N uptake (kg N ha ⁻¹)	NUE (%)	ANE (kg grain kg ⁻¹ N applied)
Control	8.72±0.58	1.97±0.12	17.26±2.25		
MSWC	9.47±0.35	6.67±0.09	63.15±3.32	76.49±1.78	21.16±5.57
VC	8.78±0.29	3.93±0.16	34.57±0.27	28.85±3.29	15.91±7.58
PC	8.56±0.03	4.68±0.33	40.08±2.70	38.11±0.74	17.47±5.77
CF	10.36±2.02	2.98±0.06	30.98±6.75	22.87±15.01	23.25±10.09
MSWC+CF	9.59±0.28	5.41±0.36	51.86±1.91	57.67±0.56	28.11±7.77
VC+CF	10.67±0.18	3.88±0.18	41.40±1.28	42.09±1.61	33.33±7.93
PC+CF	12.43±1.57	5.92±0.19	73.44±6.92	93.64±15.30	50.25±19.28

Table 23: Two-way analysis of variance of growth and yield characteristics.

Sources	TNP P (cm)	ETN PP	Panic le lengt h	Spikel ets numbe r per panicle	Filled spikel ets numbe r per panicle	Unfill ed spikel ets numbe r per panicle	Percenta ge of filled spikelet s number per panicle (%)	100 0 grai n wt. (g)	Grai n yiel d (t ha ⁻¹)	Straw yiel d (t ha ⁻¹)	H I
Year	**	**	**	**	**	NS	**	**	**	**	**
Treatm ent	**	**	**	**	**	**	**	**	**	**	**
Year× Treatm ent	NS	NS	NS	**	NS	**	NS	NS	NS	NS	N S

NS indicates not-significant and ** indicates significant at $p < 0.05$. TNPP: tiller number per plant; ETNPP: effective tiller number per

4.9. Estimation of GHG emissions from rice fields in response to different treatments

CH₄ flux and seasonal cumulative CH₄ emission

The CH₄ flux during the various cropping stages exhibited a similar trend irrespective of the different fertilizer treatments. The CH₄ flux ranged from 0.12 to 18.56 mg m⁻² h⁻¹ in the first year and from 1.44 to 17.01 mg m⁻² h⁻¹ in the second year. The variation in CH₄ flux at different crop stages is statistically significant ($p < 0.05$, Table 24). The gas fluxes were low during the early stages of the crop and then gradually increased with crop development. The peak emission of CH₄ was observed during the active tillering and reproductive stages of rice. Subsequently, at the maturity stage, the emission rate of CH₄ declined (Fig.21 a and b). The highest CH₄ flux during the first year occurred at 56DAT in the MSWC treatment (18.56 mg m⁻² h⁻¹), PC treatment (13.02 mg m⁻² h⁻¹), CF treatment (12.55 mg m⁻² h⁻¹), and PC+CF treatment (13.90 mg m⁻² h⁻¹), while VC and MSWC+CF treatments were recorded at 49DAT with values of 10.88 mg m⁻² h⁻¹ and 12.03 mg m⁻² h⁻¹, respectively. The control (7.74 mg m⁻² h⁻¹) and VC+CF (9.54 mg m⁻² h⁻¹) treatments were observed at 42DAT. However, during the second year, only the MSWC treatment showed peak emission at 56DAT, while

the other treatments were noted at 42DAT and 49DAT. The prominent peaks during active tillering stage correspond to the split application of fertilizers. Tang et al. (2017) reported that pattern of CH₄ emission during the growth stage can be influenced by fertilizers application timing. The decomposition of organic matter under anaerobic conditions has become the primary source of CH₄ emission in the early stages of rice development (Zou et al. 2005). Moreover, during the reproductive stage, the plant's rate of photosynthesis is higher, and organic substrates in the form of root exudates are released in higher amounts (Kumar et al. 2016), resulting in increased CH₄ emissions. Ali et al. (2015) and Bharali et al. (2018) reported similar findings regarding peak emissions during these stages. The CH₄ emitted from the rice field is transported to the atmosphere mainly through rice aerenchyma. During the reproductive stage, the rice plant has well-developed aerenchyma, leading to the increased capacity for plant-mediated emission of the gas (Khosa et al. 2011). Cicerone and Shetter (1981) stated that during the reproductive stage, more than 90% of the CH₄ emission was transported through the rice plant. And as the crop matured, there was no standing water inside the plot. It converted the anaerobic conditions of the soil into aerobic which did not favour the formation of CH₄, and hence lowered the CH₄ flux during the late stage of the rice crop.

In the study, the CH₄ fluxes were significantly affected by different fertilizer treatments ($p < 0.05$, Table 24). Among the treatments, MSWC emitted substantially higher CH₄ in both years, leading to the highest seasonal cumulative CH₄ emission. The mean flux of CH₄ in the MSWC treatment was 5.96 mg m⁻² h⁻¹ in the first year and 8.90 mg m⁻² h⁻¹ in the second year, respectively. VC+CF treatment recorded the lowest CH₄ flux in both years among the fertilizer treatments, with the values of 3.83 mg m⁻² h⁻¹ and 2.69 mg m⁻² h⁻¹ in the first and second years, respectively. The cumulative CH₄ emission in the VC+CF treatment was higher than in the control treatment during the first year; however, in the second year, the emission reduced considerably. The mean cumulative CH₄ emission over the two years was in the order of control (74.56±23.79 kg ha⁻¹) < VC+CF treatment (76.85±18.92 kg ha⁻¹) < VC treatment (100.71±6.25 kg ha⁻¹) < MSWC+CF treatment (103.03±2.60 kg ha⁻¹) < PC+CF treatment (103.61±9.27 kg ha⁻¹) < PC treatment (139.49±32.38 kg ha⁻¹) < CF treatment (120.13±36.37 kg ha⁻¹) < MSWC treatment (174.89±48.95 kg ha⁻¹) (Fig.22).

The application of composts alone, especially MSWC and PC treatments, resulted in higher CH₄ emissions than the CF treatment. This could imply that municipal solid waste compost and *phumdi* compost contained more C-rich materials that stimulate the activities of methanogenic bacteria under the anaerobic conditions of rice field. This hypothesis was supported by the results of Wang et al. (2018). The higher CH₄ emission from the application of composts as the main nutrient source could also be due to the priming effect of labile C from the exogenous organic material. CH₄ is produced by the decomposition of organic substances in anoxic conditions. Therefore, the addition of organic fertilizer enhanced CH₄ emissions from the flooded soils of rice fields. Similar results showing higher CH₄ emission with organic fertilizer application compared to the chemical fertilizer application were reported by Bhatia et al. (2005), Yuan et al. (2017), Yuan et al. (2018), and Zhao et al. (2015). Traore et al. (2017) reported that amendment of organic fertilizer in rice fields reduced the soil redox potential and increased the CH₄ emissions by 19 to 52 times compared to the chemical fertilizer. However, studies of Soebandiono et al. (2021) reported better performance of organic fertilizer application in lowering CH₄ emission from rice field compared to chemical fertilizer application. It is aligned with the findings of our present study that the application of vermicompost as the 100% source of N produced lesser CH₄ emission compared to the CF and the other two composts. The result of lesser CH₄ emission in vermicompost fertilized plot was supported by the findings of Singh et al. (2009). The reason behind the lower CH₄ emission in the present study could be that vermicompost influenced the microbial population of methanogens and methanotrophs. At the same time, vermicompost contained more stabilized C which reduces the availability of substrate to the methanogens. The emission of CH₄ from the rice fields is affected by the nature of the organic substrate applied to the field (Jiang et al. 2011; Kim et al. 2014).

The present investigation found out that there was a significant difference in seasonal cumulative CH₄ emission between the different treatments, years and treatments × years ($p < 0.05$). The results of the mean cumulative CH₄ emissions showed that the VC+CF treatment significantly inhibited CH₄ emission from rice fields, with a reduction of 56.37% compared to the CF treatment. Moreover, the integrated

application of composts and chemical fertilizer treatment MSWC+CF and PC+CF, effectively reduced CH₄ emission with greater production of grain yield. Similar observation was reported by Malyan et al. (2019) and Bharati et al. (2020), where combined organic and chemical fertilizer application lowers CH₄ emission as compared to chemical fertilizer alone. The VC, MSWC+CF, VC+CF and PC+CF treatments decreased the gas emission by 9.18%, 3.63%, 42.17% and 13.50%, respectively in the second year. Meanwhile, the treatments MSWC, PC and CF showed an increasing trend of CH₄ emission in the second year, compared to the first year. The decomposition of residual organic matter from the first year provides more C substrate to the methanogenic bacteria and induces more CH₄ production in the second year.

Additionally, the EF of CH₄ varied from 0.76 to 1.78 kg ha⁻¹ d⁻¹ when averaged across the two years (Table 25). The highest EF was found in MSWC treatment, which was significantly higher than other treatments, while the lowest was in the control treatment. The VC+CF treatment had the lowest EF of 0.784 kg ha⁻¹ d⁻¹ among the fertilizer treatment plots which is lower than the IPCC (2019) default EF of CH₄ (0.85 kg ha⁻¹ d⁻¹) from rice fields without organic amendment. The application of vermicompost integrated with chemical fertilizer reduced the EF of CH₄ by 56.37% compared to the sole application of chemical fertilizer. The result can infer that substituting 50% of N chemical fertilizer with vermicompost significantly helps in mitigating CH₄ emission from inceptisol soil type of rice field cultivated under rainfed conditions. A significant positive and linear relationship was found between the CH₄ emission and air temperature ($r = 0.63$, $p < 0.05$) recorded during the sampling period. It implies that increase in temperature accelerates the activities of methanogenic bacteria, leading to higher decomposition rate of the organic matter. CH₄ emission was also found to be correlated positively with SOC ($r = 0.68$, $p < 0.05$) and soil pH ($r = 0.70$, $p < 0.05$) (Fig.38). SOC and soil pH play a significant role in controlling the dynamics of CH₄ emission. Organic materials are the main source of energy for microbial population. Higher availability of organic matter induced the activities of methanogens and increase CH₄ production under anaerobic condition. Methanogens are pH sensitive bacteria with a relatively narrow pH range of 6 – 8 (Xu et al. 2023).

The soil of the rice field ranging from 6.29 to 7.38 which is the optimal range for methanogenic growth.

Table 24: Three-way ANOVA table for CH₄ flux.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	11196.226	239	46.846	45.050	0.000
Intercept	16228.173	1	16228.173	15605.870	0.000
Treatment (T)	1251.332	7	178.762	171.907	0.000
Days (D)	6541.951	14	467.282	449.363	0.000
Year (Y)	110.961	1	110.961	106.706	0.000
T*D	1435.617	98	14.649	14.087	0.000
T*Y	362.880	7	51.840	49.852	0.000
D*Y	512.681	14	36.620	35.216	0.000
T*D*Y	980.803	98	10.008	9.624	0.000
Error	499.141	480	1.040		
Total	27923.539	720			

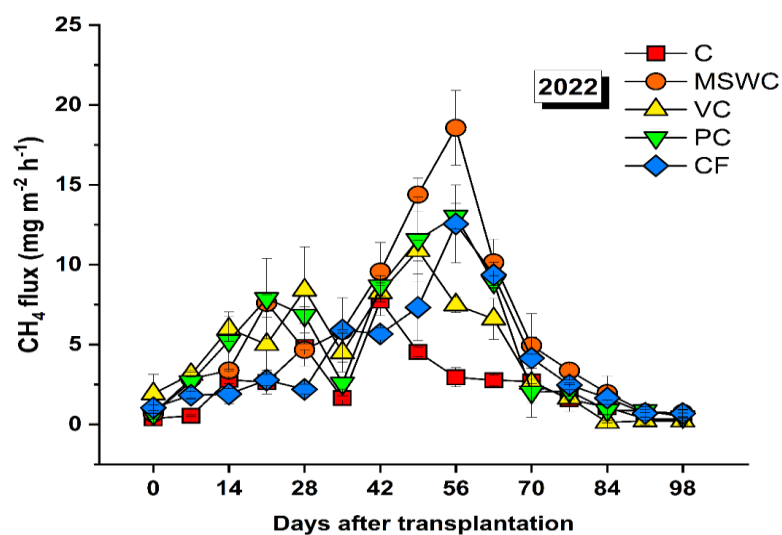


Fig.17: Variation of CH₄ flux from rice field between chemical fertilizer and sole application of composts during rice growing season of 2022 (mean±SD), where C=control; MSWC=municipal solid waste compost; VC=vermicompost; PC=phumdi compost; CF=chemical fertilizer.

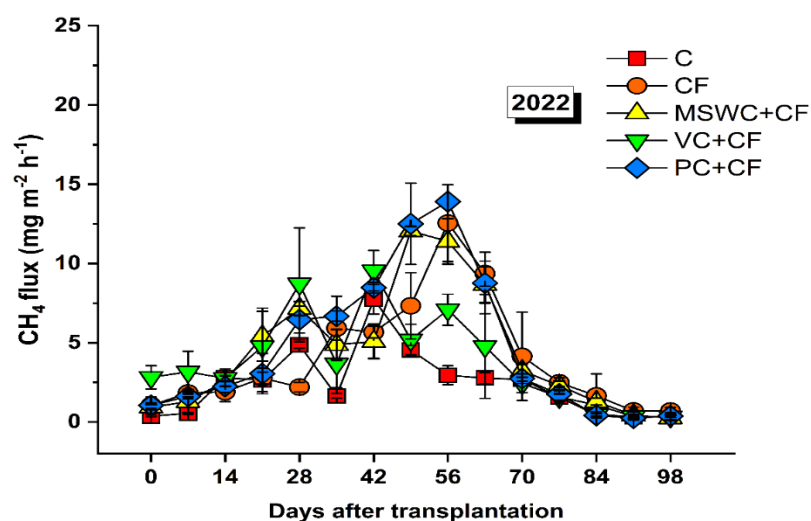


Fig.18: Variation of CH₄ flux from rice field between chemical fertilizer and integrated application of composts and chemical fertilizer during rice growing season of 2022 (mean±SD), where C=control; CF=chemical fertilizer; MSWC+CF=50% municipal solid waste compost+50% chemical fertilizer; VC+CF=50% vermicompost+50% chemical fertilizer; PC+CF=50% phumdi compost+50% chemical fertilizer.

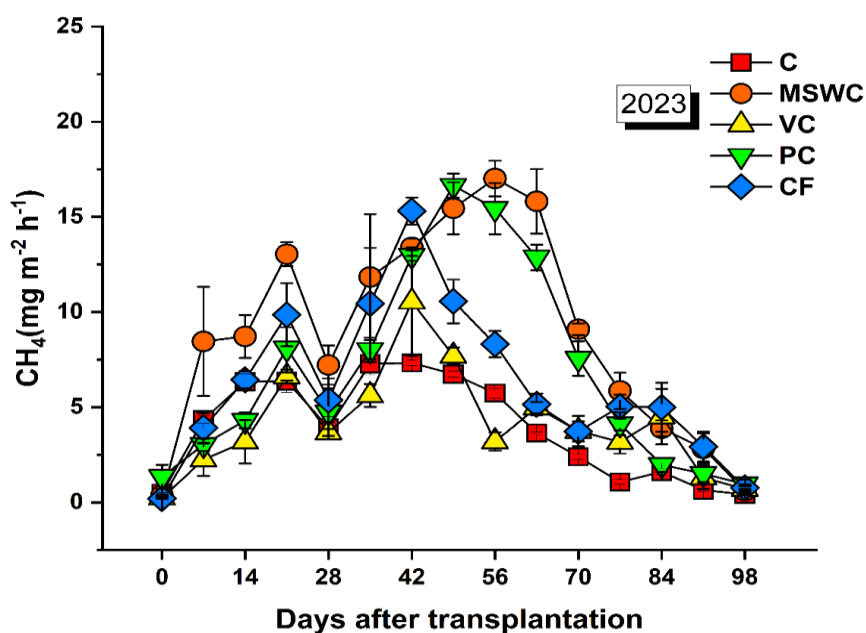


Fig.19: Variation of CH₄ flux from rice field between chemical fertilizer and sole application of composts during rice growing season of 2023 (mean±SD), where C=control; MSWC=municipal solid waste compost; VC=vermicompost; PC=phumdi compost; CF=chemical fertilizer.

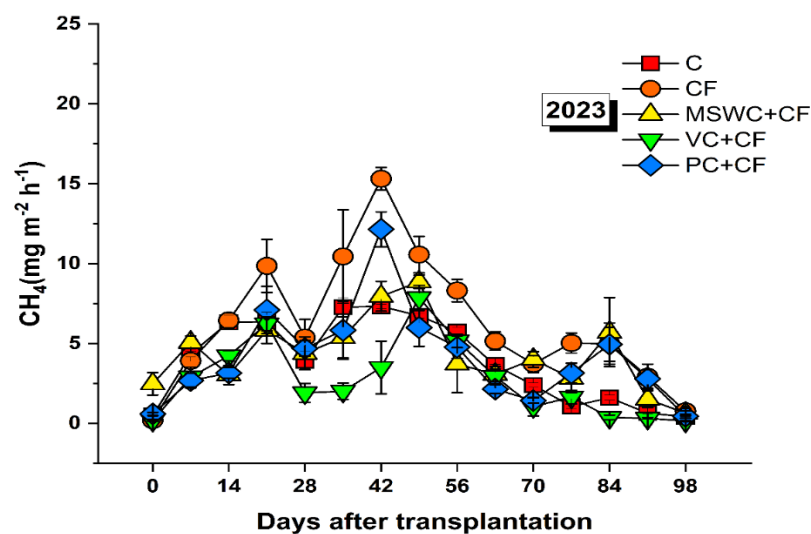
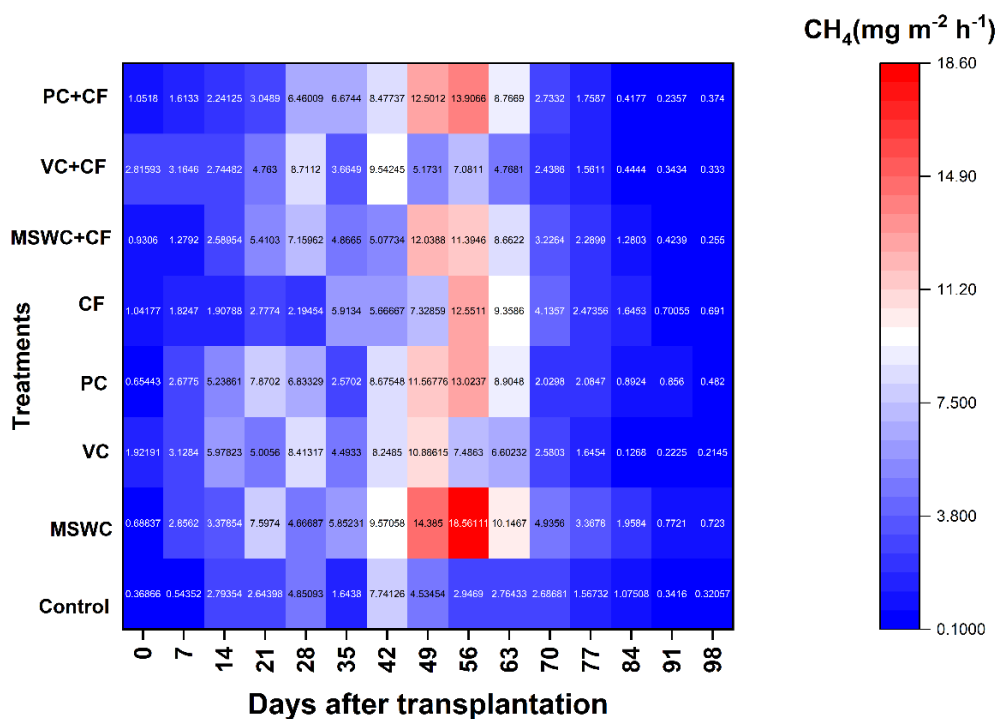
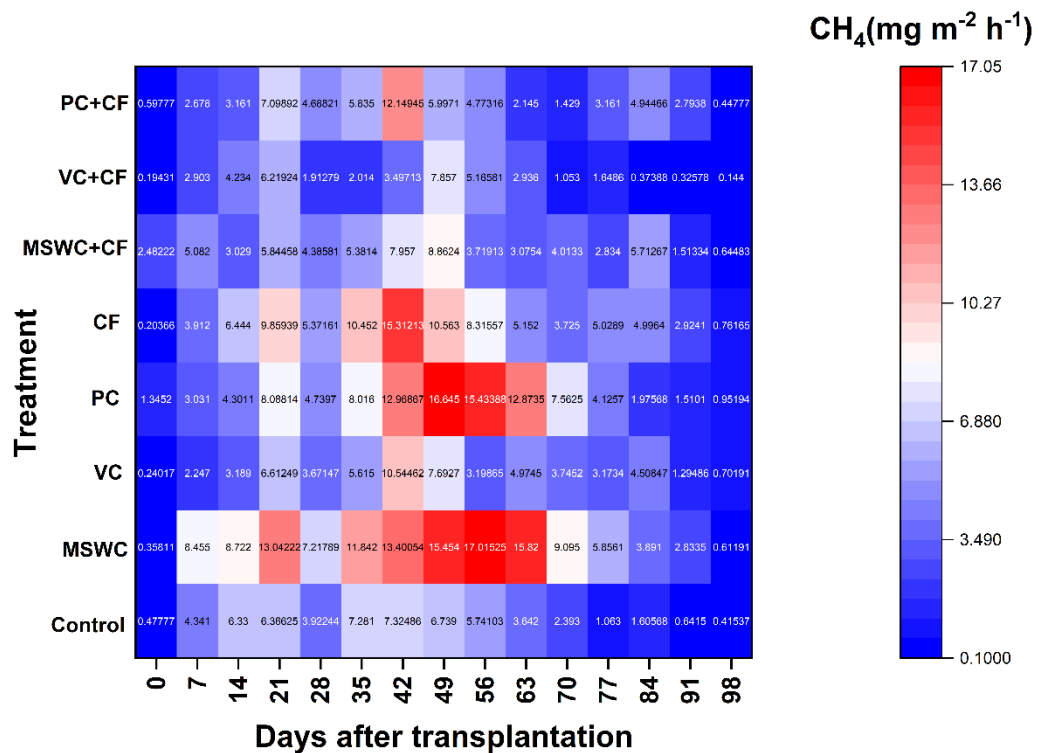


Fig.20: Variation of CH₄ flux from rice field between chemical fertilizer and integrated application of composts and chemical fertilizer during rice growing season of 2023 (mean±SD), where C=control; CF=chemical fertilizer; MSWC+CF=50% municipal solid waste compost+50% chemical fertilizer; VC+CF=50% vermicompost+50% chemical fertilizer; PC+CF=50% phumdi compost+50% chemical fertilizer.



a)



b)

Fig.21: Heatmap of CH₄ flux under different fertilizer treatments recorded during the rice growing season of (a) 2022 and (b) 2023.

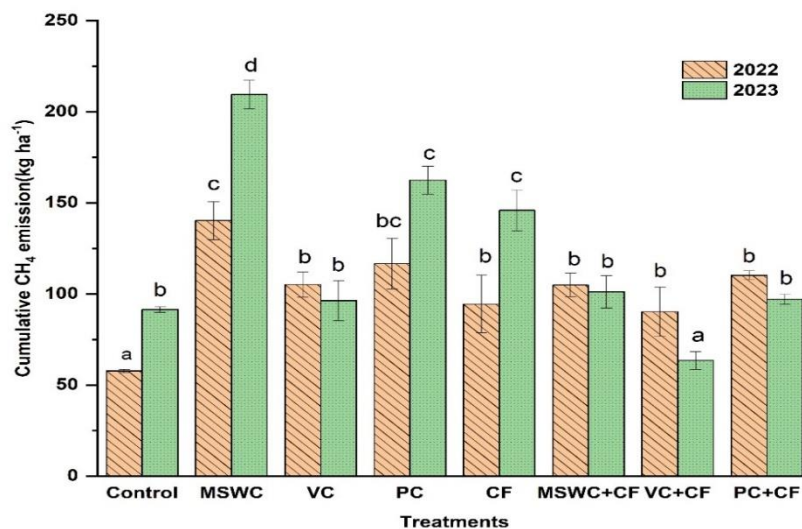


Fig.22: Cumulative CH₄ emission in the two years under different treatments in the rice field (mean $\pm$ SD). Bars with different letters at each year are significantly different in Tukey's HSD test ($p < 0.05$).

Table 25: Emission factors of CH₄ in different treatments in rice field in the two years.

Treatments	EF of CH ₄ (kg CH ₄ ha ⁻¹ d ⁻¹)		
	2022	2023	Average
Control	0.589 a	0.932 b	0.761
MSWC	1.431 c	2.138 d	1.785
VC	1.073 b	0.983 b	1.028
PC	1.190 bc	1.657 c	1.423
CF	0.963 b	1.488 c	1.226
MSWC+CF	1.070 b	1.033 b	1.051
VC+CF	0.921 b	0.648 a	0.784
PC+CF	1.124 b	0.990 b	1.057

In a column, the means followed by the same letter are not significantly different in Tukey's HSD test ($p < 0.05$). C, Control; MSWC, municipal solid waste compost; VC, Vermicompost; PC, *Phumdi* compost; CF, Chemical fertilizer.

N₂O flux and seasonal N₂O emission

The pattern of N₂O flux during the cropping season of two years is depicted in Fig.21. The flux of N₂O was event-specific, where the flux accelerated after N application, irrespective of treatments. The peak emission of N₂O was observed at 28DAT in both years, after that the flux subsided sharply until the next fertilizer application. This could be attributed to the increased rates of nitrification and denitrification of the N substrate supplied from the fertilizer. The result of peak N₂O emission following the fertilizer application is in good agreement with the study of Islam et al. (2020) and Ju et al. (2024). The emission of N₂O from agricultural soil is reported to be influenced by the fertilizer application timing (Bell et al. 2016). In both years, N₂O flux was found between the range of 0.02 to 0.60 mg m⁻² d⁻¹. The study observed no significant differences in N₂O flux between the two years ($p < 0.05$). The highest average flux of 0.22 mg m⁻² d⁻¹ was observed in CF treatment in both years. It was followed by MSWC treatment with 0.21 mg m⁻² d⁻¹ and 0.19 mg m⁻² d⁻¹ of the gas flux in the first year and second year, respectively. The higher N₂O flux in the MSWC treatment could be explained by the availability of easily mineralizable C in the treatment which provides substrate to accelerate microbial activities. The increased SOC content provides

energy source to the nitrifiers and denitrifiers for the process of nitrification and denitrification (Steinbach et al. 2006; Signor et al. 2013; Mehnaz et al. 2018). According to Stein et al. (2003), the availability of organic C to the microbes determined whether denitrifiers produced N_2 or N_2O . The lowest N_2O was recorded in control treatment with the value of $0.10 \text{ mg m}^{-2} \text{ d}^{-1}$ and $0.11 \text{ mg m}^{-2} \text{ d}^{-1}$ in the first and second year, respectively. However, among the fertilizer treatment plots, MSWC+CF emitted the lowest N_2O flux, with the value of $0.12 \text{ mg m}^{-2} \text{ d}^{-1}$ across the two cultivation periods.

In the present study, the seasonal cumulative N_2O emission was significantly different among the fertilizer treatments ($p < 0.05$, Fig.28). The average cumulative N_2O emission was in the order of control ($0.106 \pm 0.003 \text{ kg ha}^{-1}$) < MSWC+CF treatment ($0.122 \pm 0.002 \text{ kg ha}^{-1}$) < VC+CF treatment ($0.136 \pm 0.00 \text{ kg ha}^{-1}$) < PC treatment ($0.139 \pm 0.006 \text{ kg ha}^{-1}$) < PC+CF treatment ($0.151 \pm 0.001 \text{ kg ha}^{-1}$) < VC treatment ($0.159 \pm 0.01 \text{ kg ha}^{-1}$) < MSWC treatment ($0.200 \pm 0.008 \text{ kg ha}^{-1}$) < CF treatment ($0.223 \pm 0.001 \text{ kg ha}^{-1}$). The increased N_2O emission in the sole application of chemical fertilizer treatment could be due to the increased supply of inorganic N to the N_2O -producer bacteria at a faster rate compared to other treatments. CF treatment significantly increased average seasonal cumulative N_2O emission by a margin of 82.78%, 63.97%, 47.68%, and 110.37% compared to MSWC+CF, VC+CF, PC+CF and control treatments. Mohanty et al. (2017) and Bordoloi et al. (2020) also observed significantly higher N_2O emissions from chemical fertilizer application. The increased concentration of NH_4^+ -N and NO_3^- -N from chemical fertilizer stimulated nitrification in aerobic conditions and denitrification in anaerobic conditions, leading to higher N_2O production (Pandey et al. 2014; Mohanty et al. 2020). The N_2O emission from the chemical fertilizer plot was approximately 3 to 5 times higher than that from the organic fertilizer in the study by Malav et al. (2020). Chemical fertilizer act as the main source of N_2O emissions, with an approximate increase of 0.4% N_2O associated with the addition of 1 kg N ha^{-1} (Maaz, 2021). In contrast, the study by Toma et al. (2016) reported that organic amendments resulted in higher N_2O emissions relative to chemical fertilizer application. However, their result of average cumulative emissions ($0.17 - 0.62 \text{ kg N ha}^{-1} \text{ y}^{-1}$) was higher than our present study. Moreover, our study

recorded lower cumulative emission of N₂O from rice field relative to the findings of Das and Adhya (2014) and Triah et al. (2017).

In the present study, combining 50% of chemical fertilizer with 50% composts reduced N₂O emissions considerably. Similar to our findings, Bharati et al. (2020) reported lower N₂O emissions in 50% chemical fertilizer + 50% vermicompost treatment with mean emission of 0.29 – 1.10 $\mu\text{m}^{-2}\text{h}^{-1}$. The partial substitution of chemical fertilizer by organic source decreased the activities of ammonia oxidation and nitrite reduction during nitrification and denitrification, and strengthening N₂O reduction in denitrification, hence resulting in lower N₂O emissions (Kong et al.2024). In the present study, the sole application of composts recorded more N₂O emissions over their combined application of compost and chemical fertilizer treatments, except PC+CF treatment. No significant difference was found in N₂O emission between the two years of study (Table 26); however, the interaction between the treatments and years showed significant variation. The N₂O EF in treated plots ranged between 0.21 and 1.26 g N₂O-N (kg N)⁻¹ in the first year and between 0.11 and 1.19 g N₂O-N (kg N)⁻¹ in the second year (Table 27). The average EF of N₂O was in the order of MSWC+CF treatment (0.16±0.06 g N₂O-N (kg N)⁻¹) < VC+CF treatment (0.31±0.03 g N₂O-N (kg N)⁻¹) < PC treatment (0.35±0.10 g N₂O-N (kg N)⁻¹) < PC+CF treatment (0.47±0.05 g N₂O-N (kg N)⁻¹) < VC treatment (0.56±0.09 g N₂O-N (kg N)⁻¹) < MSWC treatment (0.99±0.13g N₂O-N (kg N)⁻¹) < CF treatment (1.23±0.04 g N₂O-N (kg N)⁻¹). The EF of N₂O in the present study site is relatively very low, this could be attributed to less N fertilizer applied, as the emission of N₂O from rice fields generally depend on the amount of N applied (Zou et al. 2005). The flooded conditions of rice soil inhibited or retarded nitrification which was responsible for 70% of the total N₂O production (Stevens et al. 1997; Akiyama et al. 2005; Kim et al. 2019). Hence, most of the N gas is released as N₂ in flooded rice fields, therefore emissions of N₂O are generally low in rice field (Hou et al. 2000).

Table 26: Three-way ANOVA table for N₂O flux.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	10.614	239	0.044	236.095	0.000
Intercept	17.884	1	17.884	95072.555	0.000
Treatment (T)	1.000	7	0.143	759.497	0.000
Days (D)	7.933	14	0.566	3012.173	0.000
Year (Y)	0.000061	1	0.000061	0.326	0.568
T*D	1.129	98	0.0115	61.255	0.000
T*Y	0.014	7	0.002	10.818	0.000
D*Y	0.132	14	0.009	50.215	0.000
T*D*Y	0.405	98	0.004	22.018	0.000
Error	0.090	480	0.0001		
Total	28.588	720			

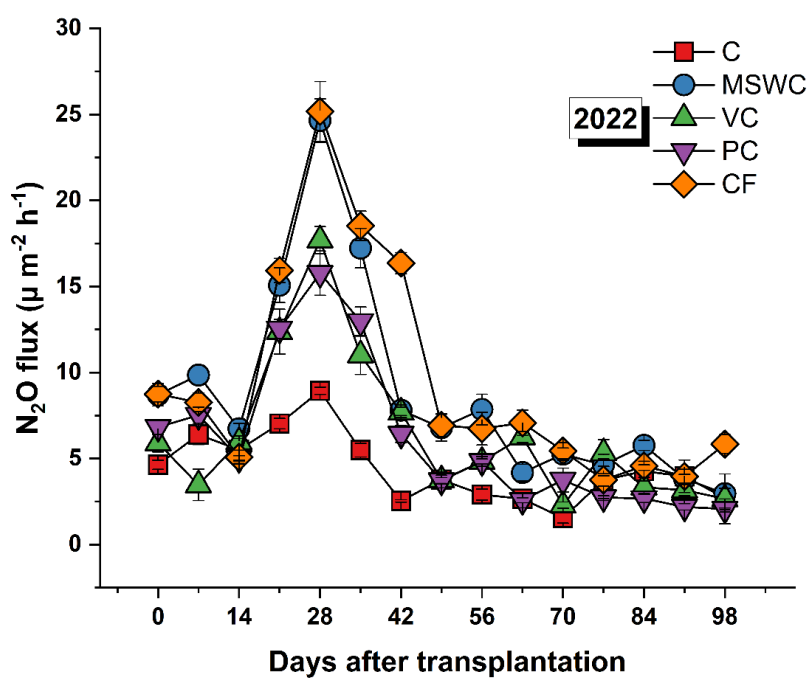


Fig.23: Variation of N₂O flux from rice field between chemical fertilizer and sole application of composts during rice growing season of 2022 (mean±SD).

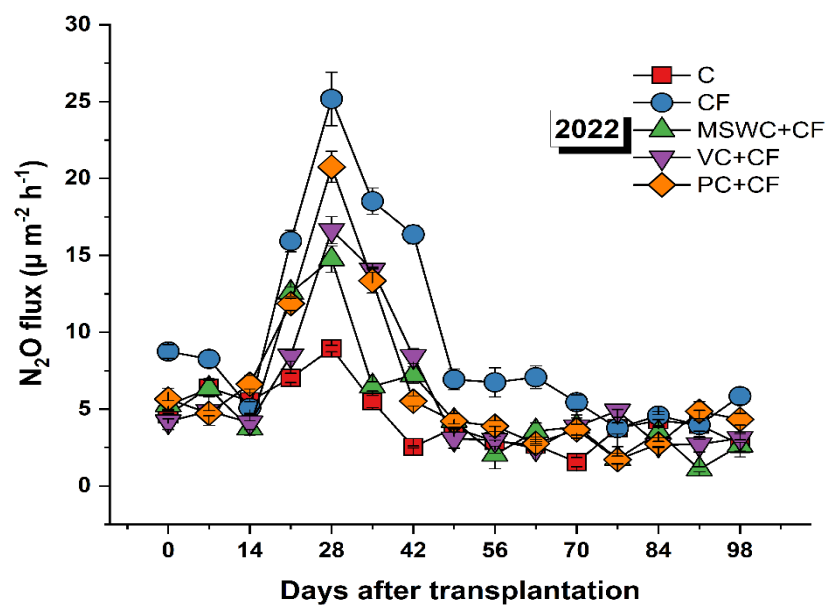


Fig.24: Variation of N_2O flux from rice field between chemical fertilizer and integrated application of composts and chemical fertilizer during rice growing season of 2022 (mean $\pm$ SD).

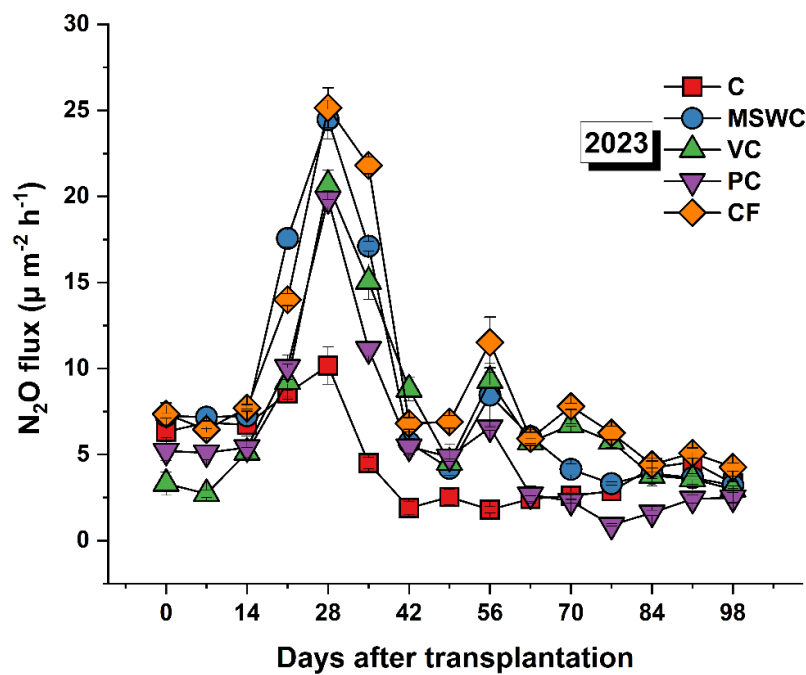


Fig.25: Variation of N_2O flux from rice field between chemical fertilizer and sole application of composts during rice growing season of 2023 (mean $\pm$ SD).

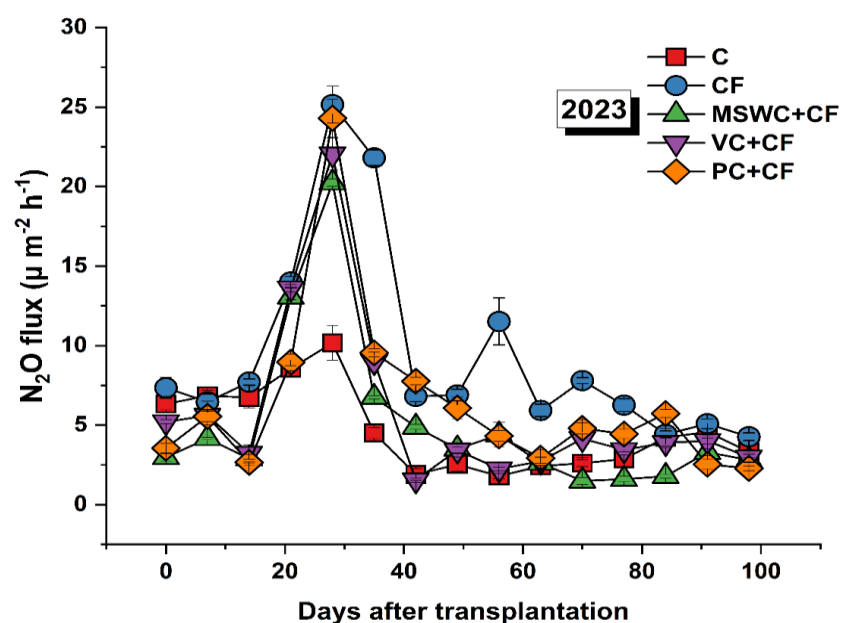
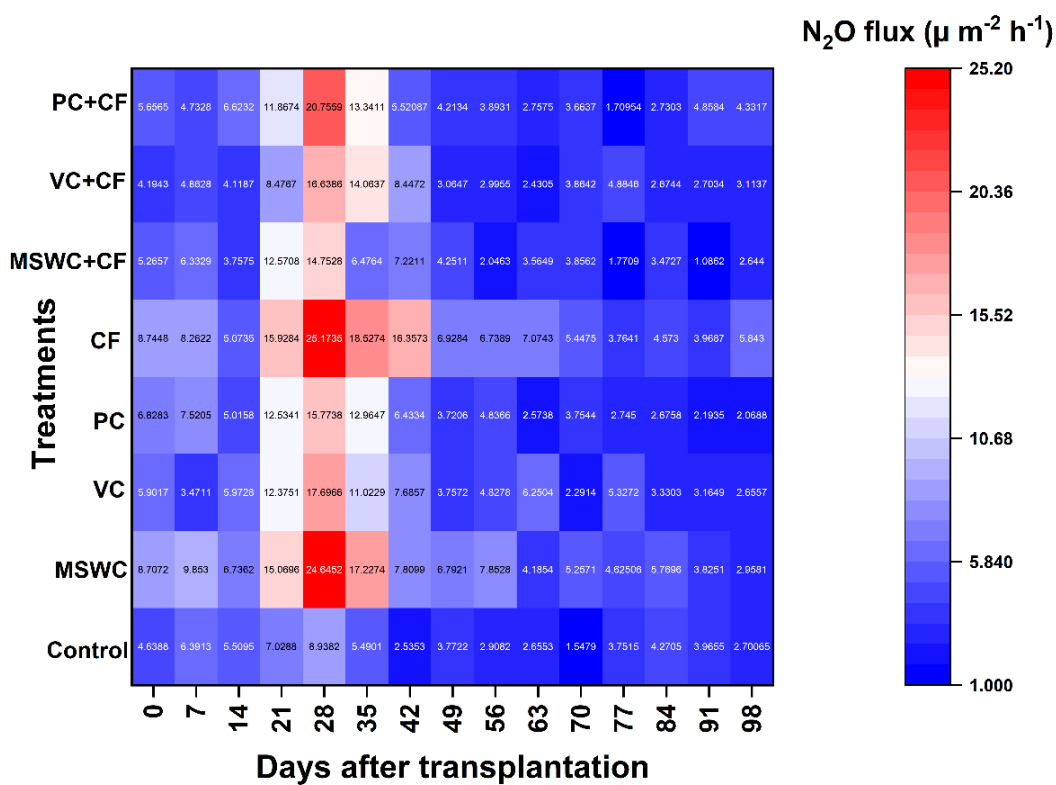
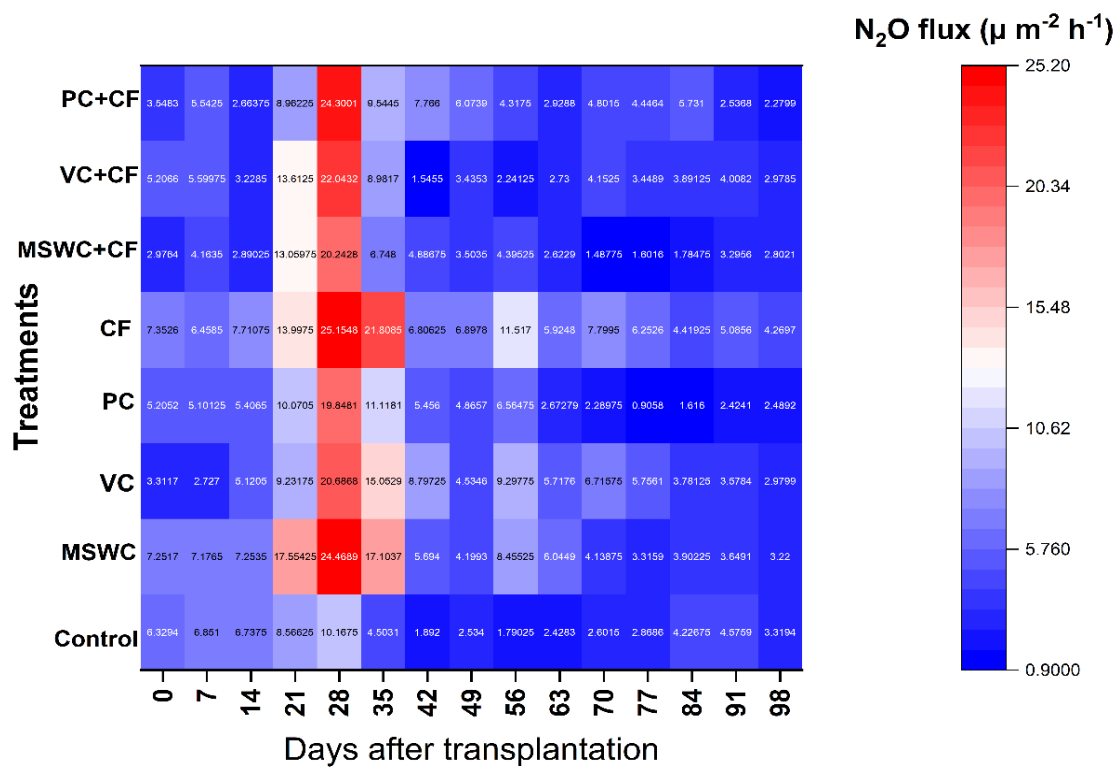


Fig.26: Variation of N₂O flux from rice field between chemical fertilizer and integrated application of composts and chemical fertilizer during rice growing season of 2023 (mean $\pm$ SD).



a)



b)

Fig.27: Heatmap of N₂O flux under different fertilizer treatments recorded during the rice growing season of (a) 2022 and (b) 2023.

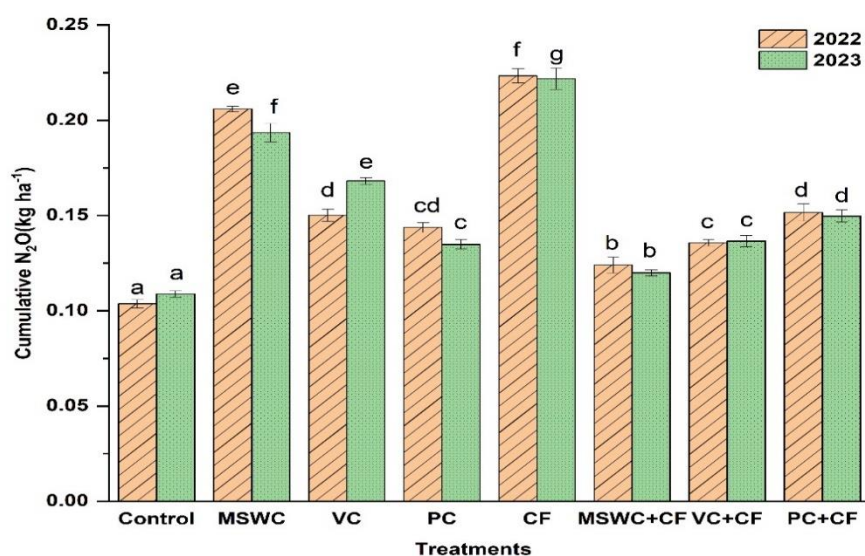


Fig.28: Cumulative N₂O emission in the two years under different treatments in the rice field (mean ± SD). Bars with different letters at each year are significantly different in Tukey's HSD test (p < 0.05).

Table 27: Emission factors of N₂O in different treatments in rice field in the two years.

Treatments	EF of N ₂ O (g N ₂ O-N (kg N) ⁻¹)		
	2022	2023	Average
Control	–	–	–
MSWC	1.084 d	0.898 e	0.991
VC	0.492 c	0.630 d	0.561
PC	0.425 bc	0.275 b	0.350
CF	1.268 e	1.198 f	1.233
MSWC+CF	0.215 a	0.117 a	0.166
VC+CF	0.339 ab	0.294 b	0.317
PC+CF	0.508 c	0.433 c	0.470

In a column, the means followed by the same letter are not significantly different in Tukey's HSD test ($p < 0.05$). C, Control; MSWC, municipal solid waste compost; VC, Vermicompost; PC, *Phumdi* compost; CF, Chemical fertilizer

Carbon dioxide flux and seasonal carbon dioxide emission

The CO₂ fluxes for all the treatments during the two study periods are shown in figures 29 and 30. There was a distinct variation in CO₂ flux during the cropping stages ($p < 0.05$, Table 28). The gas flux was relatively low at the initial cropping stage, and then gradually increased with the growth and development of the plant. CO₂ flux reached a maximum during the flowering stage in all treatments and then decreased gradually in both years. The pattern of CO₂ flux during the second year aligned with the first year. The higher flux during the flowering stage could be attributed to higher rate of plant and soil microbial respiration. During this stage, rice plant increases its metabolic activity, which increases the plant growth and root biomass and hence enhances the emission of CO₂ through their leaves and roots' respiration. CO₂ from rice fields is generated during anaerobic respiration in soil and aerobic respiration in the rhizosphere (Kirk et al. 2019). At the same time, the increased root biomass excretes more organic substrate as root exudate, facilitating the soil biological activities and stimulating the CO₂ emission. The hypothesis is supported by the study of Cheng-Fang et al. (2012). Similar peak emission during the reproductive stage of rice plant was also reported in the study of Malav et al. (2019) and Haque *et al* (2021). During the active growing period, the rice field is characterized by wet and warm

conditions. It influenced the CO₂ emission as higher temperature enhanced the rate of mineralization of organic compounds (Sosulski et al. 2023). The positive correlation between the CO₂ flux and air temperature in the present study also showed that high temperature enhanced CO₂ emission from rice field soil. As the crop matured, there was a reduction in the secretion of root exudates, which decreased or inhibited the microbial activities, and consequently reduced the gas emission. The gradual decrease in CO₂ emission at the maturity stage can also be due to declining photosynthesis rate. The result is in good agreement with the findings of Saito et al. (2005). Haque et al. (2021) also reported similar trend of CO₂ with maximum recorded at 56DAT, and then declined gradually.

During the first year, the CO₂ emissions were ranged between 10.99 to 28.55 kg ha⁻¹ d⁻¹ in control, 15.04 to 46.06 kg ha⁻¹ d⁻¹ in MSWC treatment, 12.50 to 51.25 kg ha⁻¹ d⁻¹ in VC treatment, 14.59 to 51.25 kg ha⁻¹ d⁻¹ in the PC, 13.26 to 35.89 kg ha⁻¹ d⁻¹ in the CF, 11.69 to 37.90 kg ha⁻¹ d⁻¹ in MSWC+CF treatment, 12.16 to 36.18 kg ha⁻¹ d⁻¹ in VC+CF treatment and 13.48 to 39.17 kg ha⁻¹ d⁻¹ in PC+CF treatment. The PC treatment recorded maximum CO₂ flux with 53.48 kg ha⁻¹ d⁻¹ on 42DAT while, MSWC+CF treatment recorded the least with 11.69 kg ha⁻¹ d⁻¹ on 98DAT among the fertilizer treatment plots. The MSWC, VC and PC treatments significantly increased the CO₂ flux from the rice field. The sole application of composts emitted 9.01 to 18.39% higher CO₂ compared to CF treatment. The seasonal cumulative CO₂ emission in the first year ranged between 1733.76 (control) and 2923.22 kg ha⁻¹ (PC) in all the treatments (Fig.31). In the second year, the maximum flux was recorded in MSWC treatment (66.05 kg ha⁻¹ d⁻¹) on 49DAT. Compared to the CF treatment, only MSWC treatment and PC treatment enhanced average CO₂ flux by 17.95% and 7.19% across the various growing stages. Meanwhile, the seasonal cumulative CO₂ emissions were also maximum in MSWC treatment (2003.56 kg ha⁻¹ d⁻¹) and lowest in control (3183.26 kg ha⁻¹ d⁻¹) in the second year (Fig.31).

Over the two-year average data, the mean cumulative CO₂ emissions was in the ranged of 1868.66 in the control to 3193.10 kg ha⁻¹ in the MSWC treatment. MSWC (3193 kg ha⁻¹), VC (2744.68 kg ha⁻¹) and PC (3053.24 kg ha⁻¹) treatments emitted more CO₂ compared to CF treatment (2690.85 kg ha⁻¹). The availability of more C substrate in

the sole application of compost relative to other treatments can explain the result of higher CO₂ emission. This was evidence by the significant positive correlation between CO₂ emission and SOC ($r = 0.88$, $p < 0.01$) found in the study (Fig.38). Such strong positive correlation was also observed in the study of Dhaldi and Brar (2016). CO₂ is produced by the microbial decomposition of organic materials in the soil (Hamilton and Sippel, 1995). Availability of organic carbon supplies nutrients to microorganisms which enhances CO₂ emission (Pathak et al. 2003). The seasonal cumulative CO₂ emission across the two years was 2.00 – 18.66% higher in the sole application of composts, with the highest in the MSWC treatment as compared to the CF treatment. This could be because, among the composts used in the present study, MSW compost exhibited the lowest C:N ratio. A similar result was reported by Hossain et al. (2017) where the organic fertilizer with the lowest C:N ratio significantly increased the emission of CO₂. The low C:N ratio of compost accelerates decomposition rate (Bernal et al. 1998), and consequently increased the CO₂ from the system. The amount of C contained in the respective organic fertilizer significantly influenced the CO₂ emission from soil (Ray et al. 2020). Bhatia et al. (2005) reported higher CO₂ emission by 32% in the 100% treatment of N through organic source compared to chemical fertilizer treatment. Moreover, addition of compost as the main N source provides more organic C, leading to higher soil respiration (Scott et al. 2000). Sosulski et al. (2023) also highlighted the importance of heterotrophic soil respiration in CO₂ emission due to the decomposition of organic compounds. However, the combined application of compost and chemical fertilizers emitted lesser CO₂ ($p < 0.05$), with VC+CF treatment recorded the least among the fertilizer treatments with a value of 2372.52 kg ha⁻¹. There was 5.03% to 13.41% reduction of CO₂ emission owing to the application of integrated chemical and organic fertilizer. The finding can suggest that adopting integrated nutrient management can reduced CO₂ emission from rice field. Further, it was identified that CO₂ flux in the present study was significantly influenced by treatments, stages of crop, years, and their interactions ($p < 0.05$).

Table 28: Three-way ANOVA table for CO₂ flux.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	90057.419	239	376.809	647.884	0.000
Intercept	516546.899	1	516546.899	888147.950	0.000
Treatment (T)	11027.999	7	1575.428	2708.783	0.000
Days (D)	66857.604	14	4775.543	8211.034	0.000
Year (Y)	2110.531	1	2110.531	3628.835	0.000
T*D	5678.009	98	57.939	99.620	0.000
T*Y	549.204	7	77.172	132.689	0.000
D*Y	1560.030	14	111.431	191.593	0.000
T*D*Y	2283.043	98	23.296	40.056	0.000
Error	279.168	480	0.582		
Total	606883.486	720			

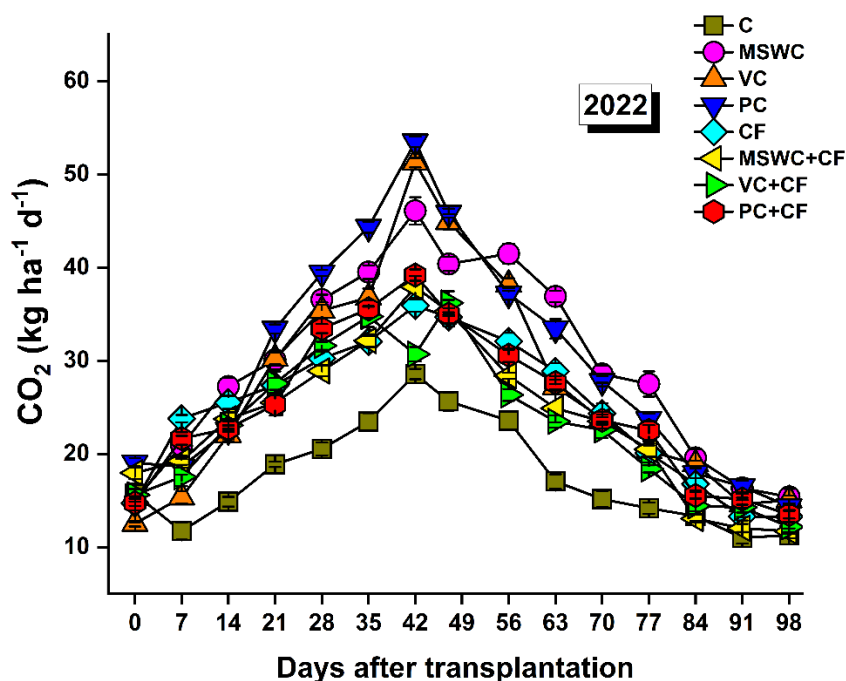


Fig.29: Seasonal variation of CO₂ flux from rice field during rice growing season of 2022 under different treatments (mean±SD).

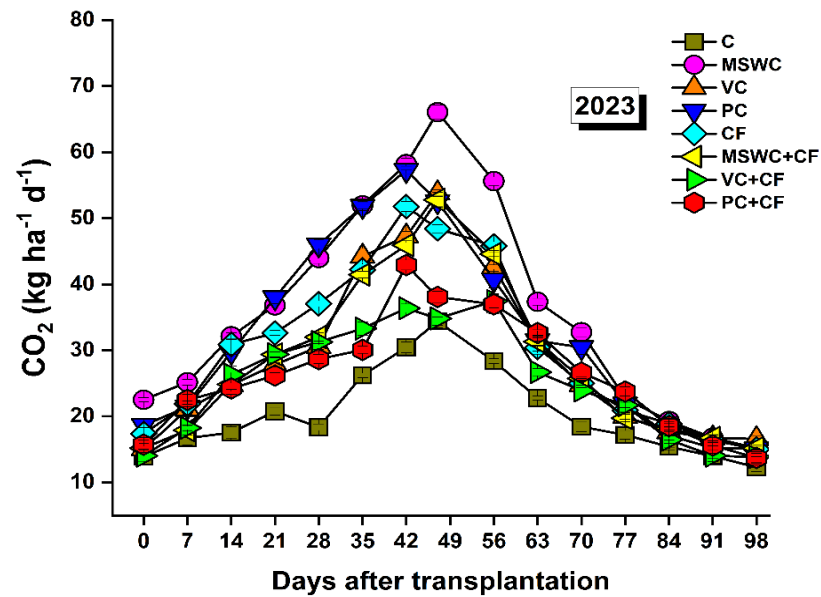


Fig.30: Seasonal variation of CO₂ flux from rice field during rice growing season of 2023 under different treatments (mean±SD).

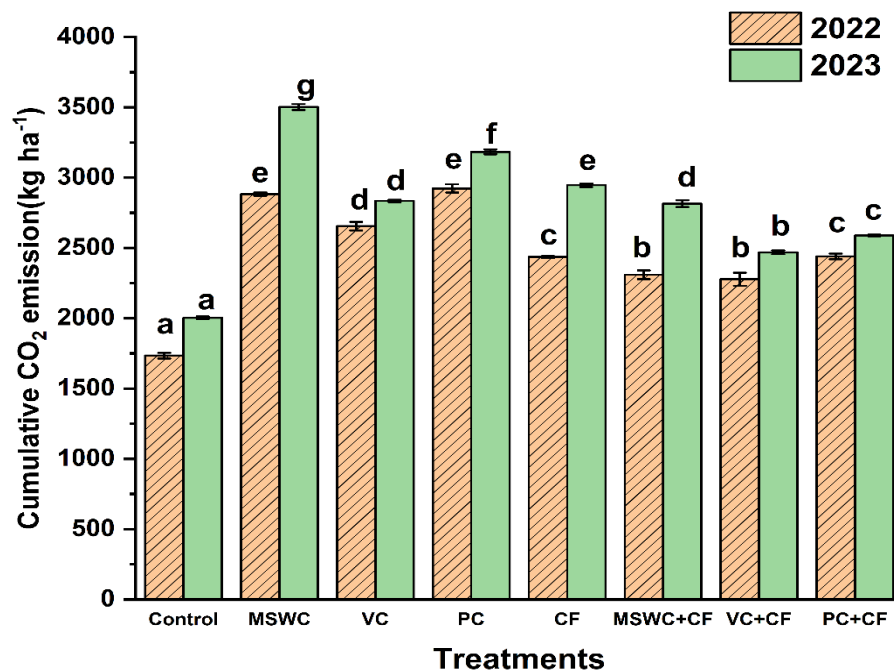


Fig.31: Cumulative CO₂ emission in the two years under different treatments in the rice field (mean ± SD). Bars with different letters at each year are significantly different in Tukey's HSD test ($p < 0.05$).

4.10. Global warming potential (GWP), greenhouse gas intensity (GHGI), and carbon equivalent ratio (CER)

GWP under different treatments varied between 3320.99 and 6727.24 kg ha⁻¹ in the first year, and 4500.77 and 9212.09 kg ha⁻¹ in the second year (Table 29). Application of different fertilizer treatments significantly influenced the GWP in the present study ($p < 0.05$). In both years, MSWC treatment recorded maximum GWP with an average of 32% more compared to the sole application of chemical fertilizer. It was followed by PC treatment with an average GWP of 6857.66 kg ha⁻¹, which significantly enhanced the GWP by 14.38% and 28.10% as compared to CF treatment and PC+CF treatment ($p < 0.05$). The amendment of organic fertilizer alone contributes to an increase in GWP through the release of higher CH₄ and CO₂ emissions. The decomposition and mineralization of C and N from the added organic material may result in higher GHG emissions in the sole application of municipal solid waste compost and *phumdi* compost. The VC+CF treatment recorded the lowest GWP among the fertilized treatments with 4750.35 kg ha⁻¹ and 4219.15 kg ha⁻¹ in the first and second year, respectively ($p < 0.05$). The substrate in VC+CF has the capability to reduce the N₂O emission by slow-release pattern of N and reduce CH₄ emission, probably by reducing the process of methanogenesis. In the first year, only the VC+CF treatment recorded a lower GWP compared to the CF treatment (5045±428.88 kg ha⁻¹). The GWP were significantly increased in the second year in all the treatments except in the VC, VC+CF and PC+CF treatments.

The average GWP across the two years was in the order of control (3910.88±834.22 kg ha⁻¹) < VC+CF (4484.75±375.61 kg ha⁻¹) < PC+CF (5353.04±146.31 kg ha⁻¹) < MSWC+CF (5377.08±286.75 kg ha⁻¹) < VC (5507.30±38.10 kg ha⁻¹) < CF (5995.23±1343.33 kg ha⁻¹) < PC (6857.66±1056.50 kg ha⁻¹) < MSWC (7969.66±1757.05 kg ha⁻¹). The integrated treatments MSWC+CF, VC+CF, and PC+CF reduced GWP by an average of 30.07% over CF treatments. Among the sole applications of composts, the GWP of VC treatment was reduced by 8.85% compared to CF treatment, while the MSWC and PC treatments enhanced GWP by 32.93% and 14.38%, respectively. The quality and nutrient composition of the composts affect the magnitude of GHG emissions from the rice fields. Overall, more than 50% of GWP

was contributed by CH₄ emission in the rice field of the present study, followed by CO₂ and N₂O (Fig.32). As rice is grown mostly in flooded conditions, the anoxic condition of the soil reduces the redox potential level and hence produces high levels of CH₄ emission through the process of methanogenesis (Liu et al. 2013; Thangarajan et al. 2013). In the current study since the water management system was depended on rain, there was time where less or no rainfall was received. It converted the anaerobic condition of the rice field to aerobic and trigger CO₂ emission into the atmosphere. Yi-hu et al. (2014) also reported that CH₄ and CO₂ emissions were the primary GHGs responsible for the higher GWP from rice fields growing under organic amendments. The GWP of N₂O is 273, which is comparatively higher than CH₄. But the magnitude of N₂O emission in the present study is quite low, resulting in less share of the overall GWP. Similar finding was reported by Islam *et al* (2020).

There was a significant variation in GHGI of rice field due to different treatments ($p < 0.05$). GHGI is a measure to identify the efficiency of crop production with relation to GWP values. The average GHGI of the two-study period was within the ranged of 847.10 to 1690.97 kg CO₂ eq.t⁻¹ (Table 30). It was found that MSWC treatment increased the GHGI considerably over other treatments. The GHGI in VC+CF treatment (982.32 ± 50.82 kg CO₂ eq.t⁻¹) and PC+CF (711.89 ± 133.02 kg CO₂ eq.t⁻¹) treatment were the lowest in the first year and second year, respectively. But across the two-year average data, VC+CF treatment recorded lower GHGI. Compared to CF treatment (1248.69 ± 26.86 kg CO₂ eq.t⁻¹), the combined application of composts and chemical fertilizer obtained lower GHGI, with VC+CF recorded the lowest. The MSWC+CF, VC+CF, and PC+CF treatments reduced GHGI by 17.78 to 47.40% relative to the sole application of chemical fertilizer. The substantial reduction of CH₄ and CO₂ emissions in the integrated fertilizer treatments with greater grain yield resulted in lower GHGI. This implies that substitution of 50% chemical fertilizer with composts could tackle the GHG emissions from rice field accompanied by higher grain yield. In all the treatments, the GHGI in the second year was significantly lower than the first year, except control, MSWC and CF treatments. Das and Adhya (2014) reported lower GHGI due to the application of compost as compare to the application of chemical fertilizer.

On average, CEE was minimum in control ($1066.60 \pm 227.51 \text{ kg C ha}^{-1}$) and maximum in MSWC treatment ($2173.54 \pm 479.19 \text{ kg C ha}^{-1}$). Among the three integrated treatments, VC+CF treatment had the lowest CEE (Table 31). It indicates that application of vermicompost combined with chemical fertilizer is one of the most mitigative strategies in reducing GHG emissions from the present study site. The CER values under different treatments ranged from 0.87 to 1.79 over the two years average. The highest CER was recorded in VC+CF treatment (1.79 ± 0.42) followed by PC+CF treatment (1.77 ± 0.46) and MSWC+CF (1.39 ± 0.15) while, the least was found in MSWC treatment (0.87 ± 0.06). The minimum CER in MSWC treatment could imply that CO_2 equivalent emission is high and C fixed in the grain yield is low. The highest CER in VC+CF treatment indicates that the combined application of vermicompost with chemical fertilizer can fix carbon in the grain more efficiently. Although MSWC+CF, VC+CF, and PC+CF treatments recorded higher CER compared to CF treatment, the variation was not significant. At the same time, the study found out that the application of compost as the sole nutrient source in rice cultivation lower the CER compared to CF treatment, the result is in line with the finding of Bhatia et al. (2005).

Table 29: Global warming potential in different treatments in rice field in the two years.

Treatments	GWP ($\text{kg CO}_2 \text{ eq. ha}^{-1}$)		
	2022	2023	Average
Control	$3320.99 \pm 20.65 \text{ a}$	$4500.77 \pm 41.79 \text{ a}$	3910.88 ± 834.22
MSWC	$6727.24 \pm 268.23 \text{ e}$	$9212.09 \pm 223.87 \text{ e}$	7969.66 ± 1757.05
VC	$5534.24 \pm 170.26 \text{ cd}$	$5480.36 \pm 296.34 \text{ b}$	5507.30 ± 38.10
PC	$6110.60 \pm 349.10 \text{ d}$	$7604.72 \pm 191.02 \text{ d}$	6857.66 ± 1056.50
CF	$5045.34 \pm 428.88 \text{ bc}$	$6945.11 \pm 307.21 \text{ c}$	5995.23 ± 1343.33
MSWC+CF	$5174.31 \pm 168.00 \text{ bc}$	$5579.85 \pm 228.78 \text{ b}$	5377.08 ± 286.75
VC+CF	$4750.35 \pm 325.84 \text{ b}$	$4219.15 \pm 130.51 \text{ a}$	4484.75 ± 375.61
PC+CF	$5456.50 \pm 83.99 \text{ bcd}$	$5249.58 \pm 68.44 \text{ b}$	5353.04 ± 146.31

In a column, the means followed by the same letter are not significantly different in Tukey's HSD test ($p < 0.05$). C, Control; MSWC, municipal solid waste compost; VC, Vermicompost; PC, *Phumdi* compost; CF, Chemical fertilizer. Values are mean $\pm$ standard deviation.

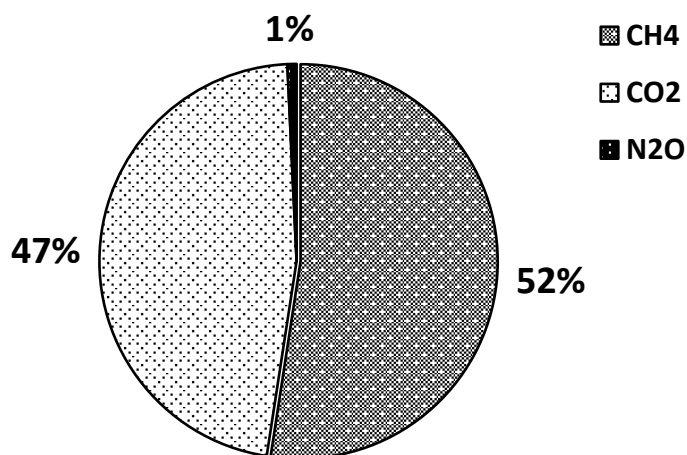


Fig.32: Contribution of CH₄, CO₂, and N₂O in GWP.

Table 30: Greenhouse gas intensity in different treatments in rice field in the two years.

Treatments	GHGI (kg CO ₂ eq. t ⁻¹)		
	2022	2023	Average
Control	1067.46±194.71 a	1229.94±166.57 bc	1148.70±114.89
MSWC	1602.29±131.02 d	1779.64±175.67 d	1690.96±125.40
VC	1453.00±46.19 bcd	1103.55±98.97 b	1278.28±247.09
PC	1538.29±78.26 cd	1523.76±63.52 cd	1531.02±10.27
CF	1229.70±201.02 abc	1267.69±144.42 bc	1248.69±26.86
MSWC+CF	1143.56±82.30 ab	976.69±41.14 ab	1060.12±118.00
VC+CF	982.32±50.82 a	711.89±133.02 a	847.10±191.22
PC+CF	1015.64±10.48 a	705.54±97.03 a	860.59±219.28

In a column, the means followed by the same letter are not significantly different in Tukey's HSD test ($p < 0.05$).

Table 31: Total carbon fixed in grain, carbon equivalent emission and carbon efficiency ratio in the rice field under different treatments.

Treatments	Total C fixed in		
	grain (t ha ⁻¹)	CEE	CER
Control	1.37±0.14	1066.60±227.51	1.30±0.13
MSWC	1.88±0.28	2173.54±479.19	0.87±0.06
VC	1.75±0.33	1501.99±10.39	1.17±0.22
PC	1.79±0.28	1870.27±288.13	0.95±0.00
CF	1.934±0.39	1635.06±366.36	1.18±0.02
MSWC+CF	2.05±0.33	1466.47±78.20	1.39±0.15
VC+CF	2.17±0.33	1223.11±102.44	1.79±0.42
PC+CF	2.58±0.61	1459.92±39.90	1.77±0.46

4.11. Soil properties under different treatments

SOC, soil C stock and soil C sequestration

In the study, it was found that the interaction between different treatments, four stages of crops, and two years, greatly affected the organic carbon of the paddy rice soil ($p < 0.05$, Table 34). SOC at active tillering, panicle initiation, flowering, and post-harvest stages is presented in Fig.33. The SOC values ranged from 0.59% to 1.08% during the first year (Table 32). SOC did not follow a specific pattern; however, the SOC values decreased at post-harvest stage in all the treatments except CF and MSWC+CF treatments. In the first year, the maximum SOC (1.08±0.09%) was found at active tillering stage of MSWC treatment, while the minimum (0.59±0.06%) at post-harvest stage in control treatment (Table 32). SOC of the rice field was ranged between 0.75% (control) to 1.08% (MSWC) during the active tillering stage, 0.65% (control) to 0.79% (MSWC) during panicle initiation stage, 0.60% (control and MSWC+CF) to 0.78% (PC+CF) during flowering, and 0.61% (control) to 0.75% (VC+CF) during post harvesting stage. Among the treatments, MSWC obtained the maximum SOC value (0.80±0.19% on average) and control exhibited the minimum value (0.65±0.08% on average). In the second year, SOC gradually increased from active tillering to the

panicle initiation stage and then declined in the later stages in most of the treatments. The values of SOC ranged between 0.63 to 1.57% during the whole cropping cycle of the second year (Table 33). PC treatment recorded maximum SOC, which is at par with MSWC treatment. SOC was found to be significantly increased in all the treatments in the second year (Table 34).

On average, SOC in active tillering and panicle initiation stages were significantly higher than flowering and post-harvest stages ($p < 0.05$). One reason for higher SOC content in the early stages of rice could be the release of root exudates at a higher rate during the crop growth stages. The availability of organic compounds as root exudates, sloughed-off root cap cells, is reported to be responsible for higher SOC content during active tillering and panicle initiation stage (Ghosh et al. 2012). This was supported by the study of Wang and Adachi (2000), where rice grown in flooded condition received more C from the root exudates. At the same time, the addition of fertilizer during the early stage might boost the SOC content. During the active tillering stage and panicle initiation stage, the average SOC ranged between 0.69% to 1.27%, and 0.64% to 1.17%, respectively. The SOC content was between 0.69% to 1.15% during the flowering stage, while at the post-harvest stage, the SOC varied from 0.76% to 0.97% in all the treatments (Fig.34). MSWC+CF, PC+CF, PC, and MSWC treatments had significantly higher average SOC values compared to CF treatment, with maximum in MSWC treatment. The findings of Tang et al. (2018) also agreed with our results that application of organic fertilizer improved the SOC content. There was an increase of SOC by 145% due to the application of compost (Kranz et al. 2020). Walia et al. (2010) reported that addition of integrated nutrient management system increased SOC content from 0.39% to 0.54%. Ma et al. (2011) reported that the incorporation of organic fertilizer substantially enhanced the SOC content owing to the increase C input. Whereas, control had the minimum SOC content, but among the fertilizer application treatments, VC+CF treatment recorded lowest SOC. It was also found that the correlation analysis of the present study observed a strong positive correlation between SOC and total N ($r = 0.72$, $p < 0.05$), and available K ($r = 0.83$, $p < 0.01$) (Fig.38). It indicates that nutrient availability of soil is influenced by SOC content of the soil. Such positive correlation was also observed in the study of Troza et al. (2021). Furthermore, SOC content of soil was significantly correlated with air temperature ($r = 0.96$, $p < 0.01$) and precipitation ($r = 0.71$, $p < 0.05$) (Table 35).

The average C-stock at the end of the harvesting was higher in CF treatment and MSWC+CF treatment, with a value of 16.48 Mg C ha⁻¹ and 16.47 Mg C ha⁻¹, respectively. It was followed by MSWC treatment (16.24 Mg C ha⁻¹), PC+CF treatment (15.86 Mg C ha⁻¹), PC treatment (15.43 Mg C ha⁻¹), VC+CF treatment (15.25 Mg C ha⁻¹) and VC (15.13 Mg C ha⁻¹). And, the minimum average C-stock was recorded in control (12.93 Mg C ha⁻¹). The C-stock was significantly higher in the fertilized plots compared to the control. When there is limited N supply, the microbes utilized the carbon which in turn, would decline the SOC accumulation. The addition of fertilizer, especially N, supplies essential nutrients to the microorganisms and reduces N mining by the microbes (Li et al. 2017). The average C-stock was significantly affected by the interaction between different treatments and years (Table 36). Compared to other agricultural soils, paddy rice field soil recorded higher SOC stock as flooding of rice field creates anoxic conditions and slows down the decomposition rate of the added fertilizers. And hence, accumulate the C into the soil (Wang et al. 2015 and Li et al. 2021). Among the three types of compost, the application of MSW compost alone or integrated with chemical fertilizer stimulates more soil C-stock relative to the *phumdi* compost and vermicompost. Liu et al. (2015) asserted that organic fertilizer with a narrow C:N ratio degrades rapidly in the soil, which in turn improves SOC accumulation. In this study, a positive impact was observed on soil C stock. Soil carbon stock significantly increased over time, irrespective of treatments. The highest C-stock at the post-harvesting stage in CF treatment was attributed to the increase in SOC content in the second year. Moran et al. (2005) observed that the application of chemical N fertilizer accelerates the residue decomposition by promoting the activities of microbes and positively impacts the formation of stable organic matter. Moreover, the SOC content in CF treatment was retained till the post-harvesting stage, which resulted in higher accumulation of C. Application of chemical fertilizer absorbed C by improving the plant biomass (Zhu et al. 2018; Ghosh and Devi 2019). However, when averaged across the whole cropping season, the trend of soil C-stock was similar to the results of SOC content, where MSWC, PC, MSWC+CF, and PC+CF treatments resulted in higher C-stock compared to the CF treatment. On the other hand, the C-sequestration rate was greatest in MSWC treatment. Compared to CF treatment, only MSWC treatment resulted in 4.18% higher C-sequestration rate. The rate of C-sequestration found in the study was in the order

of control (5.54 t ha⁻¹) < VC (6.53 t ha⁻¹) < VC+CF (6.90 t ha⁻¹) < PC (8.07 t ha⁻¹) < PC+CF (8.46 t ha⁻¹) < MSWC+CF (10.63 t ha⁻¹) < CF (10.65 t ha⁻¹) < MSWC (11.10 t ha⁻¹). Organic fertilizer amendment helps in retaining carbon in rice soil (Bhattacharyya et al. 2015).

Table 32: Variation in SOC at four different stages of rice growing under different treatments of 2022.

Treatment	2022			
	AT	PI	F	PH
Control	0.75±0.06 ab	0.65±0.02 a	0.61±0.10 a	0.59±0.06 a
MSWC	1.08±0.09 c	0.79±0.02 a	0.70±0.08 ab	0.63±0.02 a
VC	0.67±0.01 a	0.78±0.04 a	0.71±0.01 ab	0.70±0.05 a
PC	0.72±0.04 ab	0.74±0.04 a	0.74±0.20 ab	0.67±0.02 a
CF	0.75±0.02 ab	0.67±0.08 a	0.64±0.02 ab	0.65±0.04 a
MSWC+CF	0.86±0.04 b	0.74±0.04 a	0.60±0.04 a	0.65±0.04 a
VC+CF	0.72±0.04 ab	0.71±0.06 a	0.75±0.06 ab	0.69±0.03 a
PC+CF	0.68±0.04 a	0.75±0.05 a	0.78±0.03 b	0.68±0.07 a

Table 33: Variation in SOC at four different stages of rice growing under different treatments of 2023.

Treatment	2023			
	AT	PI	F	PH
Control	0.63±0.10 a	0.62±0.03 a	0.78±0.06 a	0.92±0.05 a
MSWC	1.45±0.11 c	1.55±0.09 b	1.32±0.15 bc	1.28±0.13 ab
VC	1.47±0.08 c	1.51±0.09 b	1.12±0.11 ab	1.08±0.12 ab
PC	1.45±0.06 c	1.45±0.12 b	1.57±0.11 c	1.14±0.22 ab
CF	1.35±0.05 bc	1.50±0.08 b	1.31±0.20 bc	1.28±0.11 c
MSWC+CF	1.42±0.11 c	1.44±0.10 b	1.21±0.07 bc	1.28±0.05 ab
VC+CF	1.13±0.14 b	1.35±0.02 b	1.34±0.13 bc	1.10±0.10 ab
PC+CF	1.37±0.08 bc	1.45±0.10 b	1.37±0.16 bc	1.18±0.12 ab

In a column, the means followed by the same letter in each year are not significantly different in Tukey's HSD test (p<0.05). AT= active tillering; PI = panicle initiation; F = flowering; PH = post-harvesting

Table 34: Three-way ANOVA table for SOC.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	20.798	63	0.330	52.996	0.000
Intercept	189.543	1	189.543	30427.599	0.000
Treatment (T)	2.603	7	0.372	59.688	0.000
Stage (S)	0.511	3	0.170	27.327	0.000
Year (Y)	14.448	1	14.448	2319.286	0.000
T*S	0.809	21	0.039	6.188	0.000
T*Y	1.606	7	0.229	36.819	0.000
S*Y	0.168	3	0.056	8.989	0.000
T*S*Y	0.654	21	0.031	5.001	0.000
Error	0.797	128	0.006		
Total	211.139	192			

Table 35: Pearson's correlation between SOC and climatic factors and soil pH.

	<i>Temp</i>	<i>SOC</i>	<i>Precipitation</i>	<i>pH</i>
Temp	1	–	–	–
SOC	0.96**	1	–	–
Precipitation	0.71*	0.86**	1	–
pH	0.71*	0.56*	0.40	1

** significant at 0.01 level; * significant at 0.05 level

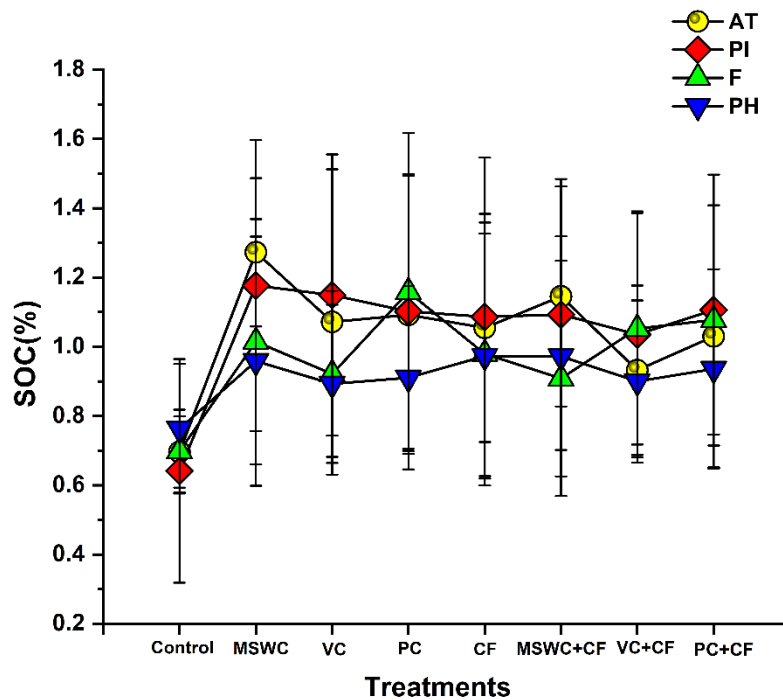


Fig.33: Variation of average SOC in different treatments during active tillering (AT), panicle initiation (PI), Flowering (F) and post-harvesting (PH) stage.

Soil pH

Soil pH during the first year was within the range of 6.29 to 7.38 in the eight treatments (Table 36). The highest pH was obtained in CF treatment during the active tillering stage, while the lowest was obtained in PC+CF treatment during the panicle initiation stage. Among the four cropping stages, pH was lowest (6.52 ± 0.27) in the panicle initiation stage, on average, and highest (6.76 ± 0.16) in the flowering stage.

In contrast to the first year, maximum pH was found at the active tillering stage (6.74 to 6.98) and the minimum at the flowering stage (6.12 to 6.35) in the second year (Table 37). Among the treatments, MSWC treatment had the highest pH (6.59), followed by VC treatment (6.58), while CF treatment had the lowest (6.47), but the variation in pH was not significant. The optimal range of pH for rice cultivation is 5.5 to 7.0 (Mandala et al. 2021). The results of pH found in the present study fall within the optimal range for the cultivation of rice. The pH in rice fields is normally neutral as rice grows mainly in flooded soil.

During the two years of study, the minimum pH value was found in control at the post-harvest stage, whereas the maximum was obtained in CF treatment at active tillering stage. The average pH throughout the cropping stages was found between the range of 6.40 and 7.09. Soil pH during active tillering stage was recorded to be the highest in all the treatments, followed by panicle initiation, post-harvesting, and flowering stages, with a remarkable interaction effect between crop growing stages and years ($p < 0.05$, Table 38). However, the interaction between treatments and stages was found to be non-significant. The higher pH recorded during the active tillering could be explained by mineralization of nutrients in the flooded soil. This supplies nutrients to the rice plant at the flowering stage. During the active tillering, panicle initiation stage, flowering stage and post-harvesting, the pH ranged between 6.63 to 7.09, 6.52 to 6.74, 6.44 to 6.60, and 6.40 to 6.75, respectively. Among the treatments, the application of MSWC treatment recorded maximum pH of the soil (6.68) when averaged across the four different stages of crop and over the two-year average data, followed by CF treatment (6.67). The humic components in MSW compost are composed mainly of humic acid, and it is considered to be more stable than fulvic acid. And it helps the soil in elevating the buffer capacity (He et al. 1995). The application of chemical fertilizer had higher pH value compared to the compost treatments with or without chemical fertilizer, except MSWC, but the variation was not significant ($p < 0.05$). Chettri et al. (2017) also reported that pH was decreased with the incorporation of organic fertilizer, which could be due to the decomposition of organic fertilizer that released organic acids. Bokhtiar and Sakurai (2005) observed a similar result of decreasing soil pH with the application of organic fertilizers, as organic C found in organic fertilizer functions as a source of energy for microbes, and when they mineralized the available C, they produced organic acid.

Table 36: Variation in soil pH at four different stages of rice growing under different treatments of 2022.

Treatments	2022			
	AT	PI	F	PH
C	6.68±0.04 a	6.65±0.94 a	6.62±0.13 a	6.47±0.25 a
MSWC	6.69±0.05 a	6.69±0.86 a	6.91±0.10 a	6.79±0.08 a
VC	6.71±0.01 a	6.42±0.89 a	6.75±0.33 a	6.93±0.06 a
PC	6.71±0.15 a	6.50±0.71 a	6.80±0.06 a	6.81±0.28 a
CF	7.38±0.13 b	6.63±0.74 a	6.73±0.13 a	6.77±0.13 a
MSWC+CF	6.68±0.12 a	6.50±0.54 a	6.88±0.12 a	6.85±0.07 a
VC+CF	6.53±0.09 a	6.49±0.48a	6.72±0.19 a	6.48±0.18 a
PC+CF	6.55±0.07 a	6.29±0.44 a	6.67±0.10 a	6.64±0.32 a

Table 37: Variation in soil pH at four different stages of rice growing under different treatments of 2023.

Treatments	2023			
	AT	PI	F	PH
Control	6.86±0.03 a	6.51±0.15 a	6.35±0.07 a	6.33±0.15 a
MSWC	6.98±0.23 a	6.80±0.08 a	6.12±0.24 ab	6.44±0.28 a
VC	6.89±0.10 a	6.63±0.06 a	6.22±0.05 ab	6.58±0.24 a
PC	6.79±0.07 a	6.61±0.14 a	6.25±0.11 a	6.42±0.20 a
CF	6.80±0.06 a	6.66±0.03 a	6.14±0.16 ab	6.27±0.07 a
MSWC+CF	6.85±0.13 a	6.93±0.06 a	6.31±0.23 b	6.21±0.29 a
VC+CF	6.74±0.07 a	6.67±0.18 a	6.19±0.04 ab	6.41±0.18 a
PC+CF	6.79±0.07 a	6.64±0.07 a	6.25±0.07 ab	6.51±0.12 a

Table 38: Three-way ANOVA table for soil pH.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	10.945	63	0.174	4.816	0.000
Intercept	8400.036	1	8400.036	232860.057	0.000
Treatment (T)	0.642	7	0.092	2.543	0.017
Stage (S)	2.332	3	0.777	21.546	0.000
Year (Y)	1.075	1	1.075	29.787	0.000
T*S	1.128	21	0.054	1.490	0.092
T*Y	0.651	7	0.093	2.580	0.016
S*Y	3.972	3	1.324	36.700	0.000
T*S*Y	1.145	21	0.055	1.512	0.084
Error	4.617	128	0.036		
Total	8415.599	192			

Soil EC

EC of soil was ranged from 30.06 $\mu\text{S cm}^{-1}$ in MSWC+CF treatment to 38.88 $\mu\text{S cm}^{-1}$ in PC+CF treatment during the first year (Table 39). And as depicted in Table 40, during the second year, it ranged between 26.77 $\mu\text{S cm}^{-1}$ in VC+CF treatment and 39.66 $\mu\text{S cm}^{-1}$ in CF treatment. When averaged across the two years, the application of PC+CF treatment recorded maximum EC value. Compared to the CF treatment ($33.92 \pm 3.02 \mu\text{S cm}^{-1}$), EC in MSWC ($29.98 \pm 1.93 \mu\text{S cm}^{-1}$), VC ($31.85 \pm 2.83 \mu\text{S cm}^{-1}$), PC ($31.57 \pm 2.17 \mu\text{S cm}^{-1}$) and MSWC+CF ($31.08 \pm 2.04 \mu\text{S cm}^{-1}$) were considerably lower. In the present study, the results of EC did not follow a definite trend among the different stages of the crop. However, the post-harvest stage exhibits the lowest EC value in all treatments except MSWC, VC and CF treatments. The average EC values ranged between 29.70 to 38.65 $\mu\text{S cm}^{-1}$, 29.4 to 36.84 $\mu\text{S cm}^{-1}$, 30.36 to 34.83 $\mu\text{S cm}^{-1}$, and 29.72 to 33.90 $\mu\text{S cm}^{-1}$ during the active tillering, panicle initiation, flowering, and post-harvesting stages, respectively. The results of EC found in the current study fall within the category of very low saline ($< 150 \mu\text{S cm}^{-1}$), as demonstrated by Hesse (1964). EC of soil is one of the chemical properties that determine the nutrient

availability and yield of crops (Delgoda, et al. 2023). The EC values found in the study were significantly affected by the interaction between treatments, different stages of crop and years ($p < 0.05$, Table 41).

Table 39: Variation in EC of soil during four different stages of rice growing under different treatments of 2022.

Treatments	2022			
	AT	PI	F	PH
Control	34.12±0.23 bcd	36.34±0.76 c	36.94±0.66 d	34.73±0.87 c
MSWC	28.00±0.47 a	30.43±0.57 a	33.06±0.58 b	31.30±0.60 a
VC	34.8±0.95 cd	33.12±0.55 b	35.06±0.92 cd	34.06±0.83 bc
PC	33.74±0.43 bc	32.76±0.90 b	33.90±0.51 bc	31.90±0.43 a
CF	32.70±0.99 b	30.70±0.45 a	30.33±0.80 a	32.40±0.36 ab
MSWC+CF	28.24±0.20 a	32.21±0.90 ab	30.06±0.20 a	31.16±0.65 a
VC+CF	35.62±0.59 d	36.50±0.79 c	34.17±0.84 bc	34.66±0.50 c
PC+CF	38.88±0.57 d	37.89±0.28 c	36.23±0.46 d	34.43±0.60 c

Table 40: Variation in EC of soil during four different stages of rice growing under different treatments of 2023.

	2023			
	AT	PI	F	PH
C	33.44±0.85 abc	34.10±0.96 bc	32.72±1.21 cd	31.06±0.55 b
MSWC	31.40±0.84 ab	28.36±1.13 a	27.65±0.87 a	29.64±0.93 ab
VC	31.71±0.93 ab	28.56±1.10 a	28.03±1.12 ab	29.45±0.98 ab
PC	30.95±0.64 a	32.23±1.20 b	29.56±0.83 abc	27.54±1.14 a
CF	39.66±1.04 d	35.56±1.13 c	34.62±1.53 d	35.41±0.65 c
MSWC+CF	33.95±0.83 bc	32.80±1.27 bc	31.62±1.53 cd	28.64±0.81 ab
VC+CF	34.63±1.02 c	33.93±0.85 bc	31.03±0.81 bc	26.77±1.87 a
PC+CF	38.42±1.01 d	35.80±0.72 c	31.76±1.14 cd	30.61±0.76 b

Table 41: Three-way ANOVA table for soil EC.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	1676.788	63	26.616	4.816	0.000
Intercept	205198.027	1	205198.027	232860.057	0.000
Treatment (T)	577.166	7	82.452	2.543	0.017
Stage (S)	145.295	3	48.432	21.546	0.000
Year (Y)	111.606	1	111.606	29.787	0.000
T*S	216.836	21	10.326	1.490	0.092
T*Y	409.886	7	58.555	2.580	0.016
S*Y	133.613	3	44.544	36.700	0.000
T*S*Y	82.368	21	3.922	1.512	0.084
Error	96.598	128	0.755		
Total	206971.413	192			

Total N

The total N content of the soil due to different treatments at different stages of crop is depicted in Fig.34. In the first year, during active tillering stage the total N content of the soil was in the range of 1285.2 to 2554.53 kg ha⁻¹, where the maximum was recorded in PC+CF treatment and the minimum in VC and VC+CF treatments. The total N content in CF, MSWC+CF, VC+CF and PC+CF treatments was increased at panicle initiation stage and then declined in the following stages, except MSWC+CF treatment, where N content was higher at post-harvest than flowering. But the other remaining treatments (control, MSWC, VC, and PC treatment) show a decreasing trend from active tillering stage to post-harvest stage. In the first year, the maximum total N content (2856.00±47.60 kg ha⁻¹) was found in PC+CF treatment at panicle initiation stage, while the lowest was found in control (444.26±72.71 kg ha⁻¹) at post-harvest stage (Fig.34 a). The average total N content during the first year ranged between 737.8 to 2405.78 kg ha⁻¹.

In the second year, the average total N content ranged between 654.50 to 2457.35 kg ha⁻¹ across the different treatments. The maximum and minimum total N content

during the second year is in line with the first year, where PC+CF treatment recorded the highest at panicle initiation stage and control recorded the lowest at post-harvest stage (Fig.34 b). During the active tillering, the result was in the range of 801.22 to 2522.80 kg ha⁻¹, at panicle initiation stage 650.53 to 2871.86 kg ha⁻¹, flowering 666.4 to 2475.2 kg ha⁻¹, and at post-harvest the range was between 499.8 to 2046.8 kg ha⁻¹.

Moreover, the average data of the two years showed that the total N content was significantly higher in PC+CF treatment, followed by MSWC+CF treatment. The application of PC+CF treatment shows pronounced effect on the total N content of soil at all four stages (Table 42). The total N content in PC+CF treatment was found in the range of 1999.2 to 2863.93 kg ha⁻¹ across the four different stages of rice. As *phumdi* compost contained higher N concentration, its combination with chemical fertilizer exerted a higher amount of total N compared to other treatments. During the two growing seasons, only MSWC+CF treatment and PC+CF treatment significantly increased average total N content by 11.21% and 32.18% respectively, over CF treatment. Although the CF treatment resulted in higher average total N content, the amount of total N in the application of vermicompost integrated with chemical fertilizer was at par.

The study also found that, other than control, MSWC and VC treatments, the average total N content was highest at panicle initiation stage in all the treatments (Table 42). It was found between the range of 658.46 to 2863.93 kg ha⁻¹. The increased total N content during panicle initiation stage could be due to the release of N from the fertilizers added in the initial stage of rice growth. And a significant decline in the total N content was observed at the post-harvest stage (472.03 to 1999.2 kg ha⁻¹). The rapid utilization of available N by plants resulted in declining trend in the later stage of rice growth. Although the N contents were decreased at the post-harvest stage, the application of MSWC+CF, VC+CF, and PC+CF treatments resulted in higher N content by 21.78%, 12.38%, and 32.28%, respectively, compared to the sole application of chemical fertilizer. This shows that the application of integrated nutrient treatments was an effective strategy to retain the N content in the soil and improve soil fertility till the post-harvest stage. Alagappan and Venkitaswamy (2016) reported that the integrated application of organic and chemical fertilizer balanced the N concentration of the rice soil. The combined nutrients application slows down the

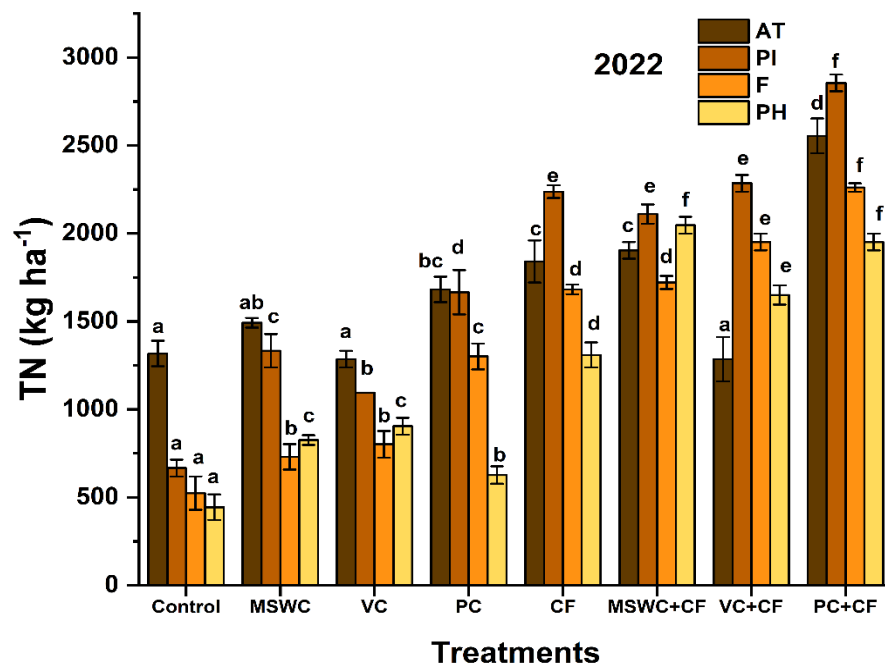
decomposition rate of organic fertilizer, which in turn releases the N steadily to the crops, fulfilling their essential requirement for the crop. At the end of five years of rice cultivation, the total N concentration of soil was higher in organic fertilizer application integrated with chemical NPK than sole application of chemical NPK (Shen et al. 2007). The interaction between treatments, stages of crop and years significantly affects the total N content of soil in the present study ($p < 0.05$, Table 43). Moreover, a significant positive correlation was shown between total N and SOC ($r = 0.72$, $p < 0.05$), and available K ($r = 0.74$, $p < 0.05$).

Table 42: Average total N concentration of the two years cropping season under different fertilizer treatments.

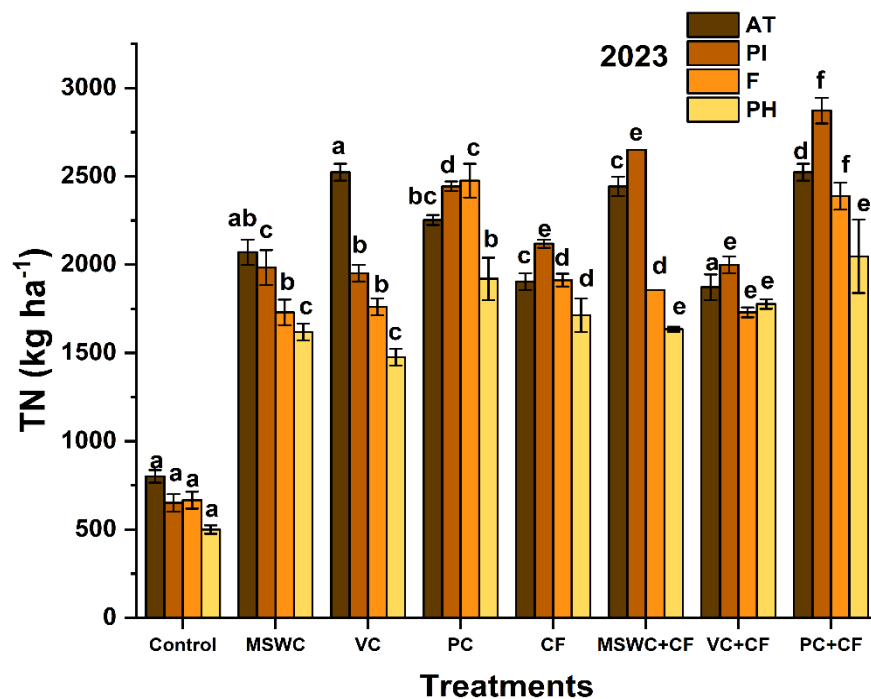
Treatment	AT	PI	F	PH
Control	1059.10±364.63	658.46±11.21	595.00±100.97	472.03±39.26
MSWC	1781.03±409.50	1658.06±459.99	1229.66±706.82	1221.73±560.97
VC	1904.00±875.11	1523.20±605.84	1281.23±678.77	1190.00±403.89
PC	1967.46±403.89	2054.73±549.75	1888.13±830.23	1273.30±914.38
CF	1872.26±44.87	2177.70±84.14	1796.90±162.68	1511.30±286.09
MSWC+CF	2173.73±381.46	2380.00±381.46	1788.96±95.36	1840.53±291.70
VC+CF	1578.73±415.11	2142.00±201.94	1840.53±157.07	1713.60±89.75
PC+CF	2538.66±22.43	2863.93±11.21	2324.46±89.75	1999.20±67.31

Table 43: Three-way ANOVA table for total N.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	73886100.2	63	1172795.242	265.906	0.000
Intercept	552835766.3	1	552835766.3	125343.626	0.000
Treatment (T)	43384179.49	7	6197739.927	1405.204	0.000
Stage (S)	8597364.366	3	2865788.122	649.756	0.000
Year (Y)	6664547.177	1	6664547.177	1511.043	0.000
T*S	4361815.166	21	207705.484	47.093	0.000
T*Y	7591260.718	7	1084465.817	245.879	0.000
S*Y	119976.122	3	39992.041	9.067	0.000
T*S*Y	3166957.189	21	150807.485	34.192	0.000
Error	564551.867	128	4410.561		
Total	627286418.4	192			



(a)



(b)

Fig.34: Total N content of soil at four different stages of rice growing under different fertilizer treatments of (a) 2022 and (b) 2023.

Available P

During the first year, the available P of soil was maximum at active tillering stage in all the treatments except CF treatment (Fig.35 a). The concentration of the available P gradually declined in the panicle initiation stage, flowering stage, and post-harvest stage, attaining its minimum concentration at post-harvest ($p < 0.05$, Table 45). At active tillering stage, the available P was recorded between the range of 6.58 and 24.27 kg ha⁻¹, at panicle initiation, 5.63 to 26.25 kg ha⁻¹, at flowering, 4.99 to 23.40 kg ha⁻¹, and at post-harvest stage, it was ranged from 4.60 to 20.98 kg ha⁻¹. However, in the second year, other than control and MSWC, the maximum available P was recorded at panicle initiation stage (4.56 to 24.43 kg ha⁻¹), and then declined gradually in flowering (4.99 to 23.32 kg ha⁻¹) and post-harvest stages (4.00 to 20.86 kg ha⁻¹) (Fig.36 b). Across the whole cropping period, the CF treatment recorded the maximum available P concentration at panicle initiation stage, while the control recorded the lowest at post-harvest stage in both years. The combined application of composts and chemical fertilizer significantly lowers the available P of soil compared to CF treatment; however, these combined treatments significantly enhance available P relative to the sole application of composts. Soil available P ranged from 4.60 to 26.25 kg ha⁻¹ in the first year and 4.00 to 24.43 kg ha⁻¹ in the second year.

And over the two-year average, the available P of soil varied significantly at different stages of rice growth ($p < 0.05$). During the active tillering, the maximum available P of 24.13 kg ha⁻¹ was recorded in CF treatment while the minimum of 6.52 kg ha⁻¹ was recorded in control treatment. At active tillering stage, the available P was found in the range of 5.09 to 25.34 kg ha⁻¹. There was a decrease in available P in all the treatment in active tillering stage except PC and CF treatments. In the remaining stages, the available P showed a declining trend irrespective of treatments. At flowering and post-harvest stages, the range of available P was 4.99 to 23.36 kg ha⁻¹ and 4.30 to 20.92 kg ha⁻¹, respectively (Table 44). It was also observed that the application of different fertilizers significantly influenced P available in the soil ($p < 0.05$, Table 45). The average available P found in the paddy soil of study area across the different stages of rice growth was in the order of control (5.23 kg ha⁻¹) < PC (8.77 kg ha⁻¹) < VC (12.77 kg ha⁻¹) < MSWC (13.72 kg ha⁻¹) < PC+CF (14.22 kg ha⁻¹) < MSWC+CF (15.38 kg ha⁻¹) < VC+CF (16.50 kg ha⁻¹) < CF (23.44 kg ha⁻¹). The lowest

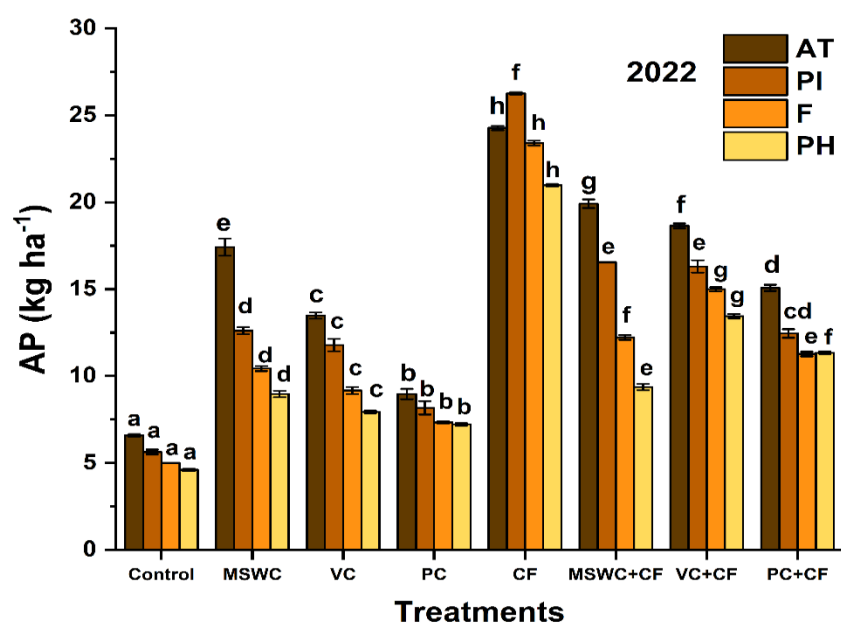
available P found in PC treatment among the fertilized plot was in the range of 8.27 to 9.22 kg ha⁻¹ throughout the crop cycle. The three-way interactions between the treatments, stages of crops, and years showed significant variation of available P ($p < 0.05$, Table 45).

Table 44: Average available P concentration of the two-year cropping season under different fertilizer treatments.

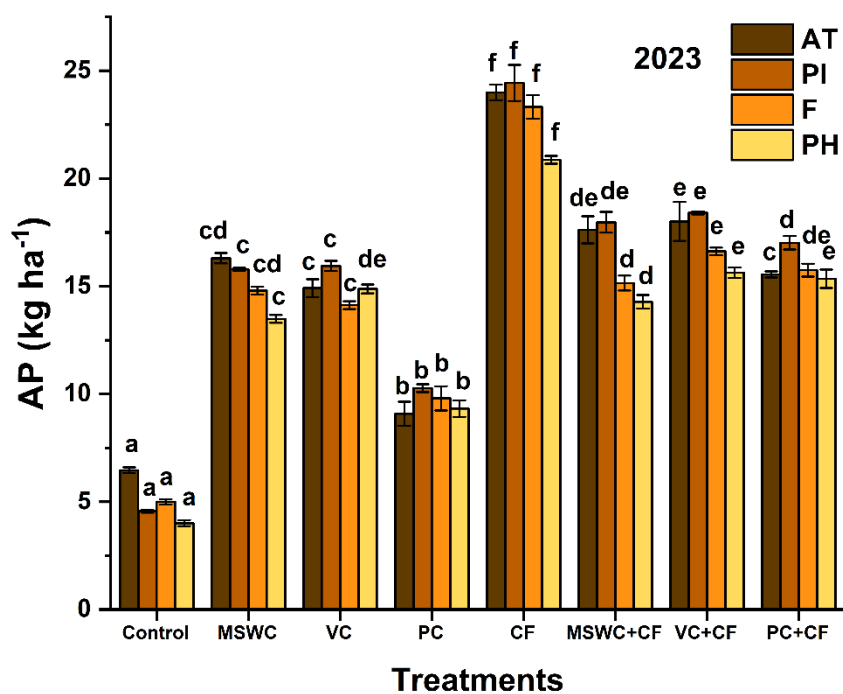
Treatment	AT	PI	F	PH
Control	6.52±0.08	5.09±0.75	4.99±0.00	4.30±0.42
MSWC	16.85±0.78	14.20±2.24	12.61±3.08	11.22±3.19
VC	14.20±1.00	13.86±2.94	11.64±3.50	11.40±4.90
PC	9.02±0.08	9.22±1.48	8.56±1.73	8.27±1.48
CF	24.13±0.19	25.34±1.29	23.36±0.05	20.92±0.08
MSWC+CF	18.76±1.62	17.25±1.00	13.68±2.07	11.82±3.47
VC+CF	18.32±0.44	17.35±1.48	15.80±1.14	14.53±1.54
PC+CF	15.31±0.33	14.73±3.22	13.50±3.16	13.34±2.83

Table 45: Three-way ANOVA table for available P.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	5749.220	63	91.257	1398.081	0.000
Intercept	36339.693	1	36339.693	556730.858	0.000
Treatment (T)	4865.825	7	695.118	10649.334	0.000
Stage (S)	342.997	3	114.332	1751.594	0.000
Year (Y)	151.879	1	151.879	2326.808	0.000
T*S	131.889	21	6.280	96.217	0.000
T*Y	125.578	7	17.940	274.841	0.000
S*Y	77.715	3	25.905	396.867	0.000
T*S*Y	53.338	21	2.540	38.912	0.000
Error	8.355	128	0.065		
Total	42097.269	192			



(a)



(b)

Fig.35: Available phosphorus concentration of soil at four different stages of rice growing under different fertilizer treatments of (a) 2022 and (b) 2023.

Available K

Available K of soil was significantly varied at different stages of rice growth ($p < 0.05$, Table 47). In the first year, the available K was found within the range of 120.80 to 226.18 kg ha⁻¹ throughout the four different stages (Fig.36 a). At the active tillering stage, the range of available K was between 147.13 and 193.57 kg ha⁻¹. The maximum concentration was recorded in PC+CF treatment, while the minimum was recorded in control. At the panicle initiation stage, the concentration of available K was found in the range of 149.66 kg ha⁻¹ in control to 266.18 kg ha⁻¹ in MSWC treatment. The concentration was significantly increased from active tillering to panicle initiation stage in all the treatments except CF and PC+CF treatments. However, in the flowering stage, available K was considerably lower except for the CF and PC+CF treatments. The available K of soil ranged between 120.80 kg ha⁻¹ and 180.69 kg ha⁻¹, with the maximum in MSWC treatment and minimum in control at the flowering stage. And, at the post-harvest stage, the value ranged between 122.81 to 156.81 kg ha⁻¹. The maximum available K was recorded in MSWC+CF treatment, and the minimum was recorded in control. Overall, among the different treatments, MSWC treatment had the maximum available K content of soil and control recorded the minimum during the first year.

During the second year, the available K of soil was not significantly increased from the first year ($p < 0.05$, Table 47). The result of the study observed that available K was in the range of 142.32 to 192.36 kg ha⁻¹ at active tillering stage. The maximum was recorded in CF treatment and minimum in control. Out of the four different stages of rice growth, the available K of soil was highest at the panicle initiation stage in all the treatments except the control and PC treatment. The range of available K at panicle initiation was 139.90 to 205.63 kg ha⁻¹. The maximum was recorded in MSWC treatment and the minimum in control at the panicle initiation stage. The concentration of available K declined in the later stages. At the flowering stage, the value was within the range of 124.82 to 173.27 kg ha⁻¹, with the minimum and maximum concentration in control treatment and PC+CF, respectively. At the post-harvest stage, the maximum available P concentration was recorded in PC+CF treatment, and the minimum was recorded in control. Moreover, it was also found that PC+CF treatment significantly

increased the available K concentration of soil, attaining the maximum result among the different fertilizer treatments.

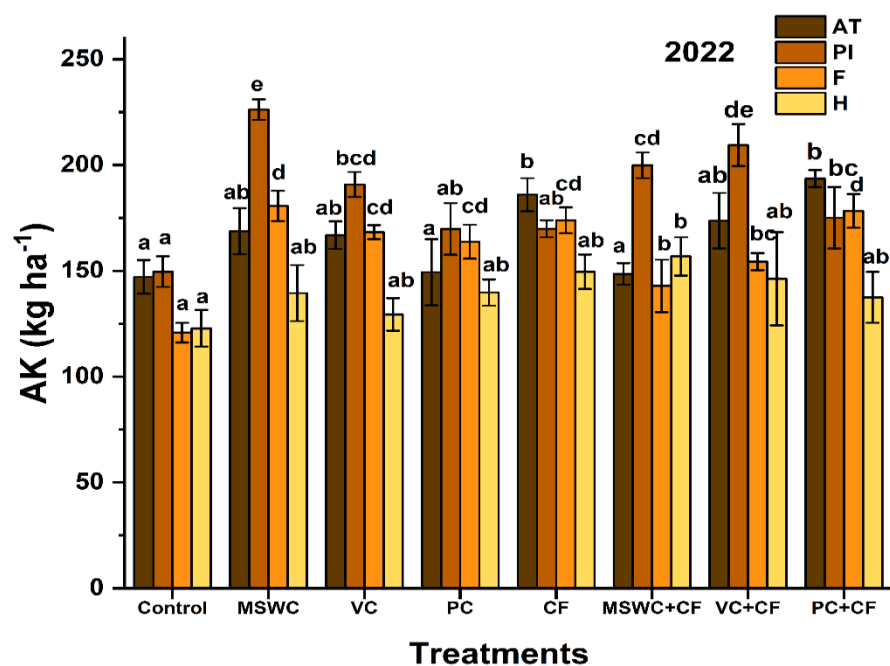
Across the two years data, the application of different fertilizer treatments at various stages of rice significantly influenced the soil available K concentration of the paddy rice field ($p < 0.05$, Table 47). There was a decreasing trend of available K from panicle initiation to the remaining stages (Table 46). The significant decrease in the concentration of available K at the flowering and post-harvest stage might be due to the utilization of nutrients by the crop during the growing stages of rice. Similar finding of declining soil available K with the advancement of crop growth was reported by Ramadass and Palaniyandi (2007). Meanwhile, PC+CF treatment ($174.28 \text{ kg ha}^{-1}$) recorded the highest average available K, followed by MSWC treatment ($173.55 \text{ kg ha}^{-1}$), VC+CF treatment ($171.66 \text{ kg ha}^{-1}$) and CF treatment ($170.46 \text{ kg ha}^{-1}$), but the variations were not significant. PC treatment ($156.03 \text{ kg ha}^{-1}$) had the lowest available K concentration among the fertilizer treatments. K is one of the essential macronutrients that help in enhancing root development, cell division, supplying osmotic pull and maintaining metabolism of rice plant (Shrestha et al. 2020). Surekha et al. (2013) reported that application of organic fertilizer with chemical fertilizer remarkably increased the soil available K by 8 to 25% compared to the application of chemical fertilizer alone. Similar result of enhanced available K due to the application of organic fertilizer was also reported Paikaray et al. (2002), Melero et al. (2008), and Walia et al. (2010).

Table 46: Average available K concentration of the two years cropping season under different fertilizer treatments.

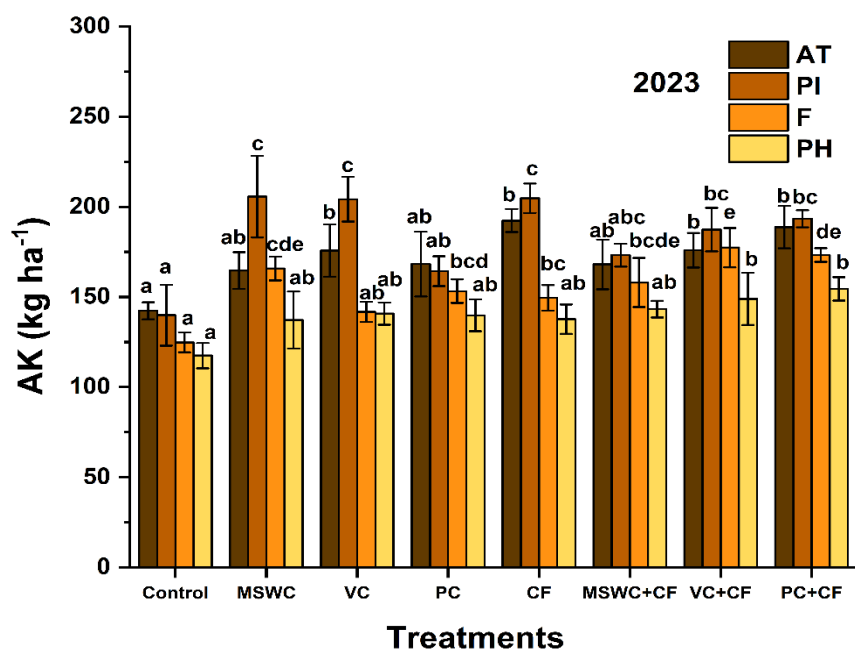
Treatment	AT	PI	F	PH
Control	144.73±3.40	144.78±6.89	122.81±2.84	120.14±3.77
MSWC	166.70±2.86	215.91±14.53	173.23±10.54	138.35±1.61
VC	171.30±6.28	197.49±9.46	154.98±18.78	135.09±8.04
PC	158.80±13.43	167.05±3.88	158.46±7.46	139.79±0.04
CF	189.18±4.49	187.31±24.65	161.71±17.21	143.63±8.38
MSWC+CF	158.30±13.79	186.56±18.87	150.44±10.70	150.04±9.57
VC+CF	174.82±1.57	198.39±15.59	165.82±16.34	147.6±1.89
PC+CF	191.13±3.45	184.23±12.98	175.79±3.55	145.98±12.06

Table 47: Three-way ANOVA table for available K.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	108802.519	63	1727.024	16.788	0.000
Intercept	5110361.648	1	5110361.648	49675.470	0.000
Treatment (T)	31592.445	7	4513.206	43.871	0.000
Stage (S)	52099.187	3	17366.396	168.811	0.000
Year (Y)	13.057	1	13.057	0.127	0.722
T*S	13664.011	21	650.667	6.325	0.000
T*Y	1037.773	7	148.253	1.441	0.194
S*Y	670.116	3	223.372	2.171	0.095
T*S*Y	9725.930	21	463.140	4.502	0.000
Error	13167.994	128	102.875		
Total	5232332.161	192			



(a)



(b)

Fig.36: Available potassium concentration of soil at four different stages of rice growing under different fertilizer treatments of (a) 2022 and (b) 2023.

4.12. Principal component analysis

As a result of the PCA, two components are identified, which explained over 79% of the total variability. The first component PC1 explained 55.58% of the observed variance and the second component PC2 showed 23.56%. The result of the analysis could suggest that soil nutrient content, particularly total N, available P, available K and SOC, were positively correlated with each other. As soil pH, CO₂, and CH₄ were clustered together, it shows a positive correlation. The analysis further explained that the EC of soil was negatively correlated with the gas parameters and pH of soil.

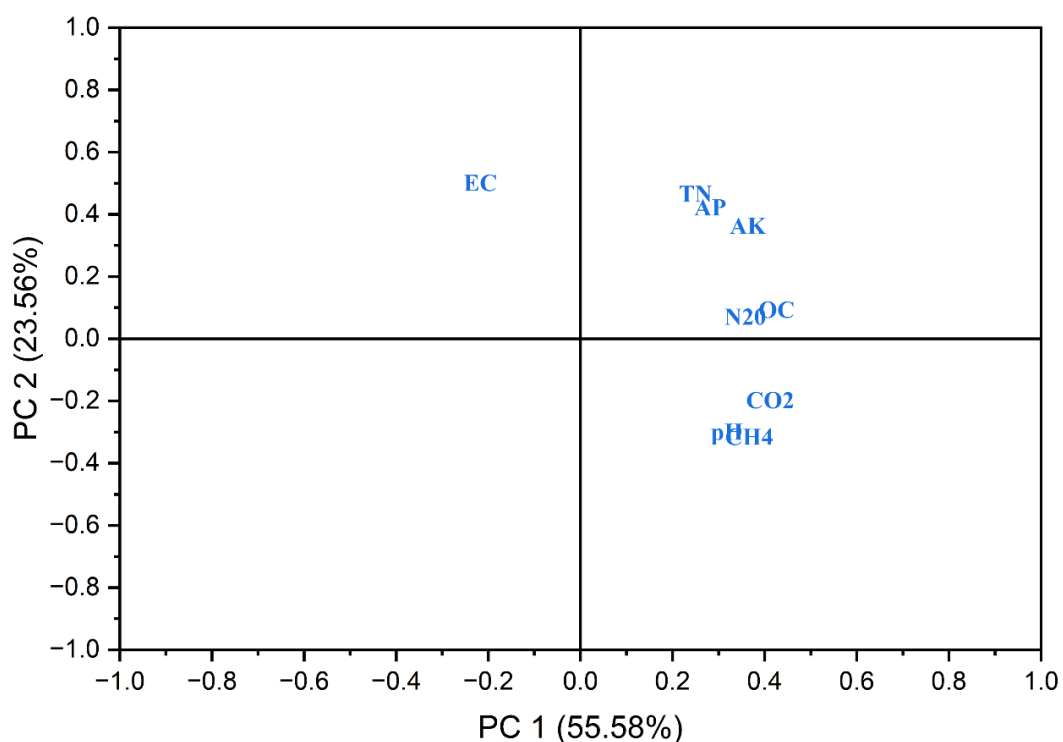


Fig.37: Factor loading plot of the GHG emissions and soil parameters (SOC, pH, TN, AP, AK and EC).

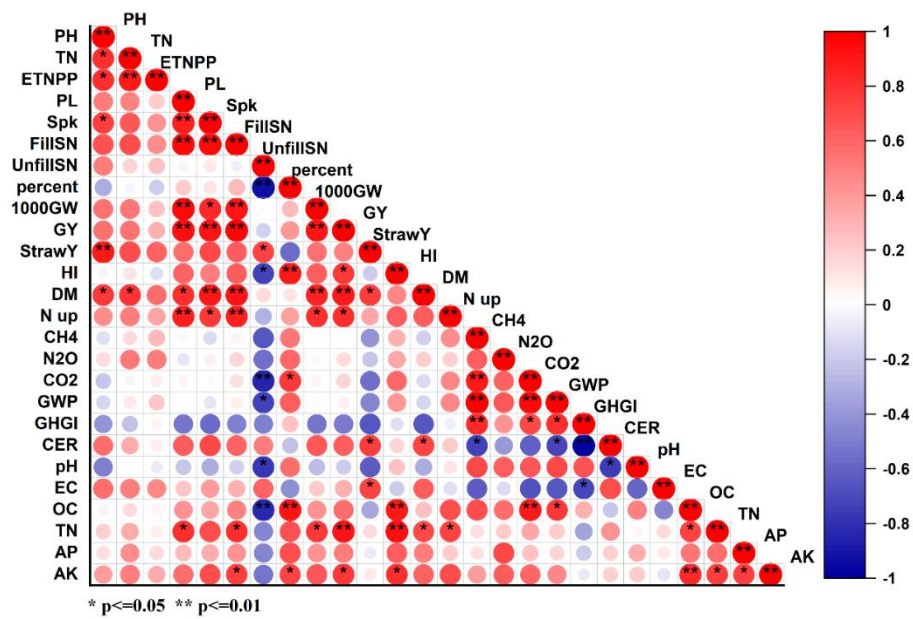


Fig.38: Pearsons's correlation between different plant parameters, greenhouse gas emissions and soil parameters for two years data.

5. SUMMARY AND CONCLUSION

5.1. Plant parameters

The study determined the effectiveness of three composts on the growth and yield characteristics of rice plant. The application of different fertilizer treatments significantly influenced the growth characteristics of rice. Plant height was highest at 60DAT and decreased at the maturity stage, irrespective of treatments. The application of PC+CF treatment attained the maximum plant height in the two years of study, with 8.7% and 5.94% higher than the application of CF treatment. The TNPP and ETNPP were also higher in the PC+CF treatment plots compared to other fertilizer treatments.

During the two years of study, the yield characteristics of rice, including panicle length, number of spikelet per panicle, number of filled spikelets per panicle, and 1000-grain weight, were maximum in the PC+CF treatment, resulting in the maximum grain yield of rice. The positive correlation between grain yield and panicle length, spikelets per panicle, filled spikelets per panicle, and 1000-grain weight in the present study supported our hypothesis. The application of PC+CF treatment produced 33.6% more grain yield relative to the CF treatment. The integrated fertilizer treatments, VC+CF and MSWC+CF, also recorded higher grain yield compared to the sole application of composts and chemical fertilizer. Furthermore, the study observed higher grain yield in the second year compared to the first year.

The straw yield was observed to be maximum in PC+CF treatment, followed by VC+CF treatment, and the minimum was found in PC treatment. Compared to the CF treatment, PC+CF and VC+CF treatments produced 26.44% and 12.86% higher straw yield. The HI of rice was found between the range of 0.44 to 0.48 in all the fertilizer application plots. HI was higher in MSWC+CF treatment and PC treatment compared to other treatments, with values of 0.48 and 0.47, respectively. The positive correlation between HI and soil available K, total N, and SOC indicated that applying compost with chemical fertilizer could supply nutrients to the plant and enhance the economic yield of rice plant.

The plant N uptake was higher in the combined application of compost and chemical fertilizer and the sole application of compost compared to the CF treatment. The application of PC+CF, MSWC+CF, and VC+CF increased the N uptake by an average of 79.35% compared to the CF treatment. It was further found that the application of different fertilizer treatments remarkably influenced the NUE and ANE. The application of PC+CF, VC+CF, and MSWC+CF treatment significantly increased the NUE and ANE compared to the sole application of chemical fertilizer. However, the application of compost alone resulted in lower ANE by an average of 29.89% compared to the chemical fertilizer treatment.

5.2. GHG emissions

The study measured the magnitude of GHG emissions from the rice field to determine the effect of the composts on GHG emissions from rice fields cultivated under rainfed conditions. In the two years of study, it was observed that CH₄ flux followed a similar trend of increased gas flux with the development of the crop from the initial growth stage. The CH₄ flux reached its peak at the active tillering stage and reproductive stage of rice growth. And then decline at the maturity stage in all the treatments. The CH₄ flux was emitted higher in the sole application of MSW compost and *phumdi* compost, with a maximum in MSWC treatment. Meanwhile, the VC+CF, MSWC+CF, PC+CF and VC treatment recorded lower CH₄ flux compared to the CF treatment. The present study identified that the application of different fertilizer treatments significantly influenced the seasonal cumulative CH₄ emission. The application of integrated fertilizer treatments reduced the CH₄ emission from rice fields by 3.63 to 42.17% compared to the CF treatment.

The N₂O flux accelerates after N fertilizer application and then decreases sharply until the next fertilization. The application of fertilizers influenced the nitrification and denitrification process, which in turn increased the gas flux after fertilizer application. The highest cumulative N₂O emission was recorded in CF treatment (0.223 ± 0.001 kg ha⁻¹) and the minimum in control (0.106 ± 0.003 kg ha⁻¹). The integrated fertilizer treatments reduced N₂O emissions by a margin of 65% compared to the CF treatment.

The measurement of CO₂ flux from the rice field under eight different fertilizer treatments indicated that the gas flux was higher in the sole application of compost compared to the application of chemical fertilizer alone and integrated treatments of compost and chemical fertilizer. The availability of more C-substrate from the sole application of compost could result in higher CO₂ flux. Higher CO₂ flux was recorded during the reproductive stage of rice growth, which could be explained by the release of more root exudates from the increased root biomass which stimulates the activities of soil microorganisms. The increased CO₂ flux in the MSWC, VC, and PC treatments led to higher seasonal CO₂ emissions. At the same time, the application of integrated fertilizer treatment resulted in lower CO₂ emissions, with the lowest emission in VC+CF treatment (2372.52 kg ha⁻¹) compared to the CF treatment.

The study found a significant positive correlation between GHG emissions (CH₄ and CO₂) and SOC content, indicating that higher content of organic C led to higher CH₄ and CO₂ emissions. The CH₄ and CO₂ emissions were also found to be positively correlated with air temperature.

In the present study, more than half of the GWP from the rice field was contributed by CH₄ emission. It was followed by CO₂ emission and N₂O emission. Since rice cultivation is mainly done in flooded conditions, it creates oxygen-deprived environment and enhances the formation of CH₄ by the process of methanogenesis. However, there were times when adequate rainfall was not received, such conditions favour CO₂ emissions, contributing 47% of the total GWP. The maximum GWP was recorded in MSWC treatment, followed by PC treatment, with 32.93% and 14.38% higher compared to the CF treatment. And the application of VC+CF treatment recorded the minimum GWP among the fertilized plots.

The GHGI of the rice field was decreased with the application of combined composts and chemical fertilizer treatments. The higher grain yield with lesser GHG emissions in the MSWC+CF, VC+CF, and PC+CF treatments resulted in lower GHGI. The application of MSWC treatment recorded maximum GHGI with 35.41% higher compared to the application of chemical fertilizer alone.

5.3. Soil parameters

In the two years of study, there was a distinct variation in SOC content among the four stages of rice. In the first year, maximum SOC was found in the active tillering stage in the treatments of control, MSWC, CF, and MSWC+CF treatment, but in the second year, maximum SOC was found in the panicle initiation stage in all the treatments except for control and PC treatments. Over the four stages and two years, the addition of MSWC treatment resulted in maximum SOC content.

The CF treatment recorded maximum C-stock at the end of the cropping season. However, the result was at par with the value of MSWC+CF treatment. Among the three composts used in the present study, the application of MSW compost with or without chemical fertilizer accumulates more C in the soil due to its low C:N ratio compared to vermicompost and *phumdi* compost. Moreover, the C-sequestration rate was higher in MSWC treatment, followed by CF treatment and the lowest was found in control.

The pH of soil was found to range from 6.29 to 7.38 in the first year and 6.12 to 6.98 in the second year. It falls within the ideal range of pH for rice cultivation. The highest pH was found in MSWC treatment. The EC of the soil found in the present experimental field was included in the category of very low saline soil. The application of PC+CF treatment resulted in higher total N and available K of the soil. However, the available P was maximum in CF treatment compared to other fertilizer treatments.

Conclusion

The sustainability of rice cultivation needs to be maintained through effective management in the application of fertilizers. From the study, it can be concluded that substitution of 50% chemical fertilizer by composts produces more grain yield compared to the sole application of chemical fertilizer. The addition of *phumdi* compost combined with chemical fertilizer produced a maximum grain yield with 33.6% higher than the application of chemical fertilizer alone. It was followed by integrated treatment of vermicompost with chemical fertilizer and MSW compost with chemical fertilizer. Even though the same required amount of N was added, the

application of composts alone could not be able to supply the essential amount of nutrients needed for optimal yield. Moreover, the integrated treatments of compost and chemical fertilizer significantly reduced GHG emissions from rice fields, resulting in lower GWP and GHGI. Among the three composts, application of vermicompost integrated with 50% chemical fertilizer becomes the most effective fertilizer management strategy to tackle the GHG emissions from rice fields cultivated under rainfed conditions of Northeast India with greater crop production. The treatment has a lower EF of CH₄ than the IPCC 2019 default EF OF CH₄. The study also found that the addition of integrated fertilizer treatments improved the total N and available K concentration of the soil. A positive impact on soil C stock due to the application of fertilizers was observed in the present study, where soil C stock increased over time. However, the composts used in the present study were made from different feedstocks, resulting in different nutrient release.

The results of our study indicate that application of balanced chemical and organic fertilizer could improve NUE and hence increase crop productivity. The adoption of such integrated fertilizer treatments, especially vermicompost with chemical fertilizer and *phumdi* compost with chemical fertilizer has emerged as a more substantial solution to mitigate the emissions of GHG from rice fields by maintaining the soil health.

Recommendation

Further study on microbial population due to the application of different composted material with or without chemical fertilizer is required to be investigated. Further research on vermicomposting of *phumdi* and evaluating its effect on grain yield and GHG emissions from paddy field may be carried out.

APPENDICES

Appendix 1: Plant height at 30DAT during the first year.

Control	MSWC	VC	PC	CF	MSWC+CF	VC+CF	PC+CF
72.0	71.5	70.0	69.5	69.3	65.5	70.0	82.0
69.0	69.0	66.8	63.0	68.0	64.7	69.0	68.0
68.6	68.8	64.8	62.3	66.0	64.0	68.5	67.0
67.0	67.8	63.7	62.0	64.3	63.6	68.0	66.0
67.0	67.6	63.5	62.0	64.2	63.0	67.0	65.7
66.6	67.6	63.1	61.0	61.0	62.0	66.0	65.5
65.0	67.5	62.9	61.0	57.9	61.3	65.8	65.4
65.0	66.5	62.0	58.1	57.0	60.5	64.0	65.1
65.0	66.0	62.0	58.0	57.0	58.6	63.0	65.0
64.7	66.0	61.5	57.5	55.0	58.5	63.0	65.0
64.0	65.5	61.0	56.3	55.0	57.6	63.0	65.0
64.0	65.0	61.0	56.0	53.8	57.0	63.0	65.0
64.0	64.0	59.0	55.5	53.1	56.1	62.1	63.0
63.4	63.8	58.8	55.0	52.5	54.9	62.0	62.4
63.0	63.0	57.0	54.0	45.0	53.2	61.0	62.0
63.0	62.4	54.0	53.0	44.0	53.0	61.0	61.0
62.4	62.3	51.3	51.0	66.6	52.5	61.0	60.4
60.0	62.0	53.8	46.8	64.0	52.0	61.0	60.0
60.0	62.0	53.3	46.0	62.8	51.9	60.8	60.0
59.5	62.0	53.0	43.0	62.0	51.8	60.0	59.0
58.0	62.0	52.8	42.0	61.5	50.4	59.9	59.0
58.0	61.0	51.9	62.0	61.1	50.0	59.0	58.8
58.0	61.0	51.0	56.8	60.4	48.0	58.0	58.5
58.0	60.2	50.6	55.5	60.0	45.5	58.0	58.0
57.0	59.0	49.0	55.0	57.0	64.5	57.9	57.5
56.6	59.0	48.6	53.0	57.0	56.5	56.7	56.6
55.6	58.3	57.0	52.5	56.5	56.5	56.0	55.3
51.0	56.5	56.5	48.9	56.0	56.0	53.0	55.0
48.0	42.0	56.0	48.7	47.0	43.0	52.0	52.0
44.0	54.0	60.0	44.0	51.0	47.5	43.0	50.0

Appendix 2: Plant height at 60DAT during the first year.

Control	MSWC	VC	PC	CF	MSWC+CF	VC+CF	PC+CF
101.0	95.5	95.0	98.0	101.0	87.0	101.0	103.0
99.0	90.0	89.0	97.0	96.0	84.9	96.0	103.0
93.0	90.0	89.8	93.0	91.0	81.0	91.0	101.0
90.0	83.4	87.9	90.0	88.9	80.0	89.3	96.0
87.0	83.1	84.4	87.0	84.0	80.0	89.0	92.0
86.0	82.5	84.7	85.8	83.5	79.0	85.0	92.0
85.0	82.3	84.7	81.0	82.5	78.0	86.0	95.0
83.0	79.0	79.6	79.2	78.7	78.0	77.0	89.0
80.0	77.5	74.0	79.0	77.0	77.6	77.0	90.0
78.0	76.0	72.0	74.0	71.0	73.0	75.0	90.0
99.9	105.0	99.0	97.0	95.0	101.0	91.0	89.0
98.2	99.0	98.0	94.0	88.0	86.2	83.0	85.0
90.5	97.3	95.0	84.0	88.0	84.0	82.0	81.0
88.0	94.5	95.0	84.0	86.0	77.0	81.0	80.5
86.0	90.3	94.0	83.0	84.0	76.7	78.0	80.1
83.4	90.0	83.0	83.0	84.0	75.0	77.7	77.0
82.6	89.5	81.0	80.0	80.0	75.0	77.0	83.0
80.0	87.0	81.0	79.6	77.0	74.0	75.0	72.0
79.8	82.3	78.0	79.0	77.0	72.0	74.0	80.5
74.0	75.0	73.0	69.0	72.0	63.0	74.0	72.0
104.0	102.0	103.0	92.0	96.0	100.0	108.0	113.0
103.0	100.0	101.0	92.0	93.0	89.0	107.0	110.0
102.0	100.0	93.0	91.0	91.0	88.0	105.0	105.0
100.2	100.0	92.5	86.0	91.0	86.0	100.1	100.0
98.5	96.0	89.9	86.0	88.0	86.0	100.0	99.4
97.0	90.5	86.0	83.5	86.0	84.0	100.0	98.7
97.0	87.7	85.5	81.0	80.9	84.6	95.0	98.2
88.0	87.0	85.0	80.0	80.0	83.0	97.0	98.2
91.0	86.0	85.0	77.0	79.3	73.0	91.0	96.4

Appendix 3: Plant height at 90DAT during the first year.

Control	MSWC	VC	PC	CF	MSWC+CF	VC+CF	PC+CF
93.3	90.4	81.3	87.0	86.7	81.5	76.0	98.0
88.0	89.0	79.0	86.0	86.0	79.0	85.0	96.0
87.9	86.3	79.0	85.0	82.0	78.0	93.0	94.0
86.0	85.9	76.9	84.0	81.0	73.0	83.0	91.0
84.0	85.5	74.0	80.0	80.0	71.0	75.0	90.0
83.5	84.0	74.0	78.3	77.0	69.0	79.9	90.0
83.0	82.4	73.0	74.3	74.0	67.0	86.0	89.2
82.0	82.0	73.0	73.5	71.0	66.6	87.0	88.5
79.0	81.5	67.0	73.0	71.0	66.1	79.0	88.0
74.0	67.0	66.0	68.0	65.0	64.0	70.0	87.0
92.0	97.0	92.0	92.0	90.2	98.0	86.1	82.0
89.0	97.0	91.0	84.0	87.0	80.0	73.5	79.0
87.0	88.6	87.0	83.0	86.4	79.2	86.0	74.3
85.0	87.5	87.0	82.0	85.3	74.0	75.0	78.8
84.0	87.0	81.5	77.5	78.0	72.0	88.0	72.0
83.0	86.0	79.6	74.0	77.9	71.2	68.5	67.0
81.5	86.0	78.2	74.0	75.0	71.0	92.0	79.0
75.0	85.5	78.0	68.0	73.2	68.4	69.0	68.0
77.6	75.0	71.5	68.0	70.0	68.0	85.0	73.3
65.0	73.0	70.5	63.0	65.8	60.0	68.0	68.1
99.0	97.0	100.0	92.0	88.0	92.0	105.0	103.0
102.0	96.8	92.0	89.0	87.0	87.0	98.0	102.0
100.0	94.5	87.3	88.0	85.5	84.2	103.0	98.0
98.6	90.2	85.0	83.0	84.1	83.1	84.0	97.9
97.0	90.0	82.1	80.0	82.0	80.0	90.0	97.0
94.3	88.7	82.0	76.0	81.0	79.8	101.0	93.0
89.0	87.0	79.5	73.0	79.0	73.3	96.0	94.5
70.0	86.0	79.0	70.4	77.3	70.0	94.0	94.4
84.5	85.0	79.0	70.0	72.0	65.0	98.8	93.2
69.0	73.0	78.6	66.8	68.0	61.0	95.0	93.0

Appendix 4: Plant height at 30DAT during the second year.

Control	MSWC	VC	PC	CF	MSWC+CF	VC+CF	PC+CF
66.3	57.0	55.4	62.0	67.0	68.0	67.7	65.4
64.5	56.8	54.8	58.0	65.5	66.5	66.8	65.2
63.0	56.7	53.8	57.2	61.0	63.0	64.6	63.2
59.0	56.7	53.5	54.8	60.8	61.0	64.3	62.6
58.0	56.4	53.2	53.8	60.7	60.0	62.7	53.3
57.3	54.6	52.2	53.5	60.0	60.0	61.8	61.5
57.2	53.2	51.8	45.0	57.9	59.6	60.6	61.2
57.2	52.9	51.5	51.6	57.2	57.8	58.7	61.0
57.0	52.5	49.0	50.6	54.5	56.6	57.8	59.5
56.5	45.5	47.0	50.5	52.0	55.8	57.6	58.9
67.0	62.0	60.8	64.3	68.0	60.0	72.0	75.0
65.4	62.0	58.0	58.6	66.8	59.0	69.0	74.5
60.0	57.8	54.2	57.5	65.2	58.8	65.4	66.0
60.0	56.2	54.0	54.5	65.2	58.0	64.5	65.5
54.0	54.0	53.3	53.5	62.1	57.0	61.0	65.0
54.0	53.5	53.0	50.3	55.4	56.8	50.0	63.8
51.5	52.4	52.3	49.5	54.3	53.8	59.0	62.3
49.0	52.0	52.0	49.0	51.0	52.6	58.0	60.5
48.3	51.0	50.0	47.5	49.5	50.0	57.5	57.8
47.0	50.6	43.0	37.0	48.5	48.5	55.2	54.7
72.0	65.4	65.0	78.4	70.2	71.5	76.4	78.4
65.0	62.4	64.3	71.0	68.0	69.9	73.4	77.0
60.0	61.0	62.0	69.8	66.8	67.1	68.0	70.0
58.0	60.0	61.7	63.5	65.6	66.8	67.3	67.7
57.0	59.5	61.0	58.6	65.0	66.1	66.0	67.5
56.2	57.8	60.0	56.5	60.0	65.0	61.7	67.0
54.6	57.5	60.0	56.4	59.6	59.6	61.6	66.7
44.8	56.7	55.9	54.3	58.4	59.4	61.0	65.0
43.0	56.0	55.6	52.3	58.0	56.3	54.8	62.6
42.0	49.0	55.5	45.7	41.5	52.0	51.7	57.5

Appendix 5: Plant height at 600DAT during the first year.

Control	MSWC	VC	PC	CF	MSWC+CF	VC+CF	PC+CF
102.0	110.0	113.0	73.0	82.3	74.5	105.0	112.0
97.8	104.0	100.2	75.4	85.5	84.0	103.0	107.0
96.3	98.0	98.0	86.0	85.5	84.7	100.0	105.0
94.0	104.0	97.8	86.6	87.0	86.4	102.0	105.0
93.0	96.6	97.0	90.0	88.4	87.0	100.0	103.0
92.3	96.0	95.6	92.3	93.0	95.0	98.2	102.0
92.0	92.7	93.8	92.8	93.5	95.5	96.0	98.0
91.0	92.5	91.0	94.0	98.0	95.5	96.0	98.9
94.8	92.0	90.5	86.3	89.2	87.8	98.0	98.8
87.0	92.0	90.0	72.0	80.0	78.6	95.0	98.5
87.0	91.0	90.0	78.0	81.0	78.8	94.5	98.2
86.2	91.0	88.3	79.0	82.1	79.3	90.0	98.0
86.2	90.5	87.2	82.3	87.5	80.0	92.5	97.0
85.0	88.8	87.2	87.0	88.0	82.0	92.3	94.0
84.7	88.7	87.0	87.4	88.2	87.3	92.0	94.4
84.5	90.8	86.3	87.6	92.9	88.5	89.7	96.0
84.0	85.0	86.0	88.4	104.0	97.5	89.7	95.6
85.6	84.5	85.0	82.7	88.0	84.0	88.0	95.0
83.5	84.0	85.0	70.0	77.8	74.5	88.7	93.0
85.0	83.7	85.0	75.3	83.5	74.7	87.7	93.0
79.8	83.7	82.1	78.8	86.0	77.0	87.0	90.0
79.7	83.5	84.0	96.0	91.5	78.0	86.7	81.0
79.6	85.5	80.0	102.0	102.0	87.0	89.2	92.0
78.8	81.0	80.5	102.0	104.0	89.0	85.5	91.0
78.0	80.3	80.5	87.4	90.8	92.1	85.0	90.1
78.0	80.3	77.0	92.0	106.0	92.4	81.0	89.3
73.0	78.2	76.8	87.0	91.4	94.0	80.4	87.9
72.3	78.0	76.7	86.0	88.4	94.3	79.2	87.5
72.0	76.8	75.3	79.0	90.0	98.0	78.0	79.0
71.0	75.0	74.6	83.9	83.0	86.4	77.6	78.0

Appendix 6: Plant height at 90DAT during the second year.

Control	MSWC	VC	PC	CF	MSWC+CF	VC+CF	PC+CF
73.7	77.0	102.0	72.0	78.0	65.0	100.0	106.0
78.0	81.0	98.0	72.8	79.0	75.0	98.5	103.0
78.0	83.5	95.0	79.7	83.0	76.0	98.0	102.0
82.4	86.5	95.0	81.3	87.0	80.0	100.0	100.0
84.0	87.0	95.6	86.0	88.0	80.0	95.0	100.0
84.5	87.0	92.0	86.0	90.0	84.0	95.0	95.0
85.0	87.0	90.0	87.0	91.5	90.0	94.0	95.0
88.0	88.0	90.0	91.2	92.0	91.0	93.0	94.0
92.0	91.0	89.8	92.0	93.0	95.0	91.0	92.0
94.2	94.0	89.6	97.0	93.0	102.0	90.4	91.5
74.0	79.2	88.9	69.7	79.0	67.0	90.3	94.0
74.5	79.5	88.4	74.8	82.1	78.5	88.5	90.0
76.1	82.3	88.2	81.0	82.6	79.5	88.2	90.5
77.5	83.0	87.0	83.4	85.0	79.7	87.0	88.5
81.7	83.8	86.4	84.5	85.8	81.0	89.0	87.6
81.9	84.3	86.0	84.8	86.8	82.6	84.0	87.5
82.6	85.3	82.0	85.0	89.0	83.0	84.0	87.0
83.7	87.0	80.0	88.5	90.0	85.0	84.2	85.4
84.9	87.9	84.8	91.5	90.8	88.8	83.0	87.0
90.4	90.6	83.9	98.0	95.3	91.0	82.0	85.0
67.3	84.0	85.0	72.0	78.0	71.0	81.9	85.0
76.4	90.0	80.2	76.0	81.0	73.5	81.6	79.0
85.2	90.0	81.0	81.3	81.8	80.5	81.5	87.0
85.3	92.0	77.9	82.5	82.8	81.7	81.3	86.0
85.8	92.5	77.4	85.0	87.0	84.0	83.0	81.0
86.5	97.0	78.0	86.0	90.0	84.6	79.0	79.4
87.0	97.4	74.8	86.7	90.5	85.3	78.8	81.0
91.4	101.0	69.8	91.0	90.6	85.9	77.8	82.0
96.0	93.0	68.5	92.0	93.0	86.0	76.5	74.7
102.0	89.0	67.3	94.0	99.8	90.0	75.5	74.0

Appendix 7: Tiller number per plant during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	4.01±1.32	4.29±1.34	3.69±1.28	5.23±1.57	5.27±1.54	4.85±1.56
MSWC	4.58±1.36	4.38±1.35	4.88±1.34	4.86±1.40	4.87±1.41	5.2±1.42
VC	3.91±1.25	4.46±1.26	4.29±1.25	4.43±1.16	4.54±1.20	5.0±1.19
PC	4.27±1.24	3.85±1.19	4.23±1.21	4.78±1.36	4.31±1.34	4.38±1.31
CF	4.57±1.32	4.81±1.35	4.61±1.32	5.28±1.33	4.81±1.36	4.94±1.40
MSWC+CF	3.99±1.22	4.33±1.21	4.45±1.24	4.67±1.29	4.64±1.36	4.46±1.30
VC+CF	4.35±1.61	4.28±1.66	4.83±1.68	4.53±1.32	4.49±1.29	5.0±1.32
PC+CF	4.62±1.40	5.00±1.42	5.08±1.45	4.96±1.68	5.31±1.67	5.21±1.61

Appendix 8: Effective tillering per plant during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	3.84±1.24	4.39±1.60	3.66±1.18	4.71±1.32	5.13±1.26	4.40±1.31
MSWC	4.44±1.40	4.26±1.42	4.63±1.46	4.55±1.43	4.48±1.44	5.10±1.53
VC	3.62±1.50	4.27±1.45	4.36±1.41	4.00±1.66	4.24±1.59	4.6±1.64
PC	4.17±1.52	3.67±1.54	4.1±1.57	4.66±1.42	4.32±1.44	4.18±1.42
CF	4.33±1.41	4.75±1.44	4.39±1.39	5.00±1.77	4.36±1.72	4.10±1.63
MSWC+CF	3.12±1.27	3.57±1.37	3.78±1.32	4.52±1.45	4.45±1.41	3.93±1.47
VC+CF	3.64±1.62	3.94±1.66	4.68±1.56	4.31±1.34	4.14±1.33	4.84±1.32
PC+CF	3.87±1.32	4.81±1.40	4.5±1.36	4.8±1.33	5.00±1.40	5.22±1.45

Appendix 9: Panicle length of rice during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	15.52±2.49	15.25±2.16	17.84±2.60	18.3±3.32	18.73±1.92	19.59±3.06
MSWC	17.52±2.26	17.88±2.47	16.71±2.53	18.81±1.88	19.74±2.42	19.38±2.80
VC	19.45±3.00	16.7±2.56	17.02±2.53	17.47±3.02	18.2±2.19	17.66±3.55
PC	16.14±1.87	16.89±2.12	16.69±1.89	19.38±2.75	19.33±1.48	19.21±2.71
CF	16.63±2.49	16.81±2.64	17.28±2.81	19.5±2.28	18.48±2.43	18.56±2.37
MSWC+CF	16.55±2.10	18.26±2.18	19.49±2.40	20.22±1.95	20.07±2.47	18.74±2.10
VC+CF	17.98±2.34	17.01±2.10	19.29±2.64	19.44±2.69	18.52±2.32	19.32±2.45
PC+CF	19.94±3.10	17.93±2.87	17.42±2.68	20.22±2.88	21.06±2.19	21.17±2.25

Appendix 10: Spikelets number per panicle during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	84.06±25.74	85.88±23.63	75.07±24.11	97.61±40.69	102.76±35.45	87.86±41.24
MSWC	93.39±32.85	85.68±30.12	89.62±31.35	102.54±36.54	120±40.69	105.24±26.04
VC	81.65±27.06	86.34±28.61	90.74±31.44	107.89±35.16	106.78±32.98	119.45±40.45
PC	78.75±24.58	71.5±22.70	79.37±21.74	100.3±39.09	109.24±26.40	97.59±33.90
CF	83.03±24.03	77.81±26.57	74.90±24.25	116.21±336.91	114.47±41.20	100.09±37.12
MSWC+CF	80.91±27.21	88.76±35.21	83.13±27.07	123.26±23.27	105.7±28.40	108.85±25.83

VC+CF	94.17±27.60	105.28±26.16	98.26±27.05	119.47±37.18	105.35±29.29	109.67±28.48
PC+CF	99.92±38.49	102.53±29.82	95.92±37.17	125.57±47.29	138.78±43.81	141.83±35.75

Appendix 11: Filled spikelets per panicle during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	62.62±22.68	64.39±24.47	58.75±27.58	88.81±36.76	93.73±23.68	81.06±23.75
MSWC	80.78±28.72	74.07±27.40	76.62±29.83	89.5±17.62	113.16±30.72	94.55±33.73
VC	65.44±21.50	74.25±25.45	76.81±25.01	91.77±35.63	85.11±38.63	97.63±27.25
PC	69.72±23.91	62.66±18.62	67.34±20.43	85.23±28.84	101.14±21.08	89.17±28.35
CF	68.97±22.32	73.54±25.69	71.34±21.71	99.2±31.05	104.45±36.23	88.3±281.14
MSWC+CF	73.45±32.91	78.63±33.03	74.52±32.14	114.47±22.12	90.33±25.42	95.8±23.70
VC+CF	74.83±26.86	86.92±31.56	80.7±29.92	108.00±30.49	91.33±27.18	99.75±28.14
PC+CF	83.76±32.71	84.70±35.91	78.04±31.53	114.42±40.85	125.44±37.54	131.66±30.73

Appendix 12: Unfilled spikelets per panicle during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	22.4±13.79	18.8±13.01	19.9±15.31	17.4±12.21	16.3±9.78	20.5±18.04
MSWC	12.6±7.31	11.6±7.48	13.7±10.08	9.3±8.40	13.3±10.93	8.3±5.62
VC	10.6±7.35	15.1±6.43	16.9±8.26	8.1±5.35	11.3±9.28	5.5±4.67

PC	9.0±6.24	8.8±5.48	12.0±9.74	15.1±12.38	9.0±7.64	8.2±6.32
CF	11.1±9.10	4.7±3.13	8.1±5.46	16.6±12.92	9.2±6.25	13.8±9.15
MSWC+CF	7.1±3.87	10.4±4.68	8.7±6.18	14.2±9.12	13.2±10.47	10.2±9.14
VC+CF	19.2±8.06	22.3±10.31	15.1±12.05	8.2±4.96	18.5±13.19	10.7±6.08
PC+CF	16.2±10.66	18.2±12.46	17.9±12.87	14.7±11.22	10.1±6.18	10.2±8.32

Appendix 13: Percentage of filled spikelets per panicle during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	75.12±11.59	79.17±12.05	72.22±25.06	84.95±14.43	82.00±10.58	82.53±21.16
MSWC	86.42±6.74	84.82±8.05	84.68±11.32	90.90±6.07	90.48±7.44	91.35±5.06
VC	84.99±13.76	86.96±12.49	79.55±9.51	90.76±6.99	90.13±10.05	93.42±6.57
PC	87.98±8.35	89.12±11.73	84.72±10.97	87.01±9.20	92.14±5.87	94.21±4.81
CF	86.24±16.00	93.68±4.97	89.76±5.35	88.07±10.62	93.44±4.17	90.64±7.79
MSWC+CF	92.51±4.24	89.79±14.53	87.81±14.97	89.57±8.11	86.54±6.93	89.64±8.133
VC+CF	88.61±16.57	75.72±11.66	84.83±17.26	92.2±4.25	87.14±15.13	92.78±9.94
PC+CF	84.47±7.45	82.01±11.35	81.92±12.40	85.91±12.59	89.51±5.21	93.34±4.40

Appendix 14: 1000-grain weight during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	33.88	32.2	32.9	35.31	34.12	34.58
MSWC	33.58	34.49	35.52	34.13	34.76	35.35
VC	34.25	33.39	33.9	33.46	33.67	34.42
PC	34.03	33.91	34.19	33.51	34.05	35.13
CF	34.11	34.26	33.86	35.8	33.66	34.38
MSWC+CF	34.18	34.19	34.22	35.17	35.71	35.86
VC+CF	34.67	34.92	35.08	35.05	34.65	35.8
PC+CF	34.47	34.85	34.23	35.67	36.85	36.09

Appendix 15: Grain yield of rice during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	3.35	3.61	2.57	3.98	3.99	3.14
MSWC	4.07	4.08	4.48	4.89	5.82	4.92
VC	3.76	3.73	3.94	4.89	4.76	5.29
PC	4.24	3.63	4.07	4.72	5.19	5.08
CF	3.92	4.59	3.92	5.71	6.08	4.79
MSWC+CF	4.36	4.72	4.52	6.09	5.41	5.66
VC+CF	4.54	4.79	5.19	6.12	5.09	6.91
PC+CF	5.53	5.3	5.29	7.28	6.64	8.69

Appendix 16: Straw yield of rice during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	6.58	6.13	5.18	6.88	6.9	6.04
MSWC	5.7	5.33	5.51	5.9	6.5	5.62
VC	4.6	5	4.7	5.77	5.7	6.58
PC	4.88	4.29	4.53	5.68	5.71	5.39
CF	4.7	4.95	4.7	6.65	6.65	5.5
MSWC+CF	4.8	5.1	4.66	6.66	5.72	5.85
VC+CF	5.14	5.76	6.23	7.02	6.03	7.25
PC+CF	5.63	6.53	5.7	7.83	7.21	9

Appendix 17: HI of rice during the two years of study.

	2022			2023		
Treatments	R1	R2	R3	R1	R2	R3
Control	0.331	0.371	0.340	0.366	0.366	0.342
MSWC	0.417	0.434	0.448	0.453	0.472	0.467
VC	0.450	0.427	0.456	0.459	0.455	0.446
PC	0.465	0.458	0.473	0.454	0.476	0.485
CF	0.455	0.481	0.455	0.462	0.478	0.466
MSWC+CF	0.476	0.481	0.492	0.478	0.486	0.492
VC+CF	0.469	0.454	0.454	0.466	0.484	0.468
PC+CF	0.496	0.448	0.481	0.482	0.479	0.491

Appendix 18: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the control treatment plots during the two years of study.

Control												
CH ₄ flux (mg m ⁻² h ⁻¹)							N ₂ O (mg m ⁻² d ⁻¹)					
DAT	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	0.35	0.42	0.32	0.45	0.45	0.52	0.105	0.111	0.118	0.145	0.162	0.149
7	0.47	0.58	0.56	4.52	4.33	4.16	0.138	0.165	0.158	0.156	0.166	0.172
14	3.42	2.51	2.44	6.41	5.86	6.71	0.113	0.133	0.151	0.147	0.159	0.178
21	3.27	2.84	1.81	6.72	6.68	5.68	0.177	0.163	0.166	0.201	0.207	0.209
28	4.96	4.62	4.97	3.39	4.56	3.81	0.219	0.216	0.209	0.267	0.216	0.249
35	1.57	1.80	1.55	7.84	6.68	7.31	0.128	0.143	0.125	0.117	0.103	0.103
42	6.85	7.63	8.73	7.47	7.30	7.19	0.059	0.063	0.061	0.036	0.053	0.047
49	4.85	4.36	4.38	6.57	6.89	6.75	0.095	0.084	0.093	0.054	0.073	0.055
56	2.67	3.63	2.52	5.96	5.80	5.45	0.079	0.064	0.066	0.040	0.042	0.048
63	2.41	2.79	3.08	3.57	3.68	3.66	0.078	0.057	0.056	0.053	0.060	0.061
70	2.57	2.81	2.66	2.42	2.24	2.50	0.033	0.046	0.033	0.068	0.058	0.061
77	1.36	1.74	1.59	1.02	1.20	0.96	0.089	0.099	0.082	0.062	0.062	0.082
84	1.57	0.88	0.75	1.78	1.47	1.55	0.113	0.097	0.098	0.109	0.109	0.086
91	0.24	0.38	0.39	0.58	0.64	0.69	0.106	0.093	0.087	0.103	0.113	0.113
98	0.31	0.27	0.37	0.44	0.43	0.37	0.057	0.087	0.051	0.081	0.082	0.076

Appendix 19: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the MSWC treatment plots during the two years of study.

MSWC												
DAT	CH ₄ (mg m ⁻² h ⁻¹)						N ₂ O (mg m ⁻² d ⁻¹)					
	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	0.65	0.71	0.69	0.37	0.31	0.38	0.191	0.214	0.221	0.173	0.178	0.171
7	3.45	2.64	2.46	5.34	9.01	11.00	0.228	0.230	0.252	0.181	0.157	0.179
14	2.94	3.54	3.65	7.58	8.73	9.84	0.177	0.157	0.151	0.179	0.163	0.180
21	8.12	7.06	7.59	13.65	12.40	13.07	0.390	0.348	0.348	0.408	0.425	0.430
28	5.48	4.99	3.52	8.28	6.23	7.13	0.591	0.622	0.562	0.561	0.615	0.586
35	5.95	5.77	5.83	8.24	12.52	14.75	0.382	0.428	0.431	0.418	0.404	0.409
42	7.65	11.26	9.79	13.79	12.90	13.50	0.185	0.196	0.182	0.129	0.128	0.153
49	14.62	15.26	13.26	15.92	16.52	13.90	0.146	0.183	0.160	0.101	0.091	0.110
56	17.42	21.24	17.01	16.86	18.01	16.16	0.190	0.166	0.209	0.210	0.156	0.243
63	11.60	8.71	10.12	17.44	14.06	15.95	0.113	0.091	0.097	0.135	0.147	0.153
70	4.43	4.84	5.52	9.43	8.88	8.96	0.132	0.116	0.130	0.108	0.093	0.097
77	3.72	3.35	3.01	4.82	6.72	6.01	0.126	0.110	0.096	0.082	0.078	0.079
84	2.45	1.45	1.97	3.75	4.35	3.55	0.141	0.144	0.131	0.113	0.088	0.080
91	0.62	1.14	0.54	2.13	2.67	3.68	0.098	0.091	0.086	0.090	0.088	0.085
98	0.53	0.97	0.66	0.86	0.56	0.41	0.063	0.076	0.074	0.083	0.074	0.075

Appendix 20: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the VC treatment plots during the two years of study.

VC												
DAT	CH ₄ (mg m ⁻² h ⁻¹)						N ₂ O (mg m ⁻² d ⁻¹)					
	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	3.28	0.92	1.55	0.26	0.17	0.27	0.127	0.151	0.147	0.092	0.085	0.061
7	3.58	3.01	3.06	2.47	2.96	1.30	0.109	0.073	0.068	0.065	0.071	0.060
14	5.86	5.26	6.80	4.28	3.26	2.01	0.163	0.114	0.152	0.126	0.115	0.128
21	6.82	3.44	4.75	6.84	6.43	6.55	0.262	0.321	0.309	0.193	0.232	0.239
28	11.50	6.60	7.13	3.85	3.47	3.68	0.427	0.442	0.405	0.520	0.485	0.484
35	3.36	5.75	4.36	5.92	4.92	5.99	0.253	0.296	0.245	0.345	0.390	0.349
42	7.57	8.67	8.49	13.82	8.75	9.05	0.193	0.181	0.179	0.203	0.200	0.230
49	11.63	10.43	10.58	7.85	8.04	7.18	0.103	0.084	0.083	0.103	0.111	0.112
56	7.97	7.43	7.04	3.75	2.85	2.99	0.112	0.124	0.112	0.211	0.224	0.234
63	6.66	5.30	7.84	4.62	5.19	5.10	0.154	0.141	0.155	0.132	0.140	0.140
70	1.60	2.69	3.44	3.18	4.64	3.40	0.060	0.051	0.054	0.163	0.160	0.161
77	0.68	2.06	2.18	3.80	2.58	3.13	0.115	0.120	0.149	0.143	0.143	0.129
84	0.15	0.12	0.10	6.15	3.37	4.00	0.070	0.085	0.084	0.090	0.095	0.086
91	0.07	0.49	0.09	1.97	1.04	0.86	0.080	0.067	0.081	0.088	0.092	0.077
98	0.09	0.06	0.48	0.57	0.90	0.62	0.062	0.099	0.030	0.069	0.054	0.091

Appendix 21: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the PC treatment plots during the two years of study.

PC												
DAT	CH ₄ (mg m ⁻² h ⁻¹)						N ₂ O (mg m ⁻² d ⁻¹)					
	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	0.38	0.65	0.92	2.07	0.97	0.98	0.176	0.157	0.159	0.129	0.110	0.135
7	3.74	1.64	2.63	3.40	2.79	2.89	0.168	0.187	0.186	0.128	0.128	0.111
14	7.10	5.07	3.52	4.75	3.96	4.18	0.123	0.117	0.123	0.146	0.114	0.129
21	10.73	6.90	5.97	6.84	8.99	8.42	0.306	0.311	0.285	0.260	0.226	0.239
28	6.26	6.93	7.29	6.17	3.97	4.06	0.345	0.383	0.407	0.471	0.489	0.468
35	2.97	2.33	2.40	8.75	7.64	7.64	0.333	0.292	0.309	0.277	0.266	0.258
42	7.95	8.98	9.09	13.29	12.80	12.81	0.141	0.163	0.160	0.128	0.121	0.143
49	14.63	10.04	10.02	17.30	16.60	16.03	0.092	0.085	0.091	0.103	0.136	0.112
56	13.85	12.25	12.96	16.97	14.86	14.46	0.119	0.116	0.113	0.154	0.158	0.161
63	8.73	9.37	8.60	13.65	12.52	12.44	0.059	0.060	0.066	0.053	0.062	0.077
70	3.85	1.02	1.20	6.70	8.51	7.47	0.074	0.089	0.107	0.058	0.052	0.055
77	2.56	1.53	2.15	4.79	3.59	3.99	0.066	0.068	0.064	0.019	0.019	0.022
84	0.55	0.86	1.25	1.58	2.31	2.02	0.058	0.069	0.066	0.041	0.035	0.041
91	0.85	0.75	0.95	2.02	1.29	1.21	0.053	0.048	0.057	0.064	0.052	0.059
98	0.28	0.42	0.73	0.78	0.81	1.25	0.050	0.051	0.048	0.063	0.051	0.065

Appendix 22: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the CF treatment plots during the two years of study.

CF												
DAT	CH ₄ (mg m ⁻² h ⁻¹)						N ₂ O (mg m ⁻² d ⁻¹)					
	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	0.86	1.20	1.06	0.17	0.22	0.22	0.209	0.200	0.221	0.129	0.110	0.135
7	1.55	1.99	1.94	4.73	3.17	3.83	0.207	0.183	0.205	0.128	0.128	0.111
14	2.63	1.64	1.46	6.93	6.01	6.40	0.125	0.130	0.111	0.146	0.114	0.129
21	3.19	2.54	2.60	11.77	8.81	8.99	0.368	0.378	0.401	0.260	0.226	0.239
28	2.23	1.87	2.48	6.62	5.13	4.36	0.652	0.580	0.580	0.471	0.489	0.468
35	6.85	3.59	7.30	13.83	8.74	8.78	0.421	0.454	0.459	0.277	0.266	0.258
42	5.89	5.24	5.86	16.11	14.74	15.09	0.380	0.409	0.389	0.128	0.121	0.143
49	9.49	5.32	7.17	11.78	10.40	9.51	0.149	0.181	0.169	0.103	0.136	0.112
56	14.32	9.79	13.55	7.54	8.88	8.53	0.188	0.149	0.148	0.154	0.158	0.161
63	9.52	8.51	10.05	5.80	4.89	4.77	0.188	0.168	0.153	0.053	0.062	0.077
70	7.31	3.03	2.06	4.32	3.33	3.52	0.120	0.131	0.142	0.058	0.052	0.055
77	2.46	2.79	2.18	4.86	5.72	4.50	0.092	0.060	0.118	0.019	0.019	0.022
84	3.23	1.05	0.65	3.87	6.40	4.73	0.103	0.116	0.111	0.041	0.035	0.041
91	0.44	0.90	0.76	2.18	2.85	3.74	0.074	0.092	0.119	0.064	0.052	0.059
98	0.55	0.94	0.58	0.64	0.68	0.97	0.152	0.126	0.143	0.063	0.051	0.065

Appendix 23: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the MSWC+CF treatment plots during the two years of study.

MSWC+CF												
DAT	CH ₄ (mg m ⁻² h ⁻¹)						N ₂ O (mg m ⁻² d ⁻¹)					
	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	0.79	0.89	1.11	3.29	2.13	2.02	0.119	0.128	0.133	0.078	0.069	0.067
7	2.07	0.84	0.93	5.34	4.64	5.26	0.164	0.138	0.154	0.102	0.099	0.098
14	2.96	2.30	2.51	3.72	2.68	2.69	0.080	0.103	0.087	0.066	0.065	0.077
21	7.15	4.08	5.00	6.75	5.68	5.11	0.303	0.292	0.309	0.318	0.311	0.312
28	7.62	7.12	6.74	4.56	5.31	3.28	0.370	0.361	0.331	0.486	0.480	0.491
35	5.30	3.76	5.54	6.82	4.34	4.98	0.151	0.164	0.151	0.163	0.164	0.159
42	6.27	4.78	4.18	8.99	7.18	7.69	0.165	0.167	0.188	0.113	0.117	0.121
49	11.89	12.38	11.84	8.42	8.89	9.28	0.114	0.096	0.096	0.076	0.090	0.087
56	12.84	9.97	11.37	5.76	3.02	2.37	0.072	0.048	0.027	0.126	0.089	0.102
63	7.41	9.65	8.93	3.62	2.75	2.86	0.092	0.094	0.071	0.056	0.062	0.071
70	2.84	3.67	3.17	3.45	4.27	4.32	0.113	0.079	0.086	0.041	0.034	0.032
77	2.50	1.95	2.42	2.04	2.64	3.83	0.052	0.040	0.036	0.043	0.037	0.035
84	1.03	1.37	1.44	5.73	7.86	3.54	0.080	0.092	0.077	0.041	0.046	0.042
91	0.65	0.39	0.23	1.42	2.07	1.04	0.030	0.026	0.022	0.085	0.078	0.075
98	0.08	0.32	0.37	0.47	0.68	0.79	0.054	0.071	0.066	0.064	0.067	0.071

Appendix 24: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the VC+CF treatment plots during the two years of study.

VC+CF												
DAT	CH ₄ (mg m ⁻² h ⁻¹)						N ₂ O (mg m ⁻² d ⁻¹)					
	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	2.46	3.66	2.32	0.15	0.17	0.26	0.089	0.114	0.099	0.129	0.123	0.124
7	4.66	2.30	2.54	3.63	2.61	2.47	0.094	0.117	0.139	0.151	0.126	0.127
14	2.59	2.85	2.79	4.30	3.89	4.52	0.108	0.087	0.101	0.085	0.062	0.085
21	7.31	2.50	4.49	6.67	5.82	6.16	0.213	0.197	0.200	0.330	0.320	0.330
28	5.34	8.39	12.40	1.74	2.57	1.42	0.378	0.420	0.400	0.526	0.506	0.555
35	5.36	2.49	3.15	2.54	2.00	1.51	0.338	0.333	0.342	0.201	0.215	0.231
42	10.87	9.42	8.34	2.75	5.39	2.35	0.202	0.215	0.191	0.034	0.040	0.037
49	6.19	4.23	5.09	6.99	8.52	8.06	0.090	0.065	0.065	0.081	0.087	0.079
56	8.13	6.93	6.18	4.79	5.62	5.09	0.096	0.057	0.063	0.057	0.052	0.052
63	8.56	3.06	2.68	2.51	3.43	2.87	0.067	0.055	0.053	0.058	0.068	0.070
70	3.10	1.97	2.24	1.72	0.83	0.61	0.078	0.104	0.096	0.081	0.133	0.085
77	1.29	1.67	1.72	1.54	2.12	1.29	0.129	0.113	0.111	0.088	0.074	0.087
84	0.39	0.42	0.53	0.23	0.37	0.52	0.059	0.066	0.068	0.093	0.086	0.101
91	0.29	0.39	0.36	0.34	0.27	0.36	0.078	0.062	0.055	0.100	0.091	0.098
98	0.52	0.14	0.33	0.13	0.12	0.18	0.081	0.076	0.067	0.070	0.066	0.079

Appendix 25: CH₄ flux (mg m⁻² h⁻¹) and N₂O (mg m⁻² d⁻¹) from the PC+CF treatment plots during the two years of study.

PC+CF												
DAT	CH ₄ (mg m ⁻² h ⁻¹)						N ₂ O (mg m ⁻² d ⁻¹)					
	2022			2023			2022			2023		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
0	0.59	1.61	0.96	0.71	0.54	0.54	0.118	0.138	0.151	0.078	0.091	0.086
7	1.78	1.48	1.58	3.18	2.55	2.30	0.110	0.118	0.113	0.125	0.140	0.135
14	2.65	2.15	1.92	3.56	2.93	2.99	0.143	0.168	0.166	0.063	0.060	0.069
21	4.52	2.32	2.31	8.79	6.46	6.04	0.293	0.289	0.272	0.201	0.223	0.221
28	7.44	6.01	5.93	4.62	5.21	4.23	0.477	0.493	0.525	0.558	0.615	0.576
35	6.98	6.33	6.72	3.75	6.64	7.11	0.334	0.299	0.328	0.223	0.236	0.229
42	8.09	8.64	8.70	13.41	11.53	11.51	0.129	0.142	0.127	0.180	0.189	0.191
49	15.42	10.58	11.50	4.72	6.27	7.00	0.089	0.113	0.102	0.149	0.161	0.128
56	12.86	14.98	13.88	5.47	4.09	4.76	0.093	0.085	0.102	0.113	0.099	0.098
63	6.53	9.78	10.00	2.39	1.85	2.19	0.070	0.064	0.065	0.085	0.066	0.060
70	2.42	2.76	3.02	1.58	1.26	1.45	0.079	0.090	0.095	0.114	0.124	0.108
77	1.68	2.27	1.33	3.84	2.98	2.66	0.034	0.044	0.044	0.113	0.100	0.107
84	0.29	0.47	0.50	3.78	5.85	5.21	0.061	0.066	0.069	0.138	0.131	0.143
91	0.17	0.36	0.17	3.43	2.66	2.29	0.116	0.102	0.132	0.056	0.057	0.069
98	0.56	0.15	0.42	0.59	0.32	0.43	0.118	0.138	0.151	0.053	0.052	0.059

Appendix 26: CO₂ (g m⁻² d⁻¹) from the control treatment plots during the two years of study.

	Control					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.126	0.135	0.132	0.122	0.117	0.108
7	0.096	0.091	0.106	0.130	0.141	0.147
14	0.124	0.119	0.128	0.152	0.138	0.148
21	0.155	0.158	0.159	0.174	0.178	0.168
28	0.170	0.177	0.166	0.151	0.150	0.158
35	0.188	0.203	0.196	0.218	0.221	0.216
42	0.243	0.238	0.234	0.261	0.252	0.248
49	0.216	0.212	0.227	0.286	0.282	0.292
56	0.187	0.197	0.205	0.239	0.234	0.236
63	0.142	0.135	0.148	0.187	0.192	0.191
70	0.118	0.129	0.131	0.147	0.155	0.160
77	0.124	0.117	0.113	0.149	0.138	0.142
84	0.106	0.114	0.112	0.124	0.130	0.131
91	0.092	0.096	0.086	0.118	0.113	0.119
98	0.096	0.091	0.095	0.108	0.103	0.097

Appendix 27: CO₂ (g m⁻² d⁻¹) from the MSWC treatment plots during the two years of study.

	MSWC					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.127	0.124	0.125	0.185	0.188	0.190
7	0.176	0.182	0.164	0.210	0.213	0.206
14	0.227	0.234	0.219	0.271	0.269	0.263
21	0.242	0.250	0.259	0.301	0.308	0.311
28	0.301	0.310	0.304	0.372	0.359	0.368
35	0.328	0.336	0.324	0.429	0.433	0.437
42	0.371	0.396	0.385	0.477	0.486	0.492
49	0.342	0.329	0.338	0.552	0.541	0.559
56	0.356	0.342	0.339	0.468	0.458	0.465
63	0.305	0.313	0.304	0.315	0.307	0.312
70	0.239	0.230	0.245	0.267	0.273	0.278
77	0.230	0.217	0.240	0.186	0.190	0.193
84	0.157	0.171	0.161	0.160	0.164	0.157
91	0.138	0.126	0.143	0.137	0.138	0.143
98	0.121	0.128	0.136	0.129	0.121	0.124

Appendix 28: CO₂ (g m⁻² d⁻¹) from the VC treatment plots during the two years of study.

	VC					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.102	0.107	0.104	0.123	0.126	0.129
7	0.122	0.128	0.133	0.182	0.175	0.169
14	0.185	0.188	0.177	0.200	0.210	0.208
21	0.252	0.257	0.247	0.232	0.229	0.234
28	0.287	0.296	0.302	0.251	0.255	0.258
35	0.308	0.297	0.313	0.379	0.368	0.359
42	0.426	0.423	0.432	0.401	0.391	0.390
49	0.366	0.377	0.379	0.445	0.447	0.453
56	0.313	0.324	0.318	0.354	0.358	0.353
63	0.223	0.227	0.229	0.251	0.255	0.269
70	0.193	0.199	0.204	0.213	0.202	0.204
77	0.164	0.170	0.174	0.163	0.167	0.169
84	0.154	0.158	0.160	0.143	0.146	0.152
91	0.121	0.125	0.118	0.145	0.139	0.135
98	0.126	0.121	0.129	0.135	0.138	0.142

Appendix 29: CO₂ (g m⁻² d⁻¹) from the PC treatment plots during the two years of study.

	PC					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.158	0.155	0.163	0.152	0.155	0.158
7	0.153	0.149	0.163	0.174	0.183	0.178
14	0.181	0.187	0.196	0.251	0.245	0.247
21	0.279	0.274	0.282	0.315	0.325	0.309
28	0.325	0.330	0.330	0.379	0.380	0.390
35	0.364	0.369	0.374	0.438	0.427	0.431
42	0.447	0.449	0.441	0.472	0.482	0.477
49	0.381	0.386	0.378	0.441	0.430	0.443
56	0.310	0.304	0.315	0.339	0.328	0.349
63	0.270	0.278	0.287	0.256	0.269	0.261
70	0.231	0.237	0.228	0.252	0.263	0.246
77	0.192	0.199	0.201	0.172	0.186	0.190
84	0.147	0.154	0.146	0.148	0.136	0.144
91	0.138	0.132	0.142	0.124	0.127	0.129
98	0.116	0.120	0.122	0.126	0.121	0.130

Appendix 30: CO₂ (g m⁻² d⁻¹) from the CF treatment plots during the two years of study.

	CF					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.115	0.127	0.125	0.140	0.146	0.149
7	0.202	0.198	0.195	0.156	0.151	0.149
14	0.215	0.206	0.217	0.264	0.250	0.259
21	0.234	0.221	0.228	0.269	0.271	0.275
28	0.247	0.258	0.250	0.305	0.312	0.310
35	0.271	0.269	0.262	0.362	0.342	0.352
42	0.305	0.295	0.298	0.438	0.430	0.426
49	0.288	0.281	0.297	0.405	0.408	0.398
56	0.264	0.262	0.276	0.387	0.376	0.381
63	0.249	0.237	0.235	0.245	0.254	0.261
70	0.204	0.211	0.193	0.207	0.211	0.207
77	0.158	0.172	0.172	0.174	0.172	0.178
84	0.133	0.143	0.142	0.158	0.162	0.152
91	0.107	0.114	0.111	0.133	0.139	0.137
98	0.113	0.105	0.114	0.126	0.115	0.134

Appendix 31: CO₂ (g m⁻² d⁻¹) from the MSWC+CF treatment plots during the two years of study.

	MSWC+CF					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.144	0.155	0.150	0.122	0.125	0.133
7	0.164	0.159	0.158	0.143	0.155	0.149
14	0.197	0.204	0.192	0.208	0.200	0.213
21	0.201	0.211	0.224	0.244	0.242	0.248
28	0.245	0.236	0.241	0.272	0.261	0.267
35	0.262	0.269	0.273	0.350	0.343	0.343
42	0.326	0.307	0.315	0.373	0.384	0.391
49	0.284	0.294	0.304	0.450	0.432	0.438
56	0.236	0.234	0.239	0.369	0.371	0.374
63	0.188	0.193	0.211	0.261	0.266	0.256
70	0.189	0.197	0.201	0.212	0.214	0.217
77	0.178	0.163	0.171	0.166	0.159	0.169
84	0.108	0.105	0.113	0.153	0.149	0.152
91	0.104	0.097	0.099	0.140	0.136	0.143
98	0.095	0.100	0.098	0.126	0.125	0.129

Appendix 32: CO₂ (g m⁻² d⁻¹) from the VC+CF treatment plots during the two years of study.

	VC+CF					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.119	0.135	0.136	0.122	0.109	0.119
7	0.154	0.137	0.147	0.150	0.154	0.152
14	0.198	0.190	0.189	0.231	0.209	0.218
21	0.219	0.240	0.230	0.244	0.241	0.250
28	0.260	0.264	0.267	0.273	0.257	0.251
35	0.289	0.280	0.299	0.276	0.286	0.270
42	0.248	0.260	0.259	0.297	0.308	0.304
49	0.290	0.304	0.311	0.279	0.289	0.302
56	0.215	0.225	0.218	0.322	0.310	0.304
63	0.191	0.194	0.202	0.217	0.227	0.223
70	0.180	0.190	0.194	0.203	0.196	0.200
77	0.152	0.157	0.151	0.181	0.184	0.178
84	0.113	0.127	0.119	0.133	0.131	0.148
91	0.115	0.112	0.129	0.115	0.125	0.111
98	0.097	0.102	0.106	0.124	0.118	0.104

Appendix 33: CO₂ (g m⁻² d⁻¹) from the PC+CF treatment plots during the two years of study.

	PC+CF					
DAT	CO ₂ (g m ⁻² h ⁻¹)					
	2022			2023		
	R1	R2	R3	R1	R2	R3
0	0.143	0.114	0.111	0.126	0.130	0.137
7	0.186	0.175	0.180	0.194	0.180	0.187
14	0.187	0.188	0.193	0.202	0.209	0.194
21	0.222	0.206	0.204	0.214	0.220	0.220
28	0.280	0.274	0.282	0.240	0.233	0.244
35	0.298	0.303	0.288	0.246	0.255	0.250
42	0.332	0.326	0.321	0.362	0.360	0.350
49	0.290	0.293	0.292	0.318	0.324	0.310
56	0.248	0.258	0.258	0.322	0.303	0.299
63	0.204	0.216	0.210	0.268	0.276	0.272
70	0.199	0.194	0.197	0.220	0.215	0.230
77	0.187	0.179	0.196	0.191	0.200	0.202
84	0.133	0.127	0.128	0.149	0.157	0.158
91	0.123	0.132	0.124	0.123	0.135	0.132
98	0.111	0.110	0.116	0.121	0.112	0.110

Appendix 34: Variation in pH of soil at four different stages due to different treatments during the two years.

		pH							
Treatments		2022				2023			
		AT	PI	F	PH	AT	PI	F	PH
Control	R1	6.63	7.62	6.78	6.64	6.83	6.36	6.33	6.20
	R2	6.70	6.59	6.54	6.60	6.90	6.66	6.28	6.28
	R3	6.72	5.74	6.54	6.18	6.85	6.53	6.43	6.51
MSWC	R1	6.63	7.70	6.87	6.86	7.04	6.85	5.85	6.25
	R2	6.71	6.16	7.03	6.81	7.19	6.86	6.29	6.77
	R3	6.73	6.23	6.83	6.70	6.72	6.70	6.24	6.30
VC	R1	6.71	7.41	6.52	6.91	6.97	6.67	6.24	6.79
	R2	6.69	6.20	7.13	6.89	6.93	6.66	6.16	6.31
	R3	6.73	5.67	6.60	6.78	6.77	6.56	6.26	6.63
PC	R1	6.54	7.32	6.78	6.83	6.72	6.45	6.29	6.19
	R2	6.74	6.19	6.75	6.52	6.80	6.72	6.11	6.59
	R3	6.84	6.00	6.88	7.10	6.86	6.66	6.34	6.48
CF	R1	7.47	7.44	6.87	6.82	6.74	6.69	5.97	6.21
	R2	7.45	6.47	6.74	6.63	6.80	6.63	6.15	6.23
	R3	7.23	5.98	6.60	6.88	6.86	6.66	6.31	6.36
MSWC+CF	R1	6.71	7.12	6.73	6.92	6.70	6.95	6.10	6.05
	R2	6.78	6.07	6.96	6.88	6.97	6.86	6.27	6.04
	R3	6.54	6.33	6.96	6.77	6.89	6.99	6.56	6.56
VC+CF	R1	6.63	7.00	6.65	6.81	6.88	6.73	6.27	6.31
	R2	6.58	6.22	6.87	6.68	6.77	6.76	6.28	6.55
	R3	6.44	6.24	6.48	6.44	6.74	6.43	6.20	6.68
PC+CF	R1	6.48	6.77	6.70	6.56	6.68	6.66	6.28	6.55
	R2	6.62	5.81	6.62	6.77	6.82	6.75	6.16	6.34
	R3	6.51	6.31	6.83	6.13	6.71	6.61	6.15	6.33

Appendix 35: Variation in SOC of soil at four different stages due to different treatments during the two years.

Treatments		SOC (%)							
		2022				2023			
		AT	PI	F	PH	AT	PI	F	PH
Control	R1	0.73	0.63	0.61	0.65	0.65	0.63	0.74	0.87
	R2	0.83	0.68	0.60	0.61	0.52	0.58	0.73	0.98
	R3	0.70	0.65	0.58	0.58	0.73	0.64	0.85	0.92
MSWC	R1	0.98	0.82	0.66	0.68	1.42	1.45	1.47	1.28
	R2	1.16	0.78	0.62	0.72	1.58	1.56	1.33	1.15
	R3	1.11	0.77	0.60	0.69	1.35	1.64	1.17	1.42
VC	R1	0.67	0.73	0.73	0.68	1.37	1.61	1.12	1.04
	R2	0.65	0.82	0.71	0.70	1.48	1.43	1.24	0.98
	R3	0.68	0.78	0.69	0.71	1.55	1.49	1.01	1.22
PC	R1	0.76	0.73	0.74	0.64	1.39	1.45	1.48	1.23
	R2	0.74	0.71	0.73	0.70	1.51	1.58	1.52	0.89
	R3	0.68	0.79	0.75	0.66	1.46	1.32	1.70	1.31
CF	R1	0.76	0.64	0.61	0.67	1.35	1.59	1.27	1.14
	R2	0.72	0.60	0.67	0.64	1.29	1.43	1.53	1.36
	R3	0.77	0.76	0.64	0.65	1.40	1.47	1.13	1.35
MSWC+CF	R1	0.91	0.74	0.64	0.65	1.32	1.45	1.20	1.22
	R2	0.82	0.72	0.61	0.68	1.40	1.33	1.28	1.34
	R3	0.85	0.75	0.54	0.63	1.54	1.54	1.14	1.28
VC+CF	R1	0.75	0.64	0.69	0.70	1.26	1.35	1.45	1.20
	R2	0.67	0.71	0.66	0.80	1.17	1.33	1.19	1.10
	R3	0.75	0.77	0.73	0.76	0.97	1.38	1.38	0.99
PC+CF	R1	0.63	0.81	0.74	0.69	1.35	1.36	1.20	1.16
	R2	0.73	0.75	0.79	0.67	1.29	1.57	1.54	1.07
	R3	0.69	0.69	0.81	0.69	1.46	1.43	1.36	1.31

Appendix 36: Variation in total N of soil at four different stages of rice growth due to different treatments during the two years.

Treatments		Total N (kg ha ⁻¹)							
		2022				2023			
		AT	PI	F	PH	AT	PI	F	PH
Control	R1	1237.6	666.4	523.6	523.6	809.2	618.8	618.8	499.8
	R2	1332.8	714.0	618.8	428.4	761.6	714.0	666.4	523.6
	R3	1380.4	618.8	428.4	380.8	833.0	642.6	714.0	476.0
MSWC	R1	1523.2	1237.6	714.0	856.8	1999.2	2094.4	1666.0	1618.4
	R2	1475.6	1332.8	809.2	809.2	2070.6	1904.0	1808.8	1570.8
	R3	1475.6	1428.0	666.4	809.2	2142.0	1951.6	1713.6	1666.0
VC	R1	1285.2	1094.8	714.0	952.0	2522.8	1999.2	1761.2	1475.6
	R2	1237.6	1094.8	856.8	904.4	2475.2	1951.6	1713.6	1428.0
	R3	1332.8	1094.8	833.0	856.8	2570.4	1904.0	1808.8	1523.2
PC	R1	1761.2	1713.6	1285.2	571.2	2237.2	2427.6	2380.0	1904.0
	R2	1666.0	1523.2	1380.4	642.6	2237.2	2475.2	2570.4	2046.8
	R3	1618.4	1761.2	1237.6	666.4	2284.8	2427.6	2475.2	1808.8
CF	R1	1713.6	2261.0	1666.0	1237.6	1904.0	2142.0	1904.0	1808.8
	R2	1856.4	2189.6	1713.6	1380.4	1856.4	2118.2	1880.2	1713.6
	R3	1951.6	2237.2	1666.0	1309.0	1951.6	2094.4	1951.6	1618.4
MSWC+CF	R1	1904.0	2142.0	1713.6	2094.4	2475.2	2665.6	1856.4	1642.2
	R2	1856.4	2142.0	1689.8	2046.8	2475.2	2665.6	1856.4	1666.0
	R3	1951.6	2046.8	1761.2	1999.2	2380.0	2665.6	1856.4	1666.0
VC+CF	R1	1237.6	2237.2	1904.0	1618.4	1856.4	1999.2	1713.6	1761.2
	R2	1190.0	2284.8	1951.6	1713.6	1951.6	1951.6	1713.6	1808.8
	R3	1428.0	2332.4	1999.2	1618.4	1808.8	2046.8	1761.2	1761.2
PC+CF	R1	2522.8	2808.4	2284.8	1951.6	2522.8	2856.0	2475.2	2189.6
	R2	2475.2	2903.6	2237.2	1999.2	2475.2	2951.2	2332.4	1808.8
	R3	2665.6	2856.0	2261.0	1904.0	2570.4	2808.4	2356.2	2142.0

Appendix 37: Variation of available P at four different stages of rice growth due to different fertilizer treatments during the two years.

Treatments		Available P (kg ha ⁻¹)							
		2022				2023			
		AT	PI	F	PH	AT	PI	F	PH
Control	R1	6.66	5.47	5.00	4.64	6.30	4.64	4.87	3.92
	R2	6.55	5.71	5.00	4.64	6.54	4.52	5.11	3.92
	R3	6.55	5.71	5.00	4.52	6.54	4.52	4.99	4.16
MSWC	R1	17.26	12.73	10.59	8.93	16.06	15.82	14.63	13.32
	R2	17.02	12.38	10.35	9.16	16.54	15.70	14.75	13.68
	R3	17.97	12.73	10.35	8.81	16.30	15.70	14.99	13.44
VC	R1	13.69	11.78	9.28	7.97	14.51	16.18	14.16	14.75
	R2	13.45	12.14	9.28	7.97	15.35	15.70	14.28	15.11
	R3	13.33	11.42	8.93	7.85	14.87	15.94	13.92	14.75
PC	R1	8.69	8.45	7.26	7.26	9.52	10.23	10.23	9.75
	R2	8.93	8.33	7.38	7.14	8.44	10.11	9.16	9.16
	R3	9.28	7.74	7.38	7.26	9.28	10.47	9.99	9.04
CF	R1	24.16	26.30	23.56	20.94	24.39	23.56	23.20	21.06
	R2	24.28	26.18	23.32	21.06	23.91	24.51	22.84	20.70
	R3	24.40	26.30	23.32	20.94	23.68	25.22	23.91	20.82
MSWC+CF	R1	19.64	16.54	12.14	9.16	17.37	17.49	15.35	14.04
	R2	20.11	16.54	12.38	9.52	18.32	17.96	15.35	14.16
	R3	19.99	16.54	12.14	9.40	17.13	18.44	14.75	14.63
VC+CF	R1	18.56	16.66	14.88	13.45	17.01	18.32	16.42	15.35
	R2	18.56	15.95	15.11	13.33	18.20	18.44	16.66	15.70
	R3	18.80	16.30	14.99	13.57	18.80	18.44	16.77	15.82
PC+CF	R1	15.23	12.26	11.42	11.31	15.47	16.66	15.47	15.70
	R2	15.11	12.73	11.19	11.31	15.70	17.13	16.06	15.47
	R3	14.88	12.38	11.19	11.42	15.47	17.25	15.70	14.87

Appendix 38: Variation of available K at four different stages of rice growth due to different fertilizer treatments during the two years.

Treatments		Available K (kg ha ⁻¹)							
		2022				2023			
		AT	PI	F	PH	AT	PI	F	PH
Control	R1	138.31	150.85	125.63	113.42	137.52	140.93	124.77	117.27
	R2	149.36	141.86	120.45	130.36	146.89	156.25	130.42	124.58
	R3	153.74	156.27	116.34	124.67	142.57	122.54	119.28	110.57
MSWC	R1	157.94	220.95	187.18	138.94	153.74	230.15	168.32	138.86
	R2	179.58	230.62	173.03	126.56	166.51	185.45	158.38	152.15
	R3	168.66	227.00	181.88	153.00	173.78	201.31	170.64	120.64
VC	R1	164.13	196.72	168.27	138.24	173.46	208.42	147.83	136.16
	R2	162.14	184.94	171.52	123.76	191.21	213.89	136.95	147.73
	R3	174.30	190.74	165.00	126.21	162.57	190.24	140.32	138.46
PC	R1	135.85	157.51	160.64	146.65	163.95	172.30	160.44	138.35
	R2	145.67	169.97	172.83	137.88	152.96	164.87	151.38	131.80
	R3	166.40	181.92	157.76	134.75	188.02	155.76	147.75	149.32
CF	R1	183.78	166.25	175.88	158.44	185.13	205.35	142.44	146.51
	R2	179.54	174.23	167.04	142.41	194.57	196.27	149.64	136.27
	R3	194.68	169.18	178.74	147.84	197.39	212.63	156.53	130.33
MSWC+CF	R1	143.47	206.16	156.14	166.24	155.32	179.72	160.70	140.68
	R2	148.55	194.06	140.85	148.23	166.25	167.08	143.27	140.53
	R3	153.65	199.54	131.63	155.97	182.62	172.85	170.07	148.62
VC+CF	R1	160.04	218.53	158.75	170.13	166.45	187.87	165.54	148.50
	R2	174.91	198.88	153.12	141.87	185.51	175.13	179.62	134.68
	R3	186.18	210.85	150.94	126.79	175.87	199.08	186.98	163.63
PC+CF	R1	189.69	158.96	179.51	135.60	201.65	189.77	176.13	161.93
	R2	193.29	187.03	169.84	150.31	178.71	191.60	168.88	151.90
	R3	197.74	179.15	185.56	126.45	185.73	198.88	174.82	149.70

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12 th or Equivalent	2015	English, Alternative English, Biology, Physics, Chemistry, Mathematics	Council of Higher Secondary Education Manipur	74.2%
B.Sc.	2018	Environmental Science (Hons.)	D.M. College of Science	56.7%
M.Sc.	2020	Environmental Science	Manipur University	7.54 CGPA
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RESEARCH EXPERIENCE

Dissertation Title in M.Sc.: Quantification of Methane Emission from Some Important Feeder Streams of Loktak Lake.

PUBLICATIONS IN JOURNAL

Devi, N.T., Devi, A.S., Singh, K.R. (2021). Emission of Methane from Wetland Paddy Fields: A Review. Journal of Climate Change. 8: 13 – 19. DOI 10.3233/JCC220017

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CONFERENCE ATTENDED

Devi, N.T. (2023). Influence of three locally available compost on the yield performance of rice. Two days National Seminar on Land Use and Bioresource Management for Sustainable Livelihood. Jointly organized by Department of Environmental Science, Mizoram University, Mizoram Science, Technology & Innovative Council (MISTIC) and National Bank for Agriculture and Rural Development (NABARD) on 27th – 28th March, 2023.

Devi, N.T. (2024). Effect of municipal solid waste compost on the emission of methane from the paddy fields. International Conference on Climate Change and Natural Resources Management for Sustainable Development. Organized by School of Earth Sciences and Resources Management, Mizoram University on 13th – 15th March, 2024.

Devi, N.T. (2025). Compost application: a sustainable approach for improving grain yield and reducing greenhouse gas emission from rice field. National Conference on Climate Change Impacts, Adaptation and Resilience organized by DST's Centre of Excellence Department of Environmental Science, Tezpur University on 19th – 20th December, 2024.

AWARDS

Best Oral Presentation Award on the topic 'Influence of three locally available compost on the yield performance of rice' presented in the Two days National Seminar on Land Use and Bioresource Management for Sustainable Livelihood. Jointly organized by Department of Environmental Science, Mizoram University, Mizoram Science, Technology & Innovative Council (MISTIC) and National Bank for Agriculture and Rural Development (NABARD) on 27th – 28th March, 2023.

DECLARATION

Hereby, I declare that the information provided above is correct to the best of my knowledge.

PARTICULARS OF THE CANDIDATE

NAME OF THE CANDIDATE	: Naorem Twinkle Devi
DEGREE	: DOCTOR OF PHILOSOPHY
DEPARTMENT	: ENVIRONMENTAL SCIENCE
TITLE OF THESIS	: Comparative Account on Influence of Organic and Chemical Fertilizers on Growth and Yield of Rice and Methane Emission in Field Conditions.
DATE OF ADMISSION	25.08.2021
APPROVAL OF RESEARCH PROPOSAL	
1. DRC	31.03.2022
2. BOS	31.03.2022
3. SCHOOL BOARD	25.05.2022
4. ACADEMIC COUNCIL	10.06.2022
MZU REGISTRATION	: MZU2108605 of 2021
Ph.D. REGISTRATION	: MZU/Ph.D./1885 of 25.08.2021
EXTENTION (IF ANY)	: NA

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Emission of Methane From Wetland Paddy Fields: A Review

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Abstract: Cultivation of rice is widely practiced throughout the world as rice is a staple food for half of the world's population. However, the emission of methane (CH₄) is an issue associated with the cultivation of rice. Many reports on the level of CH₄ emission after treatment of different kinds of organic materials in paddy fields were reported. It was observed that the application of a combination of tested locally available compost along with inorganic NPK fertilisers effectively reduced the rate of emission of CH₄. Intermittent wetting and drying in addition to the combined application of compost and NPK fertilisers will help in reducing the emission of CH₄ up to 40 to 45%. To undertake an intermittent drainage system is a difficult step for the farmers to implement as it has extra cost and labour. Therefore, lawmakers should initiate steps to help farmers in order to reduce the emission of CH₄ from paddy fields.

Keywords: Chemical fertiliser; Compost; Manure; Intermittent irrigation.

Introduction

Methane (CH₄) is a colourless, odourless and highly flammable gas. It absorbs infrared radiation and reradiates it back to the earth's surface making it a potent greenhouse gas. It is the second most important greenhouse gas after CO₂ that contributes to global warming. CH₄ has a very high global warming potential which is 34 times more than carbon dioxide (IPCC, 2013), and is responsible for 1/3rd of global warming. The atmospheric concentration of CH₄ reached an average of 1889 ppb which exceeds 262% of the pre-industrial level (WMO, 2021). Agriculture is the main source of anthropogenic CH₄ emission (UNEP, 2021) accounting for 43% of the net emission (Shang et al., 2021). Emission from paddy fields contributes about 20% of the total global CH₄ emission (Forster et al., 2007). India is among the top ten emitters of

CH₄ emission which emits 6.08 Tg and whose share is approximately 10% of the total emission (Crippa et al., 2020). CH₄ is produced by the action of methanogens—the bacteria when they decompose organic substrates in anaerobic conditions provided by flooded conditions in paddy fields. CH₄ that is left after the oxidation process reaches the atmosphere by diffusion, ebullition or by plant-mediated transport through the aerenchyma (Mer and Roger, 2001).

In India, rice cultivation is widely practiced throughout the country for food as well as for economic sustainability. Half of the world's population depends on rice for their calorie intake. In order to meet the demand of the growing population, the production of rice is estimated to increase by 24% in the year 2030 (FAO, 2009). People extensively use synthetic fertilizers to get higher yields. It not only deteriorates the soil quality but also increases CH₄ emission from the field (Wassmann

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et al., 2009) which increased by an average of 3.9% per year from 1961-2010 (Tubiello et al., 2013). Numerous studies have reported that the emission of CH_4 from paddy fields can be reduced through modification of fertiliser application rates, type of fertiliser amendment (Zheng et al., 2012; Kong et al., 2019) and water management (Hou et al., 2012; Zhang et al., 2016; Souza et al., 2021). Through improved management practices the paddy fields can also act as a sink for CH_4 by sequestering carbon in the soil (Smith et al., 2008). Therefore, there is an urgent need to implement the mechanisms for reducing the emission of CH_4 without affecting crop yield. Attention has been shifted towards the use of organic fertiliser due to their beneficial effect on soil and less impact on human health. However, some studies reviewed that the use of organic materials or fertilisers enhances CH_4 emission from paddy fields (Kong et al., 2019; Fauzan et al., 2021).

Reducing the amount of CH_4 emissions will really help in countering global warming because CH_4 has a lifespan of 12.4 years whereas the lifespan of CO_2 has hundreds to thousands of years. Therefore, reducing CH_4 emissions from all sources by taking up different measures will help in achieving the goal of limiting the rise in global temperature up to 1.5°C under the Paris Climate Change Agreement.

In the present review, the authors sought to make a comparative study on the level of CH_4 emission due to organic and chemical fertiliser amendment in paddy fields and the effect of the water regime in order to propose a suitable method of reducing the emission of CH_4 .

Organic Fertiliser and CH_4 Emission

In a study conducted by Hwang et al. (2017) in paddy fields at Jinju, South Korea it was observed that in the control plot where the standard level of chemical fertilisers was applied, emission of CH_4 was recorded to be 220 kg ha^{-1} whereas, in the green biomass of barley and hairy vetch treated plot, a drastic increase in CH_4 emission with 904 kg ha^{-1} was recorded. Although a slight increase in grain yield was recorded in the green biomass treatment, they have suggested the application of composted biomass in place of green biomass to reduce the emission of CH_4 from paddy fields. Wang et al. (2021) also applied digested Chinese milk vetch in place of fresh biomass before rice transplanting and the process led to reduced availability of labile C source for the methanogens and control reduction of Eh (redox potential of soil). Therefore, application of the digested Chinese milk vetch compost led to the

emission of only 34.74 kg ha^{-1} of CH_4 compared to straw incorporation ($118.08 \text{ kg ha}^{-1}$) and without organic amendment (48.21 kg ha^{-1}). Treatment with compost of *Azolla caroliniana* a tiny floating aquatic fern led to 1.1 to 1.4 fold greater soil carbon sequestration and more grain yield compared to the treatment of cow dung and green manure (*Sesbania aculeata*) in Northeast India. It also suppressed the emission of CH_4 by 30-36% due to the enhancement of porosity, C-storage and recalcitrant C fractions of soil (Bharali et al., 2021).

Treatment with indigenous organic fertiliser could be a viable option for reducing CH_4 emission, getting a good quality grain yield and reducing the use of inorganic fertiliser. Soebandion et al. (2021) observed treatment of indigenous banana hump liquid organic fertilizer and bamboo root liquid organic fertiliser generate CH_4 1.001 times compared to no fertilizer treatment. Whereas, inorganic fertiliser and cow manure treatments emit CH_4 1.952 and 1.884 times the no fertiliser treatment. Jeong et al. (2018) observed that the application of commercial biofertiliser has lower emission of 0.954 times than no fertiliser treatment. Utilisation of composted swine manure decreased the global warming potential by 25% over application of the fresh swine manure. During the process of composting, a 35% increase in global warming potential was observed, however, there was a reduction in CH_4 emission by 60% due to utilisation of compost overcome by emission during its utilisation. Therefore, the application of compost is a good management strategy to reduce CH_4 emissions from rice fields (Jeong et al., 2018). Haque et al. (2021) observed that the application of vermicompost reduced CH_4 , CO_2 and N_2O flux by 13-19%, 17-21% and 4-9%, respectively, compared to the treatment of fresh cow manure. Vermicompost and cow manure treatment significantly increased the grain yield compared to the application of chemical fertiliser alone although emission of CH_4 was lower in the chemical fertiliser. Maximum emission of CH_4 was recorded from the treatment of non-composted manure with $47\text{-}61 \text{ mg/m}^2$. The application of rapidly and commonly composted cattle manure decreased the CH_4 emission by 44.4 and 91.0%, respectively, compared to non-composted manure. The result also indicated that the application of fresh non-composted manure leads to an increase in emission of CH_4 although the grain yield may be enhanced. The number of methanogens in the rapidly and commonly composted cattle manure treatment was the lowest leading to a lower CH_4 emission (Zhou et al., 2016).

In spite of using fresh manure alone experiments in combination with other materials were also conducted. Fauzan et al. (2021) performed an incubation study to determine the effectiveness of chicken manure combined with steel slag at different ratios to mitigate CH_4 emissions from paddy fields. The treatment of chicken manure and steel slag in the ratio of 1:2.5 emitted the lowest cumulative CH_4 with a value of $0.01 \text{ mg C kg}^{-1} \text{ Period}^{-1}$. The study revealed that amendment of steel slag with chicken manure at a higher rate reduced CH_4 emission since iron content in the steel slag helped in inhibiting CH_4 production. Amendment of Azolla-cyanobacteria with phosphogypsum was also found to reduce by 29.7% and 32.6% of cumulative seasonal CH_4 emission in Japan and Bangladesh, respectively, compared to sole chemical fertilizer treatment. The Azolla-cyanobacteria inoculation improved soil redox potential thereby increasing oxidation of CH_4 , and reducing its emission (Ali et al., 2015).

In a study conducted by Yuan et al. (2018) in Shanghai, China, it was observed that the application of organic fertiliser leads to a maximum rate of CH_4 emission with $145.31 \text{ kg ha}^{-1}$ compared to a combined treatment of organic and chemical fertiliser (84.62 kg ha^{-1}), chemical fertiliser only (77.88 kg ha^{-1}) and no fertilisation (32.19 kg ha^{-1}). The treatment with organic fertiliser enhances soil nutrients, carbon, nitrogen, phosphorus and potassium and soil humic acid. Thereby, the potential of methanogens in paddy soil to produce CH_4 could be enhanced. Combined treatment of organic and chemical fertiliser partially mitigated CH_4 emission and also guaranteed a higher grain yield; therefore, they recommended the process of mixed fertilisation. According to Bharali et al. (2017), the incorporation of Azolla compost along with recommended NPK significantly increases the soil carbon storage capacity and improves crop yield by 27.3% over the control treatment (no fertiliser). However, its application resulted in enhancing methane emissions by 15.66% higher than the control. Das and Adhya (2014) observed that a combined application of manure and urea-N at a ratio of 1:3 produced $185.24 \text{ kg ha}^{-1}$ of CH_4 providing a 63.4% increase compared to control (no treatment) and 65.1% increase in crop yield compared to control. The treatment of urea-N fertiliser alone leads to an emission of 149.64 which was only 31.9% more than control and the crop yield was 38.5% higher than control. A combination of 0.5 t ha^{-1} of vermicompost with a recommended dose of chemical fertilisers was proposed as it reduced 37-77% of CH_4 emission compared to chemical fertiliser application and it also gives a 5%

higher grain yield of rice over sole chemical fertilisation (Haque and Biswas, 2021).

From the information collected it can be observed that the application of fresh manure and green manure alone in paddy fields led to an increase in emission of CH_4 . The application of locally available indigenous compost and vermicompost combined with chemical fertilisers is a good option for reducing the emission of CH_4 from paddy fields. Trials of locally available compost should be performed and tested under the field condition, before actual application by the farmers, to record the reduction in CH_4 emission. Utilisation of phosphogypsum and iron-containing wastes like steel slags along with compost also reduces the emission of CH_4 .

Chemical Fertiliser and CH_4 Emission

The application of chemical fertilisers in paddy fields is a normal process that is performed to increase the yield in order to meet the growing demand. Fertilisation provides nutrients to plants to improve their growth and yield (Moe et al., 2019). The influence of nitrogen fertilisation on CH_4 emission is difficult to predict since it shows either positive, negative or no effect at all (Cai et al., 2007). Some studies suggest that nitrogen fertiliser application decreased emissions of CH_4 during the rice growing seasons compared to no nitrogen fertiliser. For instance, the amount of annual cumulative CH_4 emission was lowest in the nitrogen fertiliser treatment plot with $793.8 \text{ kg CH}_4\text{-C ha}^{-1}$ while the highest emission ($882.8 \text{ kg CH}_4\text{-C ha}^{-1}$) was found in no nitrogen fertiliser plot (Zhou et al., 2018).

Shang et al. (2011) have reported that compared with control, NK fertiliser application slightly increased the net annual global warming potential, whereas NP and NPK fertiliser application decreased the greenhouse gas index by 23-29%. Therefore, they suggested a balanced P fertiliser supplement to reduce CH_4 emission and increase grain yield.

Datta et al. (2013) investigated the effect of chemical fertilisers on CH_4 emission from tropical rice fields of India. It was observed that the plots treated with N-fertiliser showed the highest amount of CH_4 emission with 80.27 kg ha^{-1} and $451.27 \text{ kg ha}^{-1}$ during the dry season and wet season, respectively. Minimum CH_4 emission was recorded from the NPK treatment plots in both dry (34.60 kg ha^{-1}) and wet seasons ($233.66 \text{ kg ha}^{-1}$). The result indicated that the application of P and K fertiliser help in developing aerenchyma of plant and stimulated the growth of methanotrophs – the bacterial population which increases oxidation of CH_4 in the soil.

Yang et al. (2012) also reported a lower CH_4 emission from NPK fertiliser applied to paddy fields compared to only N-fertiliser plots. Troare et al. (2017) again reported a minimum emission of CH_4 by the application of NaNO_3 fertiliser when compared to other types of chemical fertiliser application.

The average emission of CH_4 in the different growing stages due to the application of chemical fertilisers was calculated from the literature cited and represented in Figure 1. Emission from different kinds of treatment could not be depicted graphically although the range of reducing the emission of CH_4 could be established. The growing stage of paddy can be classified as 1. Vegetative growth stage: ranging from 0 to 49 days after transplantation (DAT) 2. Reproductive stage: 4 weeks (50 to 78 days) and 3. Ripening stage: 4 weeks (79 to 107 days). During the three stages, the maximum emission was observed in the reproductive stage and the minimum in the vegetative growth stage.

A total emission rate was $9.37 \text{ mg m}^{-2} \text{ hr}^{-1}$ as shown in Figure 1. Total emission during the 107 days of the active growth period was $24062.16 \text{ m gm}^{-2}$ and it comes to approx. 240 kg ha^{-1} . The total rice growing area of the world according to FAO (2011) is 161,420,743 ha. Therefore, the total average global emission of CH_4 during a rice growing season comes to 39 million tonnes (Tg) which is comparable to the range of 20 to 100 Tg gyr^{-1} with an average of 60 Tg, the data as provided by IPCC (1996).

Water Regime and CH_4 Emission

Water management acts as an important strategy to mitigate emissions of CH_4 from paddy fields. Haque

et al. (2016) studied the effect of two different water regimes – intermittent drainage and continuous flooding on CH_4 emission. They observed that intermittent drainage reduced the CH_4 emission rate by 54-58% compared to continuous flooding. Pramono et al. (2022) also observed that alternate wetting and drying reduced 14-18% of CH_4 emission and increase 6-7% grain yield compared to continuous flooding

Hadi et al. (2010) reported that the use of intermittent drainage increased the redox potential of soil in both Indonesia and Japan, limiting CH_4 emission without significantly changing the soil microbial population. The amount of CH_4 emitted from alluvial paddy soil of Indonesia and Japan due to continuous flooding was 1384 and $632.2 \text{ kg C ha}^{-1} \text{ season}^{-1}$, respectively. The study identified that the practice of intermittent drainage helped in reducing approximately 37% of the CH_4 emission. Shang et al. (2011) also reported similar positive results due to intermittent drainage patterns.

In another study by Hou et al. (2012), intermittent irrigation has proved to reduce the CH_4 emission by 81.8%, compared to continuous irrigation. Hwang et al. (2017) also reported that intermittent irrigation reduced CH_4 emission from compost-treated paddy fields by 37% on an average across sites without affecting the grain yield compared to continuous flooding. Alternate wetting and drying irrigation reduce greenhouse gas emissions due to more diffusion of atmospheric O_2 into the soil, thereby reducing the formation of CH_4 (Yang et al., 2012). An increase in N_2O emission may be slightly more due to increased nitrification of NH_4^+ during the dry period and denitrification of NO_3^- during re-wetting of dry soils. However, decreasing the emission

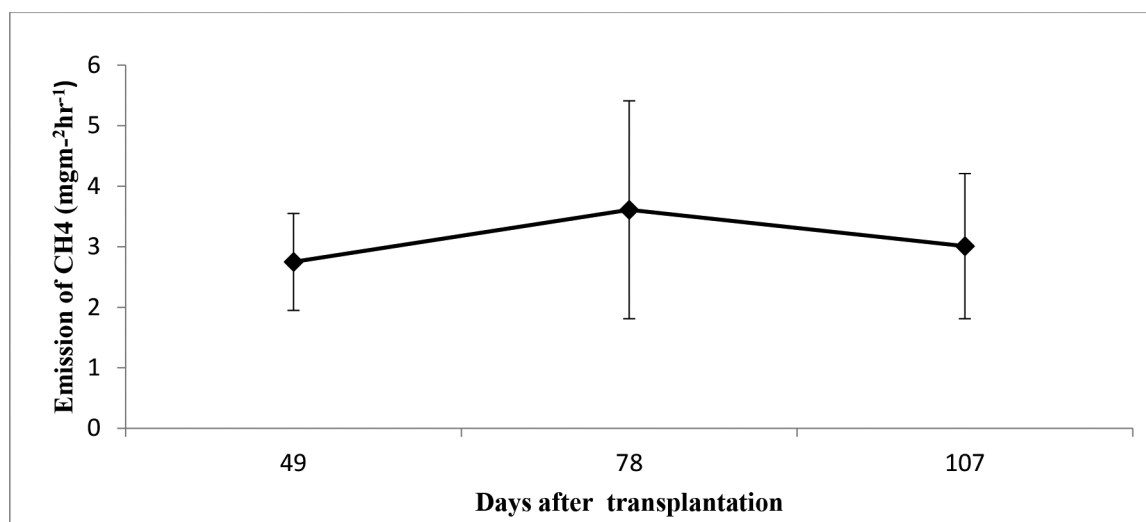


Figure 1: Average emission of CH_4 during the three growth stages of paddy due to application of chemical fertiliser.

of CH₄ from rice cultivation is the most effective way to mitigate global warming potential in rice cultivation as 15-20% of the total global emission of CH₄ is from paddy fields and total N₂O emission from all sources is responsible for only 6% in enhancing global warming (Abbassi et al., 2019).

Souza et al. (2021) revealed that the timing of drainage from paddy fields is important in reducing CH₄ emissions as optimal drainage timing maximises the mitigating efficiency of the drainage. For compost amended field, the average optimal wetting should be from 20 and 50 days after transplantation and it decreased 45% and 35% CH₄, respectively. Intermittent drainage reduced the logging of soil with water, which will enhance soil oxidation capacity thereby reducing CH₄ emissions.

Mitigation Measures

The total global emission of CH₄ was 590 Tg in 2019 out of which 230 Tg (40%) was from natural sources and 360 (60%) from anthropogenic sources (IEA, 2022). The average emission from paddy fields was 60 Tg (16%) according to IPCC (1996) and 39 Tg in the present review due to the application of chemical fertilisers. From the literature reviewed, it was observed that the application of compost/vermicompost mixed with chemical fertilisers reduced the emission of CH₄ from 29.7% (Ali et al., 2015) to 57% (Haque and Biswas, 2021). In addition, intermittent flooding also helps in reducing the emission from 16% (Pramono et al., 2022) to 37%, including compost treatment (Hwang et al., 2017) of CH₄ emission from paddy fields. Therefore, a combination of both the remedial measures would help in reducing 40 to 45% of the total emission of CH₄ from the paddy fields.

Conclusion

From the observations made from the literature cited, it can be concluded that the application of green manure and non-composted animal manure does not help in reducing the emission of CH₄ although the yield of rice may be enhanced. The application of compost or chemical fertilisers alone is also not sufficient for maintaining a balance between CH₄ emission and crop production. A combination of tested locally available composts/vermicompost and NPK fertilisers is necessary in order to reduce the emission of CH₄ from paddy fields without compromising the yield and soil quality. In addition, intermittent wetting and

drying instead of continuous irrigation also help in reducing the CH₄ emission. A combination of both process would help in reducing 40 to 45% of the total CH₄ emission from paddy fields. However, the process of intermittent irrigation will be a difficult step for the farmers to take up, as they are adapted to the age-old practice of continuous flooding. It will also need extra expenditure and labour which they may not be able to bear. Therefore, steps can be taken up by lawmakers to minimise the cost.

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OPEN Impact of chemical fertilizer and composts application on growth and yield of rice in Northeast India

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Formulation of effective fertilizer management practice is crucial for sustainable rice cultivation. Prolonged application of chemical fertilizers can result in N loss into the environment, causing harmful effects. Application of organic fertilizer acts as an alternative source of nutrient supply for rice cultivation. The present study evaluates growth and productivity of rice due to sole application of three different types of composts, along with their combined application with chemical fertilizer. The three types of composts are compost made from organic component of municipal solid waste, vermicompost made from a combination of rice straw and cow manure and compost made from a floating mat found in Loktak Lake consisting of a heterogeneous mass of soil and aquatic macrophytes locally known as *phumdi*. Eight different kinds of treatments were maintained to determine growth and yield of a local rice variety (RCM-13), in field condition for two growing season in two years: (1) Control, no fertilizers applied (2) MSWC (Municipal solid waste compost, 100%) (3) VC (Vermicompost, 100%) (4) PC (*Phumdi* compost, 100%) (5) CF (Chemical fertilizer, 100%) (6) MSWC + CF (50%+50%) (7) VC + CF (50%+50%) (8) PC + CF (50%+50%) arranged in randomized block design. The combined application of *phumdi* compost and chemical fertilizer (50%+50%) produced 33.6% more grain yield and 26.21% more straw yield compared to 100% application of chemical fertilizer. Application of 50%+50% of municipal solid waste compost with chemical fertilizer and 50%+50% of vermicompost with chemical fertilizer were also able to produce more grain yield compared to sole application of chemical fertilizer, with an increase of 5% and 13.16% respectively. The finding indicates substituting 50% of chemical fertilizer with composts can enhance production of the present rice variety. Moreover, utilization of *phumdi* in the form of compost can also help in the management of the lake from further eutrophication.

Keywords Grain yield, Loktak, Municipal solid waste compost, Panicle length, *Phumdi* compost, Vermicompost

Rice provides sustenance for a majority of the world's population. The population of India continues to accelerate at an exponential rate and to feed its large population, food production needs to be accelerated. India has the largest production of rice, next to China with 116.42 million tons covering an area of 43.79 million hectares¹. Global demand of rice is expected to increase approx. 650 million tons by the end of 2050² however, due to rapid urbanization and industrialization area under crop cultivation is declining³. Rice needs especially three essential nutrients N, P and K for better yield⁴. Majority of the farmers rely on chemical fertilizers, considering it a better way to provide essential nutrients for crop production. Excessive or unbalanced inputs of chemical fertilizers jeopardize the environment and human health. Continuous application of chemical fertilizers degrades the overall health of the soil and despite greater productivity long-term application of chemical fertilizer result in declining rice yield by 38%⁵.

Application of stable organic material in intensive rice agriculture is known to improve physical, chemical and biological properties of the soil. It maintains sustainability of the soil by providing essential macro and micronutrients to the soil^{6–8}. Organic material can be of plant and animal origin, plant origins are compost and green manure, whereas animal origins are manure. Plant growth-promoting microorganisms can also be inoculated along with manure, composts and chemical fertilizers. Converting the organic component of municipal solid waste into compost saves space and reduces costs of management. However, care should be taken that the organic waste is not contaminated with harmful chemicals. Vermicompost contains humic acids, nutrients and earthworm excretions, which are rich in microbial populations, growth hormones and enzymes. Application of vermicompost in agricultural fields helps the crops withstand a wide range of biotic and abiotic

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Parameter	
pH	6.68 ± 1.11
Bulk density (g cm ⁻³)	1.12 ± 0.20
TN (%)	0.35 ± 0.01
Available P (ppm)	0.042 ± 0.00
Available K (kg ha ⁻¹)	126.93 ± 11.21
Organic C (%)	0.62 ± 0.03
Texture	Clayey loam

Table 1. Physico-chemical characteristics of soil.

Parameters	MSWC	VC	PC
pH	7.20 ± 0.05	7.10 ± 0.40	6.20 ± 0.05
Organic carbon (%)	7.40 ± 0.92	18.0 ± 2.46	16.52 ± 3.05
Total N (%)	1.60 ± 0.70	1.7 ± 0.05	2.00 ± 1.30
Available P (%)	0.56 ± 0.18	0.68 ± 0.07	0.40 ± 0.02
Available K (%)	0.89 ± 1.20	0.77 ± 1.12	1.05 ± 0.86
C: N	4.62	10.58	8.26

Table 2. Initial quality of composts. MSWC: Municipal solid waste compost; VC: Vermicompost; PC: Phumdi compost.

stress resulting in more yields of crop⁹. Amendment of organic fertilizer elevates soil organic matter levels, hence enhancing the nutrient-holding capacity of soil^{10–12}. Although organic fertilizers have many advantages over chemical fertilizers, their sole application might not meet the essential nutrient requirement of the crops due to their slow nutrient-released pattern. The integrated use of chemical and organic fertilizers resulted in a significant increase in the growth, yield and macronutrient content of rice^{13,14}. While applying compost, total N content or the percentage of mineralizable N should be considered for proper efficiency of compost use¹⁵. Judicious use of chemical and organic fertilizer could meet sustainability by improving the environment, productivity and economic state of the region¹⁶.

There is a need to discover potential of locally made organic fertilizers which are easily available, affordable by farmers and should be environment friendly. Large scale accumulation of *phumdi*, a heterogeneous mass of soil and aquatic floating plants in Loktak Lake (a Ramsar site in Manipur, Northeast India) causes shallowing the depth of the lake. Few studies were conducted on estimating the possibility of converting *phumdi* into compost. Singh and Kalamdhad¹⁷ identified that compost made from *phumdi* contained more nutrients compared to other types of composts. Thereafter, private entrepreneurs have started producing compost from *phumdi* at small scales. India has generated considerable amount of solid waste daily, amounting to 170,339 tons per day¹⁸ and there is lack of proper management plan. However, composting of the organic component especially from the municipal solid waste has been undertaken by non-governmental organizations at small scales.

Rice is the major staple crop cultivated in waterlogged conditions especially during monsoon season mostly in the low-lying plain areas in the present study area and no work has been reported from the present study area on application of compost in rice fields. Although few studies has been reported from other Indian states^{19–21}. Therefore, objective of the present work was to evaluate efficiency of municipal solid waste compost, vermicompost and *phumdi* compost combined with chemical fertilizer on the growth and yield of rice. We hypothesize that application of composts in combination with chemical fertilizer can lead to higher productivity of rice compared to sole application of chemical fertilizer.

Results

Soil characteristics

The soil of the study area was acidic with 6.68, clayey loam in texture, with organic C content of 0.62% and bulk density of 1.12 g cm⁻³ (Table 1).

Initial quality of composts

pH of the three composts was within the range of 6.20–7.20 (Table 2). Organic C was maximum in VC and minimum in MSWC. The total N and available K of PC were maximum with 2.00% and 1.05% respectively among the three composts. C: N was low in all three composts with 4.62, 10.58 and 8.26 in MSWC, VC and PC respectively.

Growth characteristics

The height of rice plants kept on increasing from 30DAT to 60DAT and started declining till 90DAT in all treatments in both years (Figs. 1 and 2). Plant height of rice in control was more than VC and PC treatments at 30DAT ($p < 0.05$) in both the years. Compared to CF treatment plant height in PC + CF treatment was 8.77%

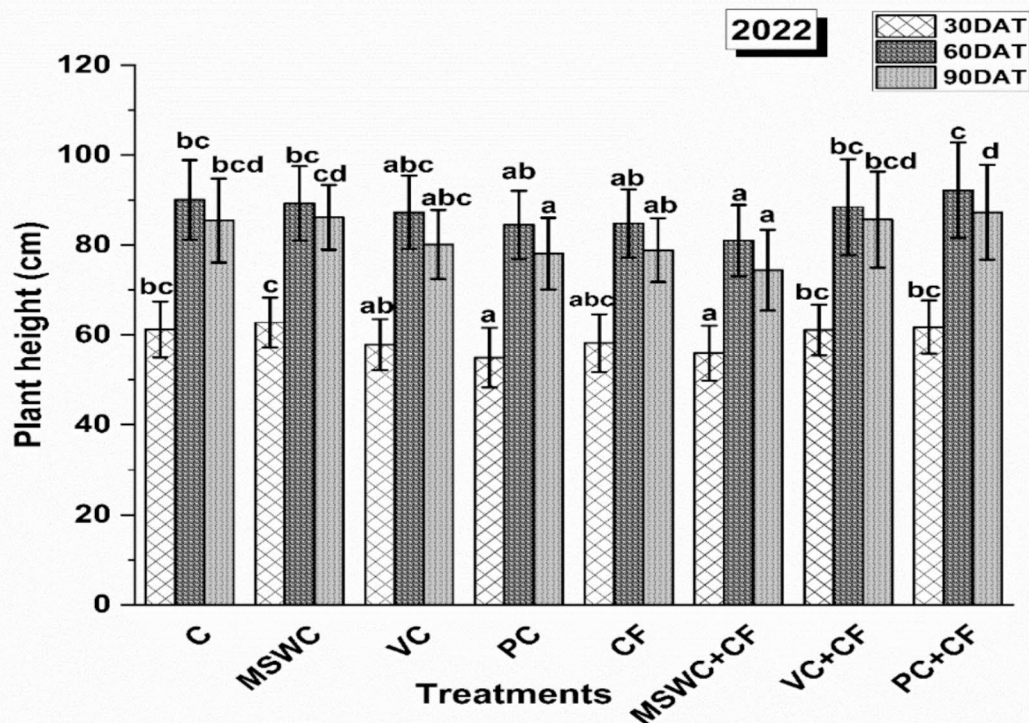


Fig. 1. Plant height of rice at 30DAT, 60DAT, and 90DAT of rice in different treatments during 2022. The bars with same letters at each sampling time are not significantly different in Tukey's HSD test ($p < 0.05$).

and 5.94% higher in the first and second year respectively at 60DAT. Tiller number per panicle (TNPP) was recorded to be higher only in PC + CF treatment (Fig. 3) compared to CF with an increase rate of 5.15% in the first year and 2.99% in the second year. The TNPP of rice in all treatments significantly increased in the second year ($p < 0.05$). Average TNPP of two years correlated significantly with plant height at 90DAT ($r = 0.73$; $p < 0.05$).

The effective tiller number per panicle (ETNPP) of rice in MSWC + CF treatment was lesser than the control (Fig. 4) in the first year ($p < 0.05$). In second year, ETNPP of rice was recorded to be more than control only in PC + CF treatment ($p < 0.05$). Maximum ETNPP was recorded in CF treatment with 4.48 ± 0.13 in the first year and PC + CF treatment in the second year with 5.00 ± 0.11 . Compared to CF treatment ETNPP of rice in PC + CF treatment was 11.60% higher in the second year. ETNPP of rice was higher in all treatments in the second year than first year except in CF treatment ($p < 0.05$). Over the two years average ETNPP of rice correlated with plant height at 90DAT ($r = 0.86$; $p < 0.01$).

Yield characteristics

The panicle length (PL) of rice was maximum in PC + CF treatment with 18.43 ± 0.76 cm in the first year and 20.81 ± 0.30 cm in the second year, indicating an increase of 9.05% and 10.45% compared to CF treatment in the first and second year respectively (Table 3). After PC + CF treatment the increase in PL of rice was followed by VC + CF treatment in the first year and MSWC + CF treatment in the second year ($p < 0.05$). Comparing between the two years higher PL of rice was recorded in the second year in all the treatments ($p < 0.05$).

The spikelet number per panicle (SNPP) of rice was higher than CF treatment in all treatments except PC treatment in first year (Table 3). In the second year the SNPP of rice in the CF treatment was higher than control, MSWC and PC treatments. In the first year increase in SNPP of rice was 26.57% in PC + CF treatment, 26.29% in VC + CF and 13.98% in MSWC compared to CF treatment. In second year there was an increase of 22.80% in PC + CF treatment, followed by MSWC + CF treatment with 2.14% and VC + CF treatment with 1.12% respectively compared to CF treatment. An increase in SNPP of rice was recorded in the second year compared to first year ($p < 0.05$). The average SNPP of rice for the two years correlated with PL of rice ($r = 0.87$; $p < 0.01$).

The filled spikelet number per panicle (FSNPP) of rice was minimum in control in both years (Table 3). Compared to CF treatment increase in FSNPP of rice was in the order of VC < MSWC + CF < MSWC < VC + CF < PC + CF in the first year ($p < 0.05$). In second year the order of increase in FSNPP of rice compared to CF treatment was MSWC < VC + CF < MSWC + CF < PC + CF ($p < 0.05$). The rate of increase of FSNPP of rice was 15.26% and 27.26% in PC + CF treatment in the first and second years respectively over CF. Increase in FSNPP was observed in second year compared to first year ($p < 0.05$). The average FSNPP of rice correlated significantly with PL of rice ($r = 0.94$; $p < 0.01$). Unfilled spikelet number per panicle (USNPP) of rice was maximum in control in both years (Table 3). Minimum USNPP of rice was recorded in CF treatment (7.97 ± 1.85) in first year ($p < 0.05$) and VC treatment (8.29 ± 1.68) in second year ($p < 0.05$). A declining trend of USNPP of rice was recorded in VC + CF,

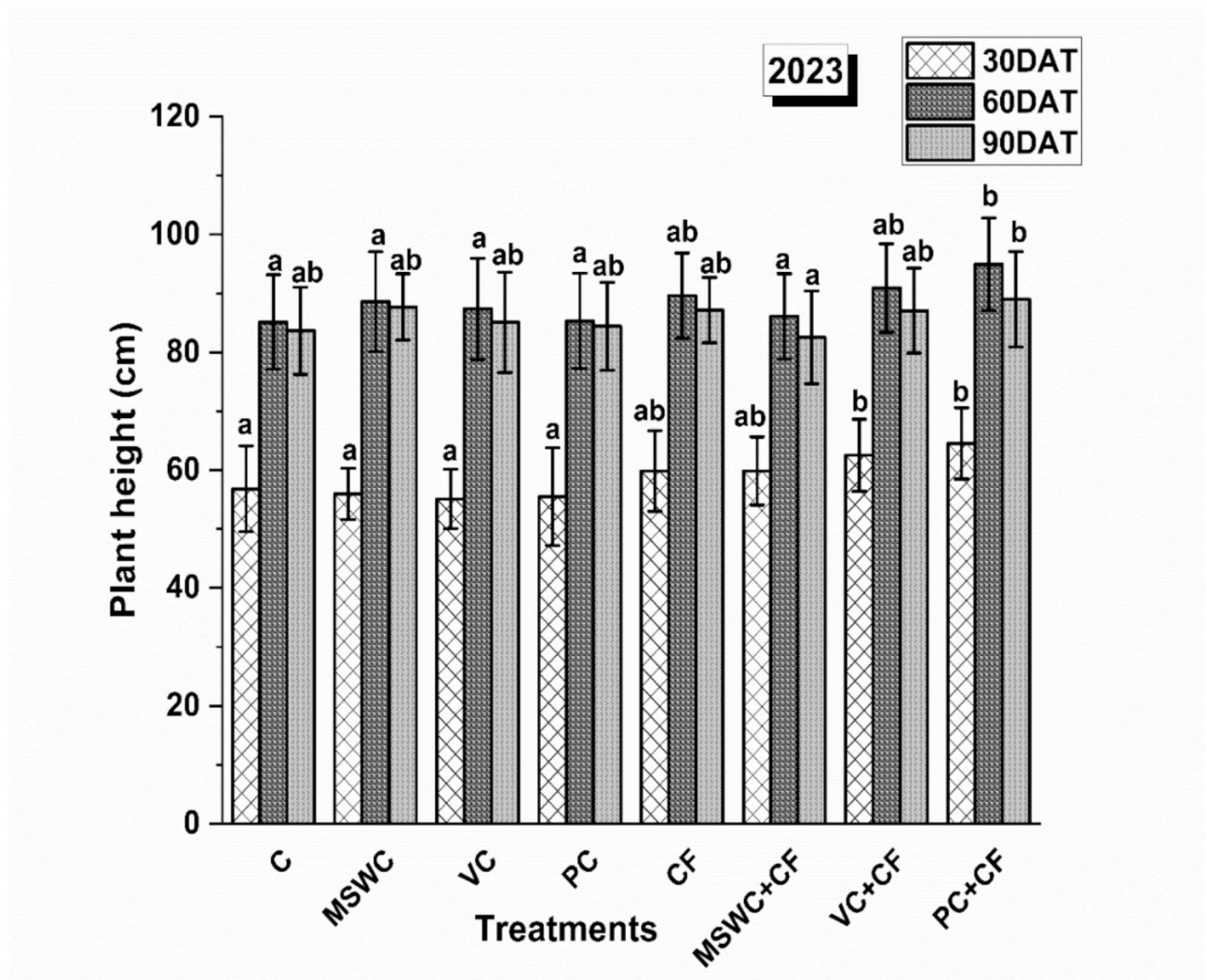


Fig. 2. Plant height of rice at 30DAT, 60DAT, and 90DAT of rice in different treatments during 2023. The bars with same letters at each sampling time are not significantly different in Tukey's HSD test ($p < 0.05$).

PC+CF and VC treatments in the second year compared to first year. The USNPP showed no significant difference between the two years ($p < 0.05$).

The minimum percentage of filled spikelet number per panicle (PFSNPP) was also recorded in control in both years (Table 3) and maximum was recorded in MSWC+CF treatment ($90.04 \pm 1.36\%$) in first year ($p < 0.05$) and VC treatment ($91.43 \pm 1.00\%$) in second year ($p < 0.05$). An increase in PFSNPP was recorded only in MSWC+CF treatment compared to CF treatment in the first year. Whereas, in the second year higher PFSPP of rice was recorded in VC+CF, MSWC, PC and VC treatment compared to CF treatment. PFSNPP was higher in the second year in all treatments except MSWC+CF treatment ($p < 0.05$).

Grain yield of rice was least in control in both years ($p < 0.05$, Fig. 5). Compared to CF treatment higher grain yield was recorded in PC+CF treatment with 29.71%, followed by VC+CF treatment with 16.90% and MSWC+CF with 9.42% in first year. In the second year grain yield in CF treatment was higher than VC, PC and MSWC treatments ($p < 0.05$). Maximum grain yield was recorded in PC+CF treatment with an increase of 36.41% compared to CF treatment in second year, VC+CF and MSWC+CF treatments were 9.42% and 0.90% respectively higher than CF. Comparing between the two years in all treatments grain yield was significantly higher in second year ($p < 0.05$) and correlated with TNPP ($r = 0.57$; $p < 0.05$), PL ($r = 0.91$; $p < 0.01$) and SNPP ($r = 0.90$; $p < 0.01$).

The straw yield of rice was recorded to be maximum in control ($5.96 \pm 0.52 \text{ t ha}^{-1}$) and minimum in PC treatment ($4.56 \pm 0.17 \text{ t ha}^{-1}$) in the first year ($p < 0.05$) however, the treatments MSWC+CF, MSWC, VC+CF and PC+CF recorded higher straw yield than CF treatment (Fig. 6). An increase of straw yield with a rate of 24.47% was found in PC+CF treatment, followed by VC+CF (19.45%) compared to CF treatment in first year. In the second year maximum straw yield was recorded in PC+CF treatment followed by VC+CF treatment while minimum was recorded in PC ($5.59 \pm 0.10 \text{ t ha}^{-1}$) ($p < 0.05$). Compared to CF the PC+CF and VC+CF treatments recorded 27.95% and 7.98% higher straw yields respectively in second year. There was a significant

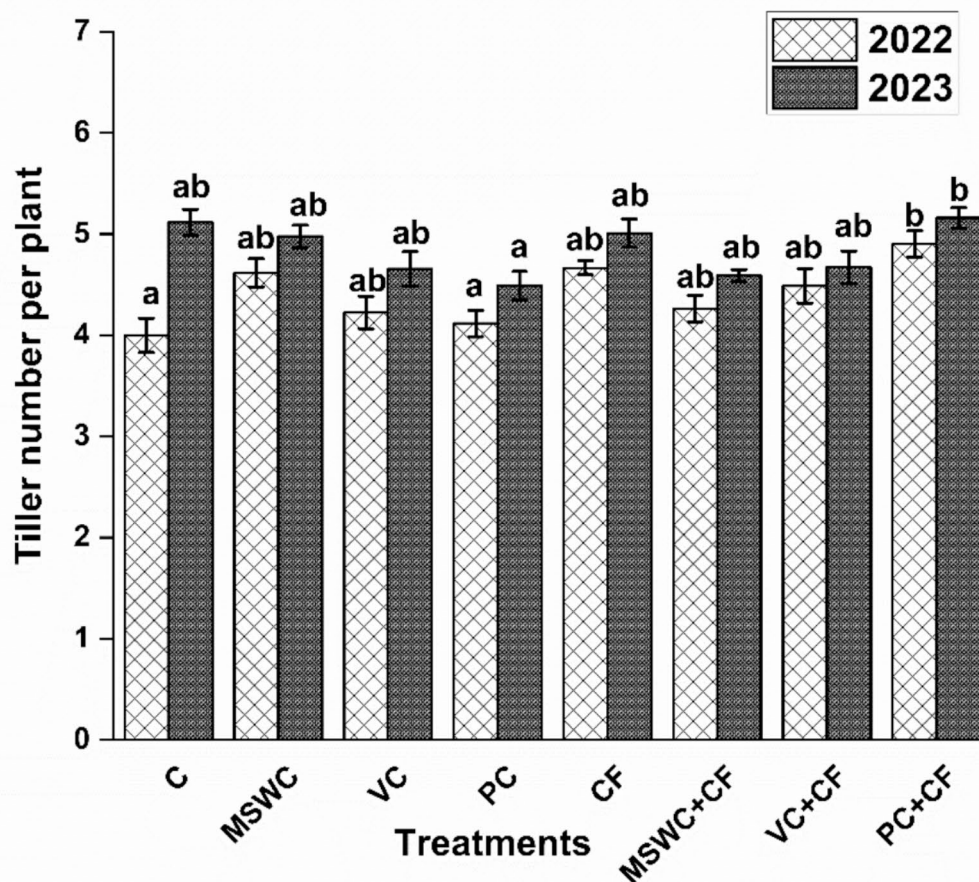


Fig. 3. Tiller number per plant in different treatments. The bars with same letters in each treatment are not significantly different in Tukey's HSD test ($p < 0.05$).

increase in straw yield in the second year in all the treatments ($p < 0.05$). The minimum harvest index (HI) of rice was recorded in control in both years (Fig. 7). The treatments MSWC+CF and PC+CF recorded higher HI than CF in first year ($p < 0.05$), and treatments MSWC+CF, PC+CF, VC+CF, PC recorded higher HI than CF treatment ($p < 0.05$) in second year. There was an increase of HI in all treatments in second year from first year except in CF and MSWC+CF ($p < 0.05$). Average HI was significantly correlated with grain yield ($r = 0.75$; $p < 0.05$).

N uptake

The biomass N content of rice plant was recorded higher in all composts treatments compared to CF (Table 4). Maximum was recorded in MSWC treatment plots followed by PC+CF and MSWC+CF ($p < 0.05$). The N uptake by rice plants does not show significant variation among the treatments although the composts treatment plots recorded higher N uptake than CF.

Discussion

The rate of application of different types of composts combined with chemical fertilizer was made in such a way that essential amount of N was provided. However, growth and yield characteristics of rice were lesser in the sole application of MSWC, VC and PC compared to CF. The results indicate that sole application of the three types of composts could not provide the required amount of N to the crop. The reason could be attributed to a slow-release pattern of N although, having lower initial C: N ratio in the composts. The present range of N in the composts was high compared to different kinds of compost derived from municipal solid waste (0.12–0.5%) reported by Lalremruati and Devi²². The C: N ratio of organic fertilizers is usually low, which can lead to a faster rate of mineralization of N⁸ however, effective result depends upon the type of crop and soil such as the present study. A similar report of lower yield of rice in the sole application of compost was reported by Kavitha and Subramanian²³. The application of chemical fertilizer has advantages over sole application of compost, as nutrients in chemical fertilizers are soluble and immediately available for growth of rice²⁴. A larger volume of

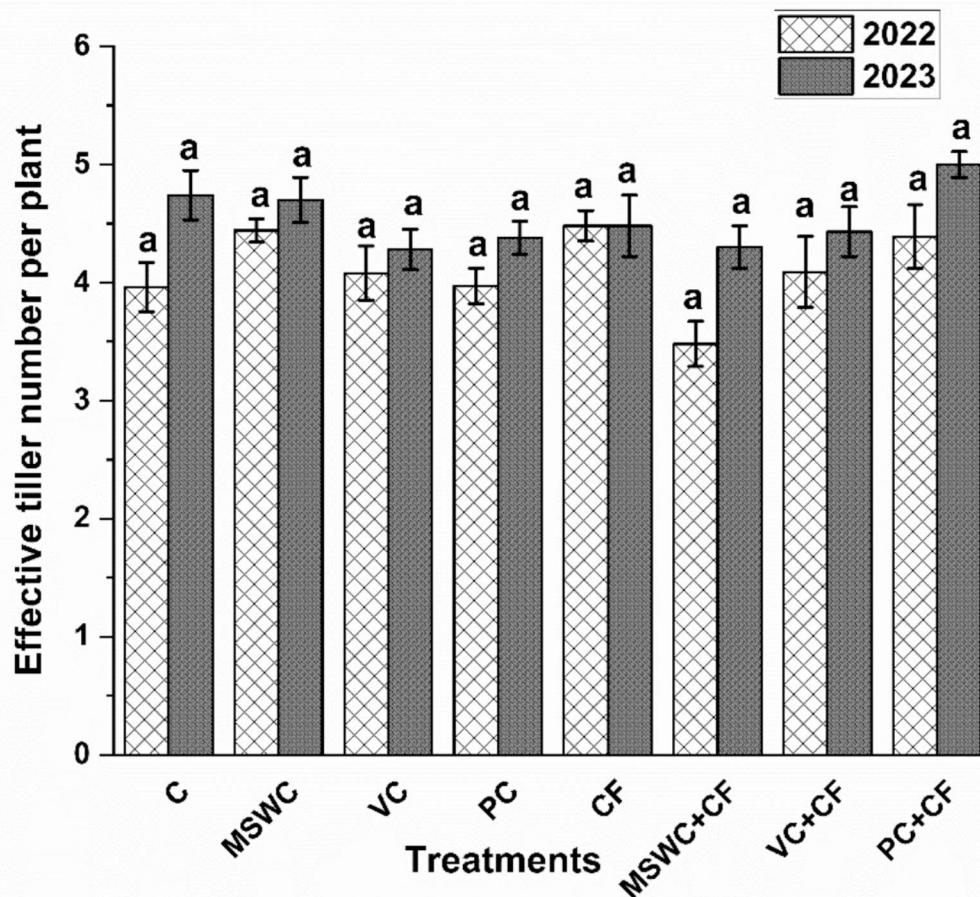


Fig. 4. Effective tiller number per plant in different treatments. The bars with same letters in each treatment are not significantly different in Tukey's HSD test ($p < 0.05$).

composts will be needed to produce the required grain yield of rice if they are amended singly, which can lead to negative impacts like occurrence of pests and more ineffective tiller numbers.

Yield of a crop is a complex character influenced by several crop characters²⁵, and the significant correlation of PL with SNPP and FSNPP showed the positive influence of PL on rice yield. Moreover, there was also a significant correlation of grain yield with PL, TNPP and SNPP showing more the PL; higher was the grain yield and spikelet number per panicle. The growth characteristics of rice showed a positive response only in PC + CF treatment, as there was an average increase of 7.35% in plant height at 60DAT and 4.7% of TNPP compared to CF application. The yield characteristics PL and FSNPP were also enhanced only in PC + CF treatment, with an overall increase of 9.7% and 21.26% respectively over CF treatment. The PC + CF treatment was able to produce maximum grain yield with an increase of 33.6% compared to CF treatment. The treatments MSWC + CF and VC + CF also increased grain yield although they could not positively impact growth characteristics. It indicates that the release of nutrients from VC and MSWC treatments was comparatively slower than PC treatment. The overall grain yield increased by 5.00% in MSWC + CF treatment and 13.16% in VC + CF treatment compared to CF treatment. Higher N content in biomass of the rice plants in composts treatment plots compared to chemical fertilizer treatment plots also indicates a positive impact of the treatments. Similar results of increased rice yield due to co-application of 50% compost with 50% chemical fertilizer were reported^{15,26–28}. Very high straw yield in control and sole application of the composts indicates that more grain bearing in the rice plant can lead to lesser straw yield.

The application of 1.5tha^{-1} of PC (50%) along with 50%CF is highly beneficial for the growth and productivity of rice in the present study area. The initial substrate of PC is *phumdi*, which are mainly composed of different types of aquatic macrophytes *Leersia hexandra*, *Azolla pinata*, *Polygonum orientale*, *Hydrilla verticillata*, etc²⁹. along with a mixture of soil and dead biomass of plants. The *phumdi* compost is locally made therefore, it can be made easily available to farmers. Converting the *phumdi* into compost also helps in managing the eutrophication rate of Loktak Lake. Similar results of an increase in grain yield of rice due to the application of compost made from *Azolla* were reported by Razavipour et al.³⁰. They have reported application of *Azolla* compost at 5% of soil weight provided 13.8% higher yield than the non-amended plots.

Year	Treatment	Panicle length (cm)	Spikelet number per panicle (SPNPP)	Filled spikelet number per panicle (FSNPP)	Unfilled spikelet number per panicle (USNPP)	Percentage of filled spikelet number per panicle (PFSNPP)
2022	Control	16.20±0.82 a	81.67±3.34 ab	61.92±1.66 a	20.36±1.05 c	75.50±2.01 a
	MSWC	17.37±0.34 ab	89.56±2.22 bc	77.15±1.95 bc	12.63±0.60 ab	85.31±0.55 ab
	VC	17.72±0.86 ab	86.24±2.62 ab	72.16±3.44 abc	14.19±1.89 abc	83.83±2.21 ab
	PC	16.57±0.22 a	76.54±2.52 a	66.57±2.07 ab	9.96±1.03 a	87.28±1.31 b
	CF	16.90±0.19 a	78.57±2.37 ab	71.28±1.31 abc	7.97±1.85 a	89.89±2.14 b
	MSWC+CF	18.10±0.85 ab	84.26±2.33 ab	75.53±1.58 bc	8.73±0.95 a	90.04±1.36 b
	VC+CF	18.09±0.66 ab	99.23±3.24 c	80.81±3.49 c	18.85±2.07 bc	83.05±3.82 ab
	PC+CF	18.43±0.76 ab	99.45±1.92 c	82.16±2.08 c	17.04±0.63 bc	82.80±0.83 ab
2023	Control	18.87±0.37 a	96.07±4.36 a	87.86±3.68 a	18.08±1.23 b	83.16±0.90 a
	MSWC	19.31±0.27 ab	109.26±5.42 a	99.07±7.19 ab	10.27±1.51 ab	90.91±0.24 b
	VC	17.77±0.21 a	111.37±4.05 a	91.50±3.61 a	8.29±1.68 a	91.43±1.00 b
	PC	19.30±0.05 ab	102.37±3.51 a	91.84±4.78 a	10.73±2.17 ab	91.12±2.13 b
	CF	18.84±0.32 ab	110.25±5.10 a	97.31±4.75 a	13.19±2.15 ab	90.72±1.55 b
	MSWC+CF	19.67±0.47 ab	112.61±5.40 ab	100.20±7.30 ab	12.54±1.18 ab	88.58±1.02 ab
	VC+CF	19.09±0.288 ab	111.49±4.17 a	99.69±4.81 ab	12.42±3.09 ab	90.74±1.80 b
	PC+CF	20.81±0.30ab	135.39±4.98 b	123.84±5.04 b	11.67±1.53 ab	89.59±2.14 ab

Table 3. Yield characteristics of rice due to treatment of different fertilizer. In a column average followed by the same letter in each year are not significantly different in Tukey’s HSD test ($p < 0.05$). MSWC: Municipal solid waste compost (100%); VC: Vermicompost (100%); PC: Phumdi compost (100%); CF: Chemical fertilizer (100%); MSWC + CF: Municipal solid waste compost + Chemical fertilizer (50%+50%); VC + CF: Vermicompost + Chemical fertilizer (50%+50%); PC + CF: Phumdi compost + Chemical fertilizer (50%+50%).

The performance by co-application of 50%VC (1.76tha^{-1}) with 50% of CF comes after PC + CF treatment while considering grain yield and straw yield and 50%MSWC treatment (1.85tha^{-1}) + 50%CF could also produce more grain yield compared to CF. Similar application rates of vermicompost of 2.25tha^{-1} , along with jeevamrutha were found to enhance the productivity of Manipur black rice³¹. A maximum yield of rice was recorded in the treatment of 50% chemical fertilizer with compost at the rate of 2.5 t ha^{-1} ¹³². Sultana et al.²⁵ also reported a combined application of MSWC at the rate of 5tha^{-1} and 75% chemical fertilizer producing 83.27% more rice yield. Maximum grain and straw yield was found in treatment having a substitution of 50% N through compost at the rate of 10tha^{-1} by Gosal et al.²². Stewart et al.³³ also reported the best compost fertilization rate for grain yield of rice to be 10tha^{-1} which is higher than the present rate of application of composts. Reports have shown presence of humic acid in vermicompost making it agronomically efficient and ecofriendly³⁴ and use of vermicompost is a simple, cost-effective and eco-friendly alternative. Moreover a wide variety of bacteria species like *Bacillus* spp., *Enterobacter* spp., *Pseudomonas* spp. and *Streptomyces* are found in vermicompost and derivatives from these bacteria inhibit growth of plant-pathogenic fungi⁷. Production of rice was higher in second year compared to first year, because the residual composts from first year in the fields were able to provide nutrients in the second year again. A similar residual effect after one year of application of compost in rice cultivation was also reported by Tran et al.³⁵.

Substituting 50% of chemical fertilizer with composts while producing more crop yield is an important step in taking up efficient nutrient management plan in rice cultivation in the present study area. The limitations of the present study is analysis of microbial population, an important parameter for such kind of work could not be carried out moreover, only N content for biomass could be provided for estimating grain quality leading to a scope for further studies.

Conclusion

The 50% substitution of chemical fertilizer with composts recorded more grain yield compared to conventional chemical fertilizer treatment in cultivation of the present rice variety. The co-application of *phumdi* compost with chemical fertilizer was able to produce maximum grain yield. The present study would recommend utilization of locally available composts as a substitution of 50% chemical fertilizer specially *phumdi* compost and vermicomposts as they were able to produce 5% more grain yield compared to sole application of chemical fertilizer.

Materials and methods

Experimental site

A field experiment was conducted at the Rice Research Station, Wangbal set up under the Department of Agriculture, Manipur (Fig. 8). Cultivation of rice is carried out in the present field for thirty years. The study area is situated in Thoubal, a valley district of Manipur, Northeast India located at latitude of $24^{\circ}36'50''\text{N}$ to $24^{\circ}36'55''\text{N}$ and longitude of $94^{\circ}1'10''\text{E}$ to $94^{\circ}1'25''\text{E}$, with altitude of 790 m asl. The region has a sub-tropical

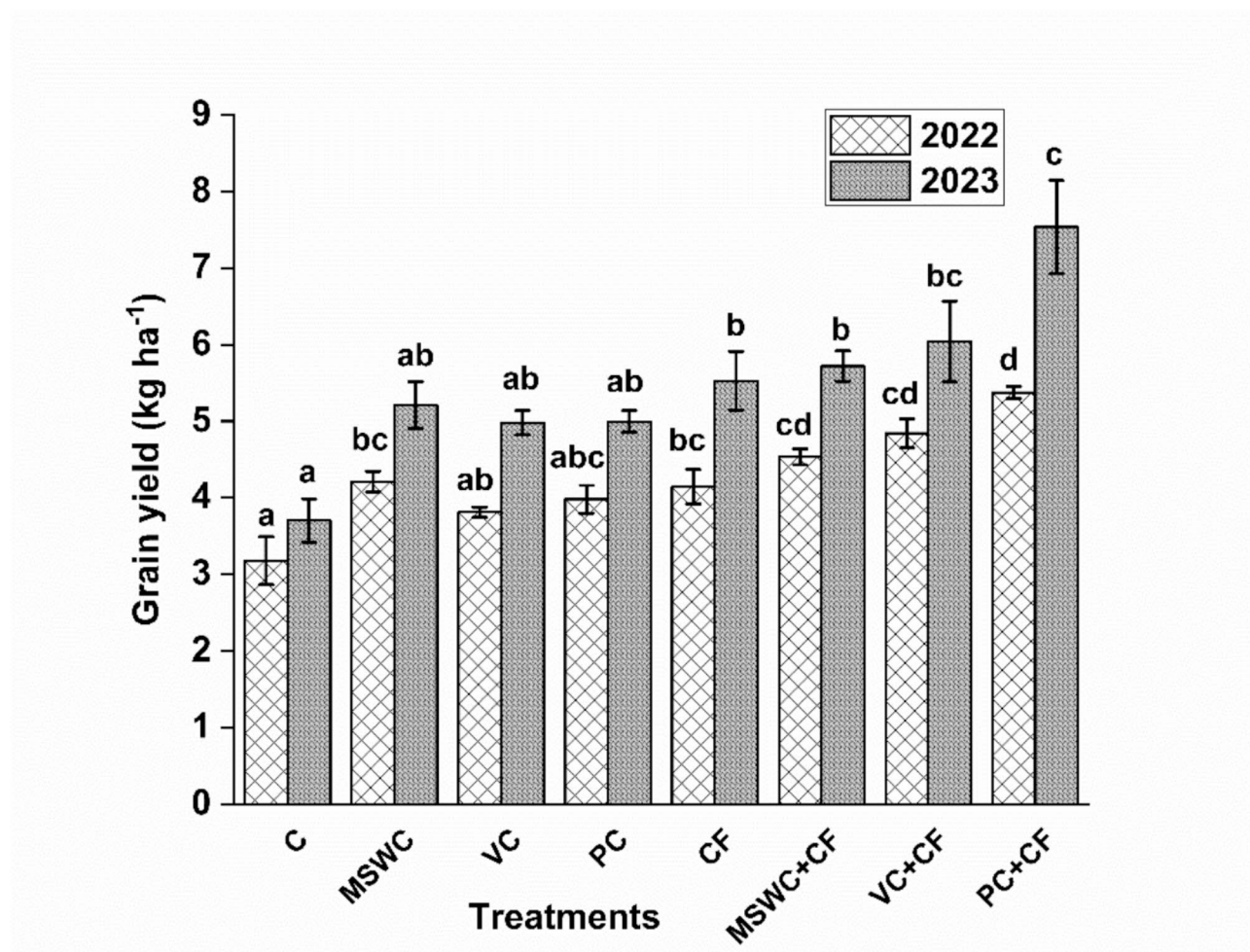


Fig. 5. Grain yield of rice in different treatments. The bars with same letters in each treatment are not significantly different in Tukey's HSD test ($p < 0.05$).

climate with a mean temperature ranging from 22 to 28 °C during the study period and annual precipitation of 1000–1200 mm (Fig. 9). The study was conducted during the months, July to November for two consecutive years (2022, 2023).

Soil analysis

Analysis of physico-chemical characteristics of soil was carried out by taking three replicates of soil sample from each experimental plots before cultivation of rice. pH of soil was determined using digital pH meter using extract of 1:5 fresh soil: water, bulk density using soil corer method, total N using Kjeldahl's digestion and titration method, available P using molybdenum blue method and organic C using Walkley and Black's method outlined in Anderson and Ingram³⁷ and AK using flame photometer.

Initial quality of composts

Proper examination of the source of organic municipal solid waste used for making compost was done. After confirming that no contamination of hazardous chemicals and heavy metals occurred, the compost derived from municipal solid waste was collected from a state government-aided compost production center. The method used was windrow composting. Vermicompost made from a combination of rice straw and cow manure using windrow method was collected from small scale local production center. Similarly *phumdi* compost was also collected from a local production center using the same method of windrow composting. Initial qualities of the three composts were determined before field application. Total N was analyzed using Kjeldahl's digestion method, available P by using molybdenum blue method³⁷, available K by flame photometer and pH by taking 1:5 compost: water extract and organic C by dry ashing method³⁸.

Experimental design

A total of 8 different types of treatments were maintained in the present study following completely randomized block design and maintained three replicates for each treatment (Fig. 10). The treatments were: (1) Control, where no fertilizers were applied (2) MSWC (Municipal solid waste compost, 100%) (3) VC (Vermicompost,

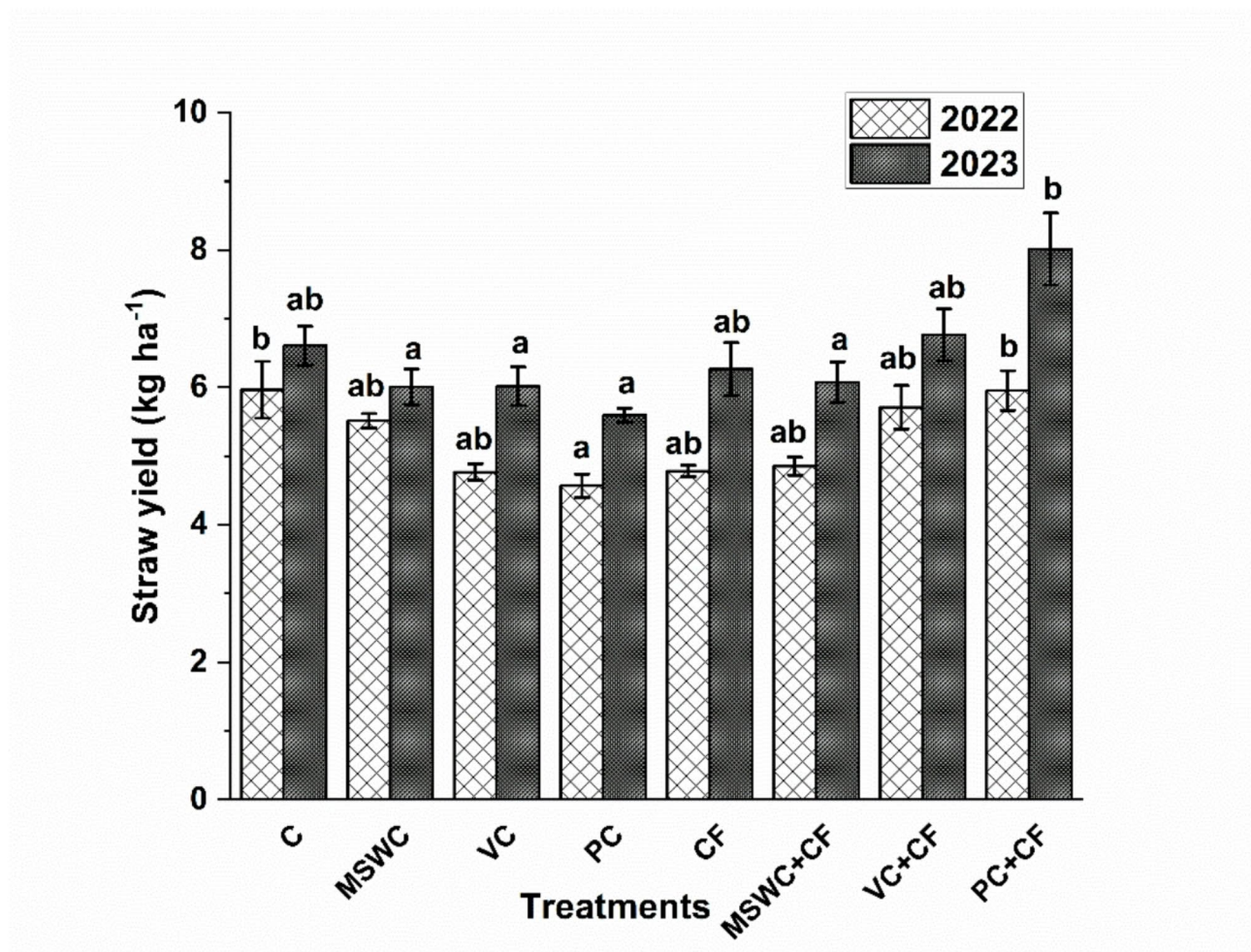


Fig. 6. Straw yield of rice in different treatments. The bars with same letters in each treatment are not significantly different in Tukey's HSD test ($p < 0.05$).

100%) (4) PC (*Phumdi* compost, 100%) (5) CF (Chemical fertilizer, 100%) (6) MSWC + CF (50%+50%) (7) VC + CF (50%+50%) (8) PC + CF (50%+50%). The size of one block was 2×2 m keeping a gap of 1 m between the adjacent blocks. Each block was separated from other blocks by a thick layer of mud.

Rice cultivation

The rice variety RCM-13 (RC Maniphou 12) was selected for the present study. RCM-13 takes 111 days for maturation which is shorter compared to other rice varieties. It was produced by cross fertilization between Leimaphou and Akhanphou, which are local rice varieties by the Indian Council of Agricultural Research, Manipur. Viable pure seeds were selected and soaked in water for 24 h, incubated for another 24 h and sowed in a separate field near the experimental plots. The 21-day-old seedlings were transplanted with one seedling per hill in the experimental plots. The plant spacing was maintained at 15×10 cm. Application of composts and chemical fertilizer was based on the amount of total N contained in the composts and the chemical fertilizer urea, fulfilling the recommended dose 60 kg ha^{-1} by dividing into three doses. The three split doses of application were 40% at the basal stage just before transplantation in the experimental field, 40% at the tillering stage (20 days after transplantation) and the remaining 20% at the panicle initiation stage (47 days after transplantation). Single super phosphate as P fertilizer and muriate of potash as K fertilizer were applied at two split doses, 60% at the basal stage before transplantation in the experimental plots and remaining 40% at tillering stage (47 days after transplantation). Detailed rate of application rate of the fertilizers is provided at the bottom of Fig. 10. Weeding was done manually whenever necessary. No artificial irrigation was done, only rain fed cultivation of the rice was carried as the rainfall normally exceeds approx. 150 mm per month during monsoon season.

Measurement of plant growth characteristics

Plant height was measured at 30-days interval from the day of transplantation, excluding the border hills of the plot. Recording of plant height was done at 30, 60 and 90 days after transplantation (DAT). Plant height was obtained by measuring the main shoot from the ground level up to the tip of the largest leaf stretched of rice plants. 30 hills were marked within each plot to record the plant height. The tiller number per plant (TNPP) and

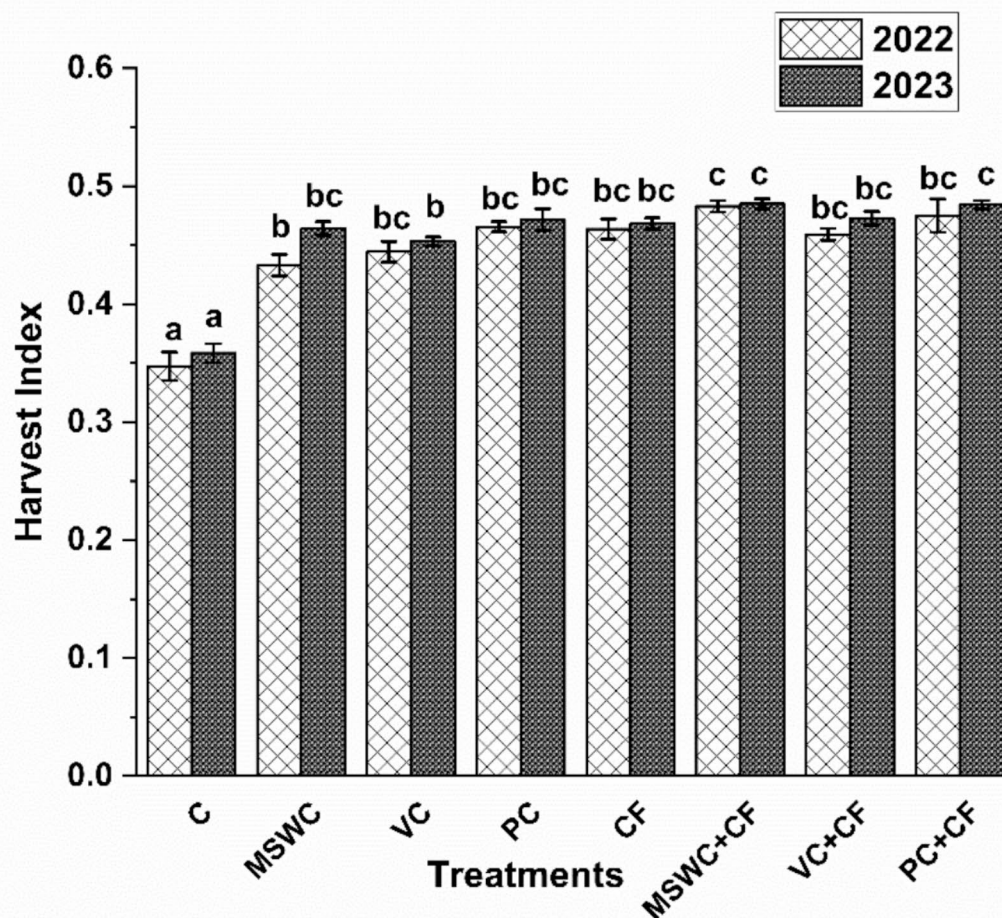


Fig. 7. Harvest index of rice in different treatments. The bars with same letters in each treatment are not significantly different in Tukey's HSD test ($p < 0.05$).

Treatment	Biomass N content (%)	N uptake (kg N ha^{-1})
Control	1.97 ± 0.12 a	17.26 ± 2.25 ns
MSWC	6.67 ± 0.09 b	63.15 ± 3.32 ns
VC	3.93 ± 0.16 c	34.57 ± 0.27 ns
PC	4.68 ± 0.33 c	40.08 ± 2.70 ns
CF	2.98 ± 0.06 ab	30.98 ± 6.75 ns
MSWC + CF	5.41 ± 0.36 b	51.86 ± 1.91 ns
VC + CF	3.88 ± 0.18 c	41.40 ± 1.28 ns
PC + CF	5.92 ± 0.19 b	73.44 ± 6.92 ns

Table 4. Biomass N content and N uptake due to treatment of different fertilizers. In a column average followed by the same letter are not significantly different ($p < 0.05$), ns indicates not significant.

effective tiller number per plant (ETNPP) were determined at the maturity stage of the plant from the selected 30 hills. The plant height (PH), TNPP and ETNPP were recorded as growth characteristics of rice.

Measurement of yield characteristics

Harvesting was done at 91 days after transplantation, during the time of harvest panicle length (PL), spikelets number per panicle (SNPP), filled spikelets number per panicle (FSNPP), unfilled spikelets number per panicle (USNPP) and percentage of filled spikelets per panicle (PFSNPP) were recorded from each plot. Grain and straw yield were also recorded from the total area of the plot. Harvest Index (HI) was calculated by following the formula given by Yoshida³⁹.

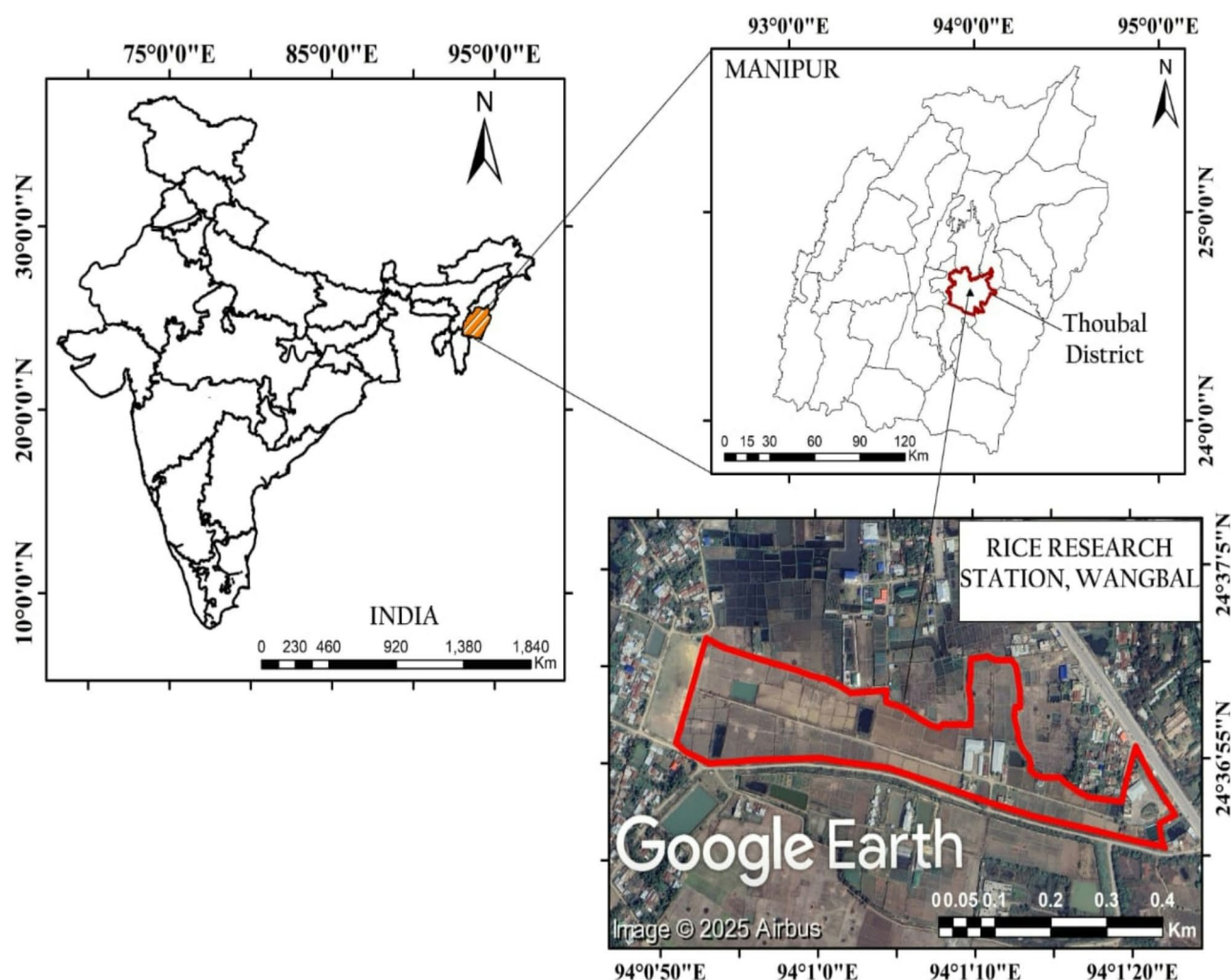


Fig. 8. Map indicating the study area prepared by using QGIS 3.36.2 and Google Earth Pro (www.google.com)³⁶.

Harvest Index = Economical yield/Biological yield.

Where, economical yield is the total grain weight and biological yield is the total grain and straw weight. The TNPP, ETNPP, PL, SNPP, FSNPP, USNPP, PFSNPP, grain yield, straw yield and HI were recorded as yield characteristics of rice.

N uptake

Dry weight of the harvested rice plants were taken after air-drying thereby, the plant N uptake (kg N ha^{-1}) was calculated as product of total dry biomass weight and biomass N concentration⁴⁰. The biomass N content was determined by Kjeldahl's digestion method³⁷.

Statistical analysis

The data collected were subjected to analysis of variance (ANOVA) one-way and two-way, followed by Tukey's HSD test for the significant variations. The standard deviation among the samples was evaluated. Karl Pearson's coefficient of correlation, followed by t-test for evaluating significant levels was done for applicable attributes. All the analyses were done using SPSS Statistics 25.0, MS Excel and OriginPro.

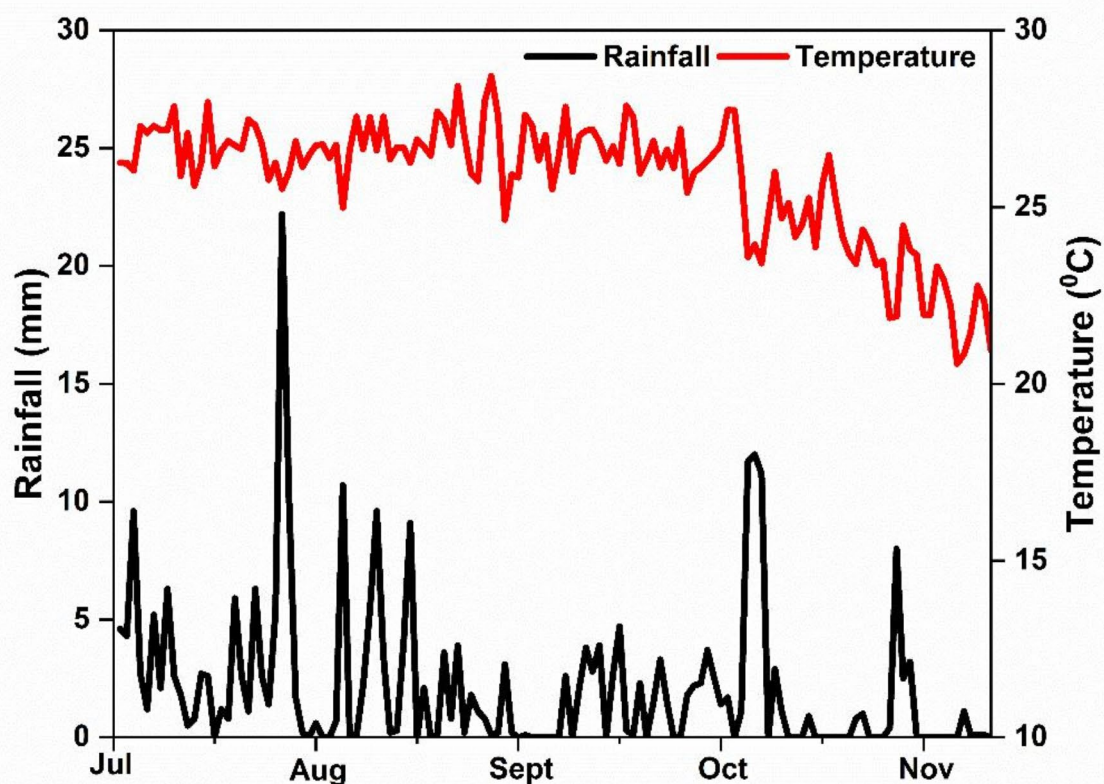


Fig. 9. Rainfall and average air temperature recorded during the study period. *Source* Meteorology Department, Government of Manipur.

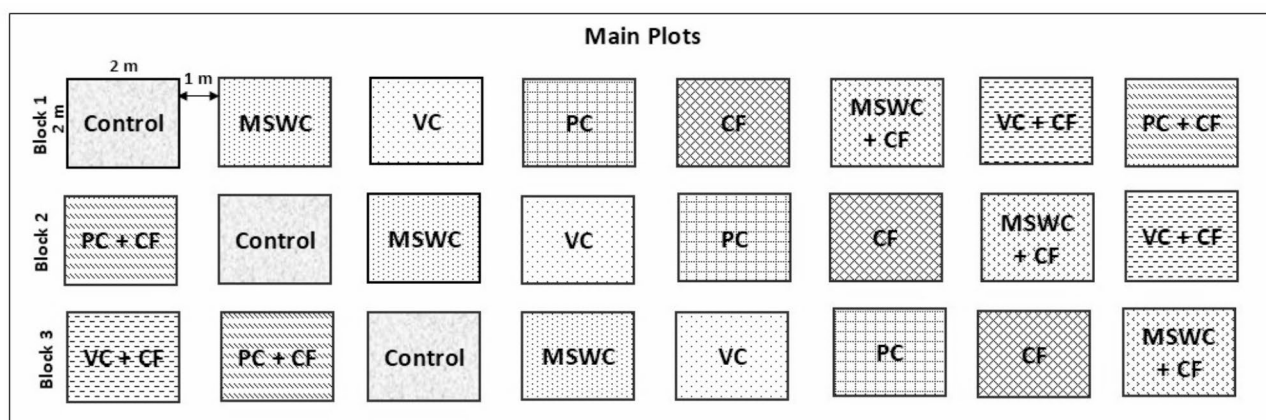


Fig. 10. Randomized block design of experimental plots. Control: no fertilizer; MSWC: Municipal Solid Waste Compost @ 3.7 t ha^{-1} ; VC: Vermicompost @ 3.5 t ha^{-1} ; PC: Phumdi Compost @ 3.0 t ha^{-1} ; CF: Chemical Fertilizer @ 0.13 t ha^{-1} (recommended dose); MSWC + CF: 1.85 t ha^{-1} MSWC + 0.06 t ha^{-1} CF; VC + CF: 1.76 t ha^{-1} VC + 0.06 t ha^{-1} CF; PC + CF: 1.5 t ha^{-1} PC + 0.06 t ha^{-1} CF.

Data availability

All data generated during this study are included in this published article and its supplementary files.

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Author contributions

NTD has done the experimental work, statistical analysis and drafting the manuscript ASD and KRS provided the facilities for completing the work and guided in every aspect to NTD.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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Integrated Nutrient Management: An Effective Strategy to Mitigate Greenhouse Gas Emission and Global Warming Potential Under Rice Cultivation

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Abstract

Nutrient management practices in rice cultivation have a profound impact on the emission of greenhouse gases, especially methane (CH₄) and nitrous oxide (N₂O). Practices involving amendment of different kinds of substrate constituting organic waste have gained momentum in finding measures to reduce the emission of CH₄ and N₂O from rice fields. A field experiment was conducted for two years consecutively in rice field to measure emission of CH₄ and N₂O under the treatment of different kinds of composts, along with their combination with chemical fertilizer. A short-duration rice variety, RC Maniphou 12 (RCM 13) was cultivated in rainfed condition. Three different types of composts were selected for the present study- compost made from organic components of municipal solid waste (MSWC), vermicompost (VC) made from rice straw and cow dung and compost made from *phumdi*, a local name given to floating mass of aquatic plants and soil found in Loktak lake in Northeastern India (PC). The plots with integrated treatments of composts and chemical fertilizer showed lower cumulative emissions of CH₄ and N₂O compared to plots treated with chemical fertilizer (CF) alone. The treatment of 50%VC+50%CF recorded minimum global warming potential (GWP) with 2112.22 kg CO₂ eq. ha⁻¹ and maximum of 4776.56 kg CO₂ eq. ha⁻¹ from the sole application of MSWC. GWP reduced by 17.37%, 56.44%, and 16.40% in the integrated treatments of 50%MSWC+50%CF, 50%VC+50%CF, and 50%PC+50%CF, respectively, compared to CF. A reduction in greenhouse gas intensity (GHGI) was also observed in VC+CF with 69.49%, followed by 48.75% in PC+CF and 22.35% in MSWC+CF compared to CF. The study showed that integrated use of chemical fertilizer with vermicompost and *phumdi* compost are beneficial in cultivation of short-duration rice crop in rain-fed conditions in North-east India in reducing emission of CH₄ and N₂O. It may help lawmakers in formulating measures to reduce global climate change related to agricultural activities.

Keywords Compost · Emission factor · Global warming potential · Greenhouse gas emission · Vermicompost

Introduction

India is among the major rice-producing countries, producing 172.58 million tonnes of rice annually, contributing maximum harvested area with 44.50 million ha in South Asia [17]. The area under rice cultivation in India is diverse and distributed unevenly throughout the country, and about 52% of the total rice-producing areas are rain-fed, while the remaining areas are irrigated [18]. CH₄ emission from rice fields of India has been estimated at approx. 4.09 ± 1.19 Tg year⁻¹ from 1979 to 2006 [36], thereby becoming one of the top ten emitters of CH₄ with 10% of the global emission share [9]. To meet the increasing demand for food for the

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growing population, global rice production is expected to increase by 24% in 2030 [14].

As rice grows favorably under submerged soil conditions, it provides suitable conditions for methanogenic bacteria and is identified to contribute around 30% and 11% of the global agricultural CH_4 and N_2O emissions [21]. Methanotrophs oxidize part of the produced CH_4 , and the CH_4 escaping is transported to the atmosphere mainly through the aerenchyma tissues of rice plants and ebullition of gas bubbles [27]. More than 90% of CH_4 emitted from the paddy fields is through the rice plants [38]. N_2O is emitted due to soil management practices, such as applying synthetic N fertilizers, N input through crop residue and enhanced mineralization of N of soil organic matter caused by continuous land cultivation or land use change [2]. The atmospheric concentrations of CH_4 and N_2O reached a level of 1889 ppb and 336 ppb, respectively, exceeding 262% and 123% of pre-industrial levels [55].

Production of greenhouse gas (GHG) from rice fields is influenced by several factors, like type and quantity of fertilizer input, water management, rice cultivars, soil types, etc [19, 43, 45, 47, 48]. Prolonged application of chemical fertilizers (CF) deteriorates the overall quality of soil, as well as assists in the emission of GHGs from the rice fields. Thereby, the global warming potential (GWP)- the amount of heat energy a GHG can trap in the atmosphere relative to CO_2 increases. With proper management practices, emission of CH_4 and N_2O from rice fields can be mitigated without compromising yield. Measurement of greenhouse gas intensity (GHGI) - the total amount of GHGs emitted per unit of grain yield and carbon emission ratio (CER), essentially giving a ratio of output C in the atmosphere to C stored in the biomass is important in formulating different measures to reduce GHG emission from rice fields. Scientists and researchers have emphasized the advantages of amendment of organic material in rice fields.

Intermittent drainage system is also proven to reduce CH_4 emissions from rice cultivation. However, the practice of intermittent drainage system in Northeast India is challenging as artificial irrigation is not a normal practice. Majority of the low-lying rice cultivated plain areas depend on the monsoon season as a kind of rainfed cultivation. Therefore, using different nutrient management practices can be more applicable in this region. Few studies have been conducted on the utilization of different kinds of organic fertilizer as a measure of reducing GHG in different parts of India [5, 6, 10, 11, 42]. A study from Assam one of the Northeast state of India, reported application of organic fertilizer enhanced CH_4 emission from rice field compared to CF application. However, application of composted *Azolla* remarkably improved grain yield and reduced CH_4 emission compared to application of green manure and cow manure [5].

According to Dhanuja et al. [13] application of vermicompost significantly increased CH_4 emission than CF, however N_2O emission was relatively higher in the latter treatment.

Loktak Lake, a Ramsar site in Northeast India, is famous for its floating mats comprising of a mixture of aquatic vegetation and soil, locally called *phumdi*. It consists of various aquatic vegetation, namely *Hydrilla verticillata*, *Phragmites karka*, *Azolla pinata*, *Polygonum orientale*, etc. along with organic debris of dead biomass and soil. Excessive *phumdi* caused degradation of the lake ecosystem and making compost from *phumdi* is carried out at small scales by private entrepreneurs. As studies on utilization of locally available organic fertilizers have been emphasized with consideration of reducing cost of agricultural output and reducing climate change, some studies were conducted to estimate emission of GHG through municipal solid waste management activities [16, 26–28, 34]. However, emission of GHG due to application of organic fertilizer in rice field is not well documented. More research is essential to identify the potential of locally available organic materials as a substantial source of organic fertilizer in reducing GHG emissions from rice field. Therefore, the present study was undertaken to investigate the impact of municipal solid waste compost, vermicompost and *phumdi* compost integrated with CF on emission of CH_4 and N_2O from rice fields. The emission factor (EF), GWP, GHGI, carbon efficiency ratio (CER) and nitrogen use efficiency (NUE) due to the application of different fertilizer treatments was also evaluated. It was hypothesized that the integrated treatment of composts and CF could reduce GHG emissions from rice fields compared to sole application of CF without declining grain yield of rice.

Materials and Methods

Experimental Setup

The study was conducted in Thoubal district of Manipur, one of the eight states of Northeast India. The experimental fields were set up at the Rice Research Station, Wangbal, Thoubal, Manipur located at latitude of $24^{\circ}36'50''\text{N}$ to $24^{\circ}36'55''\text{N}$ and longitude of $94^{\circ}1'10''\text{E}$ to $94^{\circ}1'25''\text{E}$, having an altitude of 790 m above m.s.l. The cultivation of rice was done during July to November for two consecutive years, 2022 and 2023. The region receives annual rainfall of 1200 mm, recorded average air temperature of 25.89°C . The texture of the soil was clayey loam with 33% sand, 31% silt and 36% clay and the type of soil was Inceptisol [52].

Three types of composts were collected from private firm. They were (1) Compost made from municipal solid waste (2) Vermicompost derived from cow dung and rice

straw and (3) Compost made from *phumdi*. Municipal solid waste compost was produced from the organic component of municipal solid waste by employing biological degradation using machines. *Phumdi*compost was made from windrow composting method of composting. The detailed chemical characterization of the three composts are provided in our previous publication [12].

The experimental field was thoroughly ploughed, followed by puddling and flooded for few weeks before transplantation. RC Maniphou12 (RCM-13) a rice variety having shorter life span of 95 to 115 days was procured from Indian Council of Agricultural Research, Manipur for the present study. Sowing of the seeds was done in a separate plot which was ploughed and puddled with water. The twenty-one days old rice seedlings were transplanted in the experimental plots with one seedling per hill maintaining a plant spacing of 15×20 cm. The experiment was carried out using randomized block design method consisting of eight different treatments with three replications for each treatment (Fig. 1) reproduced from Devi et al. [12]. The size of the plots were maintained at 2×2 m. The treatments were control (C), where no fertilizers were applied; municipal solid waste compost, 100% (MSWC); vermicompost, 100% (VC); *Phumdi* compost, 100% (PC); Chemical fertilizer, 100% (CF); MSWC + CF (50%+50%); VC + CF (50%+50%); and PC + CF (50%+50%) [12]. The NPK fertilizer used were urea, single super phosphate and muriate of potash. They were applied as per the recommended dose of the Department of Agriculture, Manipur which was $60:40:40 \text{ kg ha}^{-1}$. The rate of compost application was based on the amount of total N contained in the composts. Therefore, 3.7 t ha^{-1} , 3.5 t ha^{-1} and 3.0 t ha^{-1} of MSWC, VC and PC, respectively, were necessary to supply 60 kg N ha^{-1} in the field, detailed description is also provided in Devi et al. [12]. The composts and urea were amended in three split doses: 40% before transplantation of seedlings, 40% at the tillering stage, and remaining 20% at the panicle initiation stage. Single superphosphate and muriate of potash were amended

in the plots in two doses, 60% before transplantation and the remaining 40% at tillering stage. Removal of weeds was done manually whenever required. The cultivation of rice was done in natural rainfed condition without any artificial irrigation. Grain yield from the plots were recorded at mature stage. The grains were separated from the straw and sun-dried, weighed and values were expressed in t ha^{-1} . Samples of the matured rice plant were kept for estimation of biomass C and N content.

Soil Analysis

Soil samples were collected from each plot at four different stages namely active tillering (25–30 days after transplantation), panicle initiation (40–45 days after transplantation), flowering (50–55 days after transplantation) and post-harvesting (105 days after transplantation). The collected soil samples were air-dried, grounded and sieved through 2 mm wire mesh. The pH and EC were measured from the fresh soil using a portable environmental probe (Hanna, Model-HI98194). The soil organic carbon (SOC) was determined using TOC analyzer (TOC-SSM-5000 A).

Gas Sample Analysis

Closed Chamber Technique described by Hutchinson and Mosier [22] was used for monitoring CH_4 and N_2O emission. Circular aluminum base plate having a channel to accommodate the plastic chamber and water to provide air-tight condition were permanently fixed in the soil in the experimental plots. Four hills were enclosed inside the aluminum base. Cylindrical plastic chambers having diameter of 46 cm and height of 60 cm, fitted with a three-way stock cock on top of the chamber were placed in the grooves of the aluminum base to cover the rice hills enclosed within the aluminum base. The gas samples were collected at weekly intervals during growing season, starting from the day after transplantation (DAT) till one week after harvesting of rice.

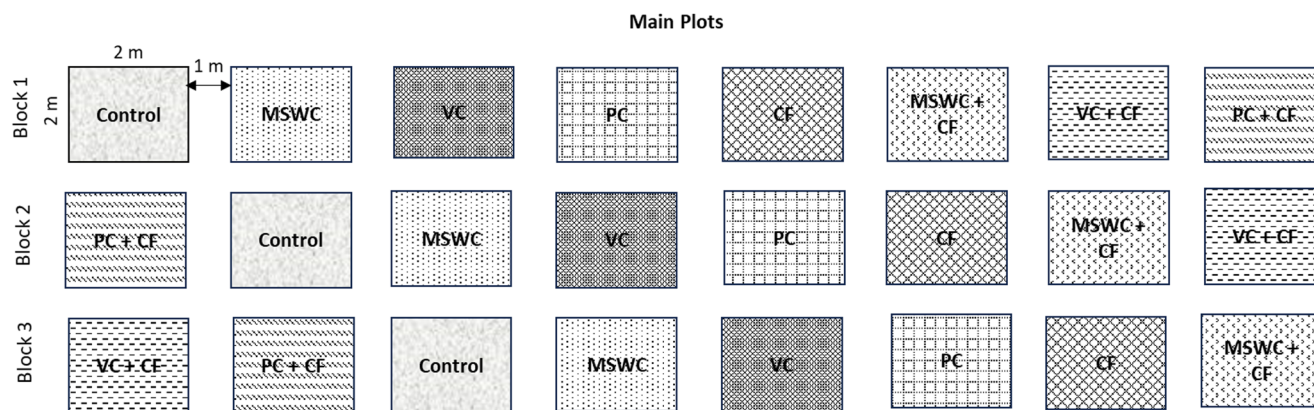


Fig. 1 Randomized Block Design of the different treatments, reproduced from Devi et al. [12]

Gas samples were drawn from the chambers using a 15 mL airtight syringe through the three-way stock cock fitted on top of the chamber at time intervals of 0, 15 and 30 min, respectively. The gas sampling was conducted between 9.00 a.m. and 11.00 a.m.

Concentration of CH₄ and N₂O were estimated using Gas Chromatography (Trace 1110, Thermo Fisher, USA) fitted with a Flame Ionization Detector (FID) and Porapak N column for both the gases and additional electron-capture detector (ECD) for N₂O. The FID and ECD temperature of the instrument were maintained at 240 °C and 300 °C respectively, nitrogen gas was used as the carrier gas. CH₄ and N₂O fluxes from each plot were calculated only from the data showing a linear increase of concentration with time.

The CH₄ flux was determined by following the formula outlined by Debnath et al. [11]:

$$F \text{ (mg m}^{-2}\text{hr}^{-1}\text{)} = \left[\frac{(C_t - C_0)}{t} \right] \times H \times 42.857$$

where, t is the time in min; C_0 is the initial concentration of CH₄ in ppm V; C_t is the final concentrations of CH₄ in ppm V; H is the height of headspace in meter; F is the flux of CH₄.

The N₂O flux was determined by following formula outlined by Pathak et al. [37]:

$$F \text{ (}\mu\text{m}^{-2}\text{h}^{-1}\text{)} = \left[\frac{(C_t - C_0)}{t} \right] \times H \times \frac{44}{22.4}$$

where, t is the time in min; C_0 is the initial concentration of N₂O in ppb V; C_t is the final concentration of N₂O in ppb V; H is the height of headspace in meter; F is the flux of N₂O.

Total emission of the gas during the entire cultivation period was determined by using the following formula outlined by Ma et al. [33]:

$$\text{Cumulative seasonal CH}_4 \text{ or N}_2\text{O emission} = \sum_{i=0}^n F_i \times D_i$$

where, F_i is the flux of CH₄ or N₂O flux in the i^{th} sampling interval; D_i is the number of days and n is sampling intervals.

The emission factor (EF) of CH₄ for treatments were computed using the following formula outlined by Sun et al. [49]:

$$EF_{\text{CH}_4} = \frac{SCH_4}{D}$$

where, EF_{CH_4} is the CH₄ emission factor for each treatment in kg ha⁻¹ d⁻¹, SCH_4 is the seasonal cumulative CH₄

emission in kg ha⁻¹ and D is the rice cultivation period in days.

$$EF_{\text{N}_2\text{O}} = \frac{SN_{2\text{O, fertilized}} - SN_{2\text{O, non-fertilized}}}{N_{\text{input}}} \times \frac{28}{44}$$

where, $EF_{\text{N}_2\text{O}}$ is the N₂O emission factor for each fertilized treatment in kg N₂O-N (kg N)⁻¹, $S_{\text{N}_2\text{O, fertilized}}$ and $S_{\text{N}_2\text{O, non-fertilized}}$ are the seasonal cumulative N₂O emissions in kg N₂O ha⁻¹ from fertilized and non-fertilized treatments, N_{input} is the total N input and $\frac{28}{44}$ is the conversion factor from N₂O to N₂O-N.

Estimation of GWP, Greenhouse Gas Intensity (GHGI) and Carbon Efficiency Ratio (CER)

The GWP (the amount of heat energy a GHG can trap in the atmosphere relative to CO₂) of CH₄ and N₂O is 27 and 273 times that of CO₂ respectively based on a 100-year time horizon with the most recent data provided by IPCC [24] and GWP of the different treatments was calculated as:

$$\text{GWP (kg CO}_2\text{ equivalent ha}^{-1}\text{)} = 27 \times \text{CH}_4 \text{ (kg ha}^{-1}\text{)} + 273 \times \text{N}_2\text{O (kg ha}^{-1}\text{)}.$$

GHGI (the total amount of GHGs emitted per unit of grain yield) was calculated by dividing total GHG emission by grain yield of rice. CER (ratio of output C in the atmosphere to C stored in the biomass) was calculated using the following outlined by Bharali et al. [5]:

$$\text{CER} = \frac{\text{Grain yield of the rice (in terms of C)}}{\text{CEE}}$$

$$\text{where, CEE (Carbon Equivalent Emission)} = \frac{\text{GWP} \times 12}{44}.$$

The C content of rice grain was estimated using the dry ashing method outlined by Campbell and Plank [8].

Nitrogen Use Efficiency (NUE)

NUE was estimated as the difference between N uptake in the fertilized plot and N uptake in the unfertilized plot divided by the total nitrogen applied [53].

$$\text{NUE} = \frac{\text{Plant N uptake in fertilized plot} - \text{Plant N uptake in unfertilized plot}}{\text{Total N applied}} \times 100.$$

where, plant N uptake in kg N ha⁻¹ was calculated as the product of total dry biomass weight and plant N concentration.

The plant N content was estimated using the Kjeldahl's digestion and titration method outlined in Anderson and Ingram [4].

Statistical Analysis

Statistical analysis was carried out using the SPSS Statistics 25.0. Data were first pre-tested for normality and homogeneity using the Shapiro-Wilk and Levene's test, respectively. The data of CH₄ flux and N₂O flux violates the assumption of normality and homogeneity, hence the non-parametric test, Kruskal-Wallis test was performed to evaluate the variation in treatment. Mann-Whitney test was carried out to compare the gas flux between the two years. And for those data that meet the assumption of normality and homogeneity, analysis of variance was done for different treatments and years. Tukey's Post Hoc test was done for pair-wise comparison of treatments at 5% probability level and t-test was used to compare the mean difference between the two years. Graphical representations were made using OriginPro.

Results

The average air temperature and annual rainfall during the two years did not vary significantly. Average maximum temperature ranged from 20.9 to 31.8 °C in 2022 and 22.8 to 32.0 °C during 2023 indicating a higher range in the second year. During the cropping months (July to November) of rice, the total rainfall was recorded to be 367.4 mm and

255.0 mm during 2022 and 2023, respectively showing lower rainfall pattern during the second year. The average soil pH ranged from 6.4 to 6.6, EC ranged from 29.44 to 36.31 $\mu\text{S}/\text{cm}^3$ ($p < 0.05$) and SOC ranged from 0.7 to 1.4% ($p < 0.05$) among the treatments.

CH₄ Emission

The variation in flux of CH₄ showed a similar trend regardless of different treatments in the two study period ($p < 0.01$). The CH₄ flux (Figs. 2 and 3) gradually increased from early stage, reached its first peak in active tillering stage and second peak in reproductive stage and declined afterwards. In both years, MSWC treatment emitted maximum cumulative CH₄ with 45.57% and 134.55% more than CF and C, respectively ($p < 0.05$). When correlation studies were done the CH₄ flux was found to be correlated only with air temperature ($r = 0.63$, $p < 0.05$). CH₄ flux was also found to be positively correlated with SOC ($r = 0.68$, $p < 0.05$) and soil pH ($r = 0.70$, $p < 0.05$) and a negative correlation was found with EC of soil ($r = -0.63$, $p < 0.05$). The cumulative emission of CH₄ in the integrated treatments MSWC+CF and PC+CF were significantly higher than those of C and CF, however, they recorded lesser emission than the sole applications of the composts. The VC+CF treatment recorded minimum cumulative emission of CH₄ in first and second years compared to all treatments ($p < 0.05$) (Fig. 4).

Fig. 2 Seasonal variation of CH₄ flux from rice field during rice growing season of 2022 under different treatments (mean $\pm$ SD)

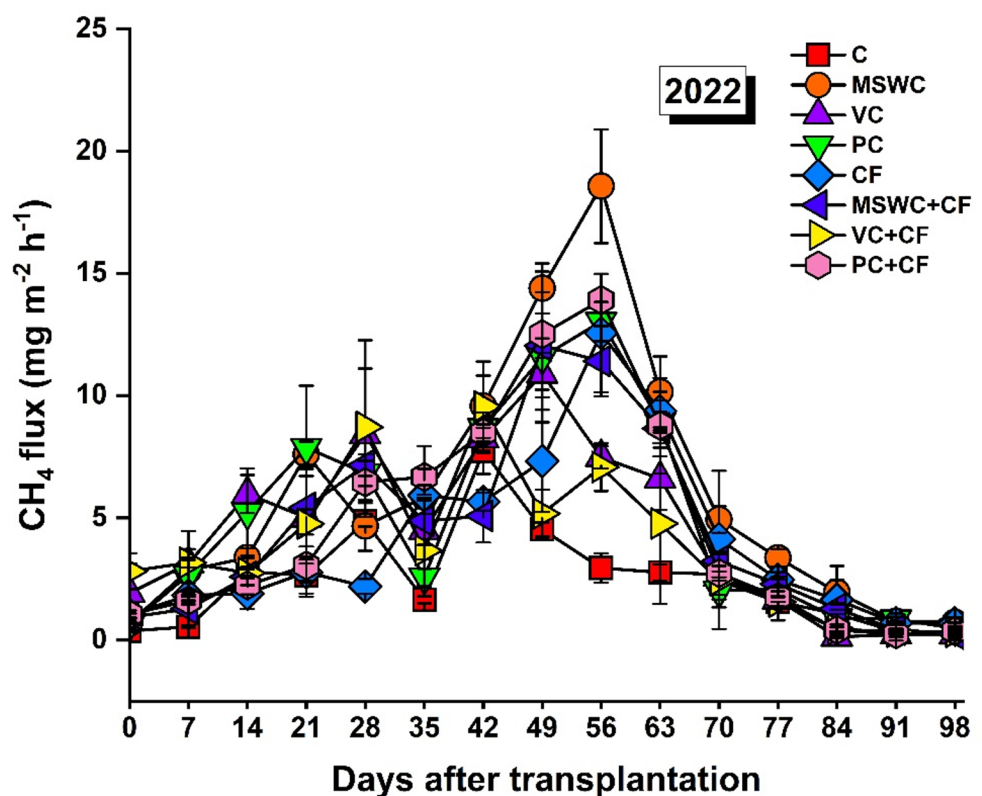


Fig. 3 Seasonal variation of CH₄ flux from rice field during rice growing season of 2023 under different treatments (mean±SD)

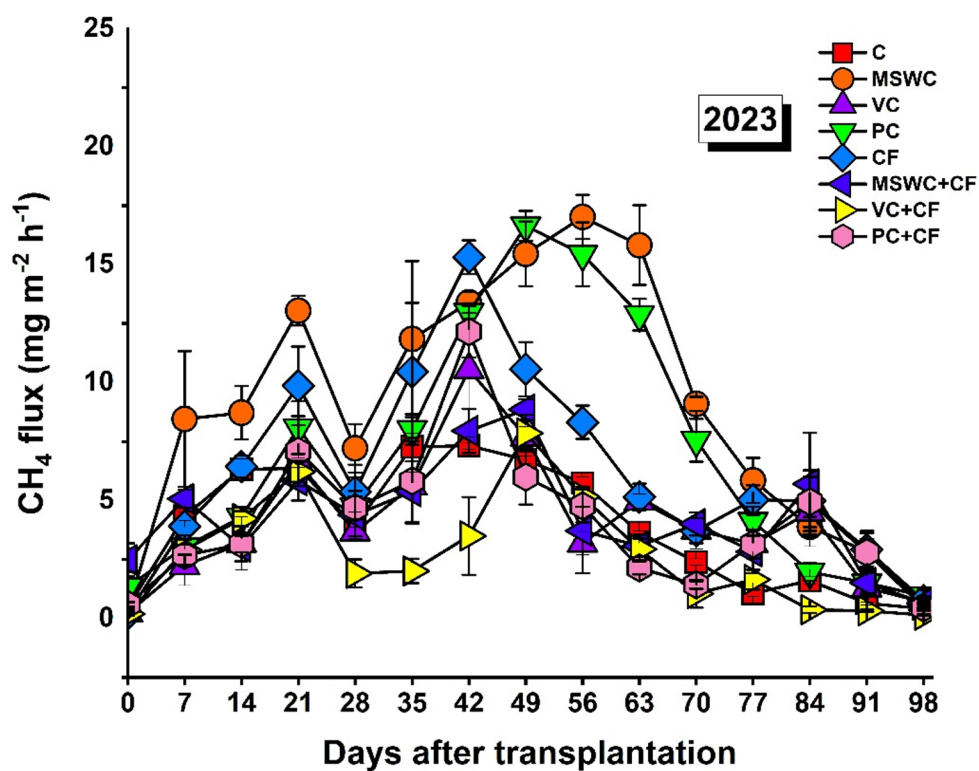


Fig. 4 Cumulative CH₄ emission in the two years under different treatments in the rice field (mean±SD). Bars with different letters at each year are significantly different in Tukey's HSD test ($p < 0.05$)

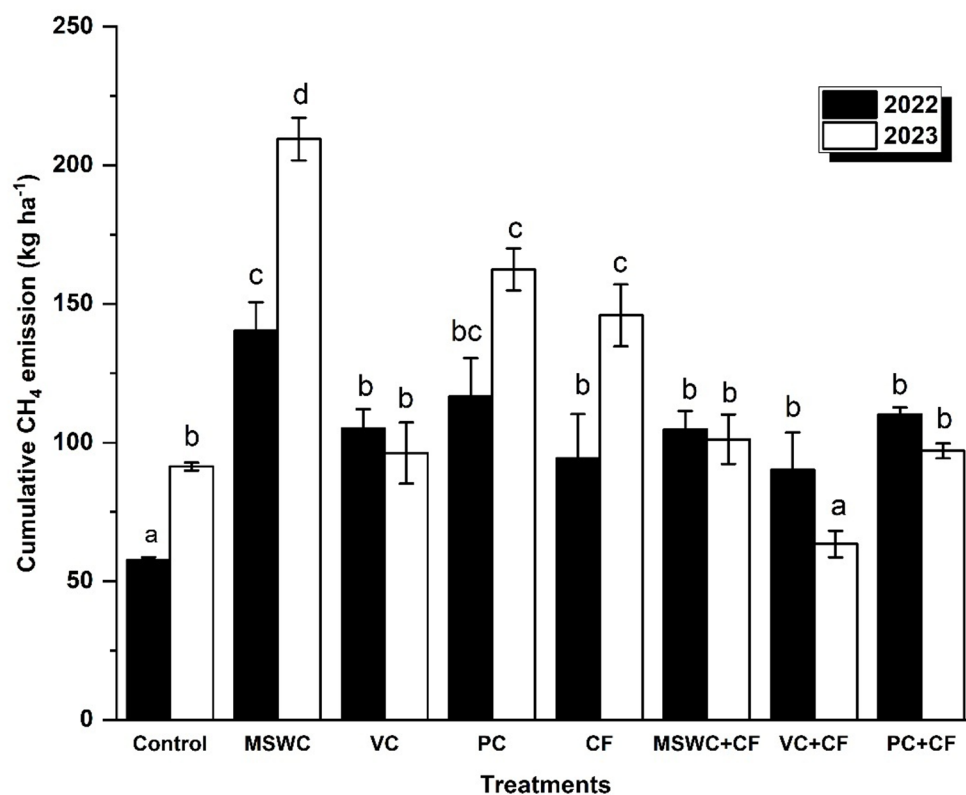


Table 1 Emission factors of CH₄ and N₂O in different treatments in rice field in the two years

Treatments	EF of CH ₄ (kg CH ₄ ha ⁻¹ d ⁻¹)		EF of N ₂ O (g N ₂ O-N (kg N) ⁻¹)	
	2022	2023	2022	2023
C	0.589 a	0.932 b	—	—
MSWC	1.431 c	2.138 d	1.084 d	0.898 e
VC	1.073 b	0.983 b	0.492 c	0.630 d
PC	1.190 bc	1.657 c	0.425 bc	0.275 b
CF	0.963 b	1.488 c	1.268 e	1.198 f
MSWC+CF	1.070 b	1.033 b	0.215 a	0.117 a
VC+CF	0.921 b	0.648 a	0.339 ab	0.294 b
PC+CF	1.124 b	0.990 b	0.508 c	0.433 c

In a column, the means followed by the same letter are not significantly different in Tukey's HSD test ($p < 0.05$). C Control, MSWC municipal solid waste compost, VC Vermicompost, PC Phumdi compost, CF Chemical fertilizer

Average cumulative CH₄ emissions were in the order of C (74.56 kg ha⁻¹) < VC+CF (76.85 kg ha⁻¹) < VC (100.70 kg ha⁻¹) < PC+CF (103.61 kg ha⁻¹) < MSWC+CF (103.03 kg ha⁻¹) < CF (120.13 kg ha⁻¹) < PC (139.49 kg ha⁻¹) < MSWC (174.89 kg ha⁻¹). The trend showed cumulative emission of CH₄ from the sole VC treatment was also lower than CF. The MSWC, PC and CF treatments increased CH₄ emissions in the second year by 49.35%, 39.27% and 54.49%, respectively, compared to the first year ($p < 0.05$). However, the remaining treatments VC, MSWC+CF, VC+CF and PC+CF showed a declining trend in the second year.

The EF of CH₄ in all treatments ranged between 0.58 and 1.43 kg ha⁻¹ d⁻¹ during the first year ($p < 0.05$) and from 0.64 to 2.13 kg ha⁻¹ d⁻¹ in the second year ($p < 0.05$) (Table 1). Average EF of the two years was maximum in MSWC with 1.78 kg ha⁻¹ d⁻¹ and minimum in C with 0.76 kg ha⁻¹ d⁻¹ however, among the treatments VC+CF recorded the least. Average EF of CH₄ in PC+CF, MSWC+CF, VC and VC+CF were 15.98%, 16.65%, 19.26% and 56.37% lower than CF on an average, respectively.

N₂O Emission

The N₂O flux showed its peak at 28 DAT in both years (Figs. 5 and 6) which gradually followed a declining trend ($p < 0.05$) and an abrupt increase trend at 56 to 63 DAT in first year and at 56 DAT in second year. The N₂O flux in all the treatments in the two years ranged from 0.02 to 0.60 mg m⁻² d⁻¹. Sole applications of composts and their integrated treatments significantly reduced N₂O emissions compared to CF. Average N₂O emission was maximum in CF, followed by MSWC, VC, PC+CF, PC, VC+CF, MSWC+CF and C ($p < 0.05$) (Fig. 7). An average reduction of 82.51% in cumulative emission of N₂O was observed in MSWC+CF, followed by 63.47% in VC+CF and 47.76% in PC+CF compared to CF treatment. No significant variation of N₂O emission was recorded between the two years.

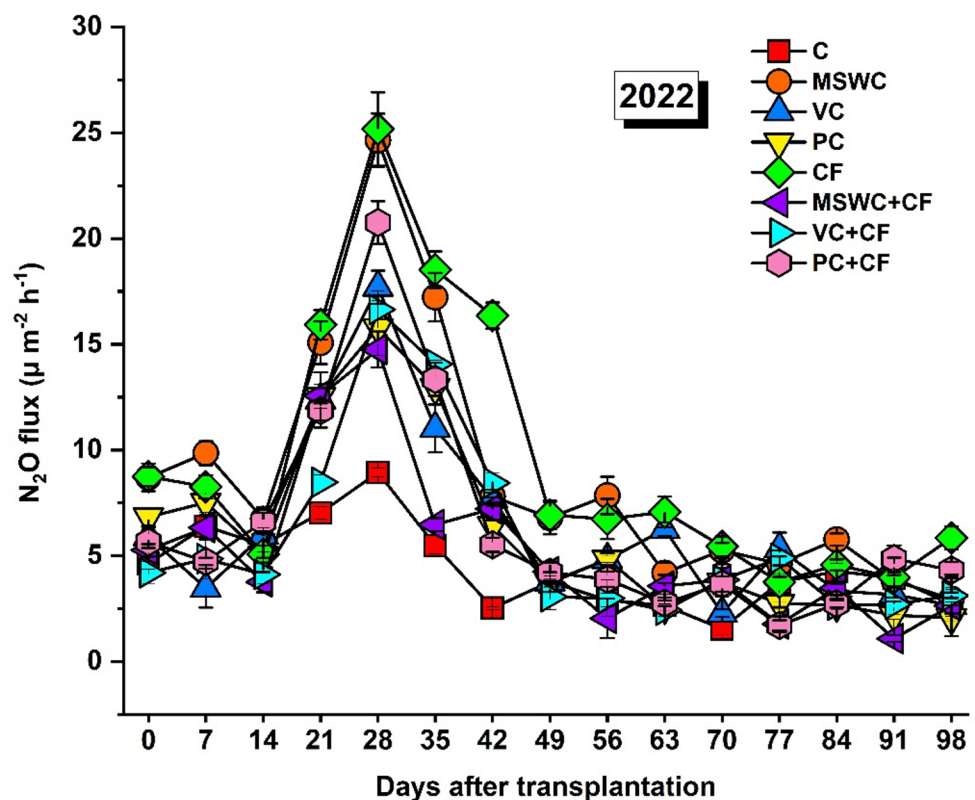
Fig. 5 Seasonal variation of N₂O flux from rice field during the rice growing season 2022 under different treatments (mean ± SD)

Fig. 6 Seasonal variation of N_2O flux from rice field during the rice growing season and 2023 under different treatments (mean $\pm$ SD)

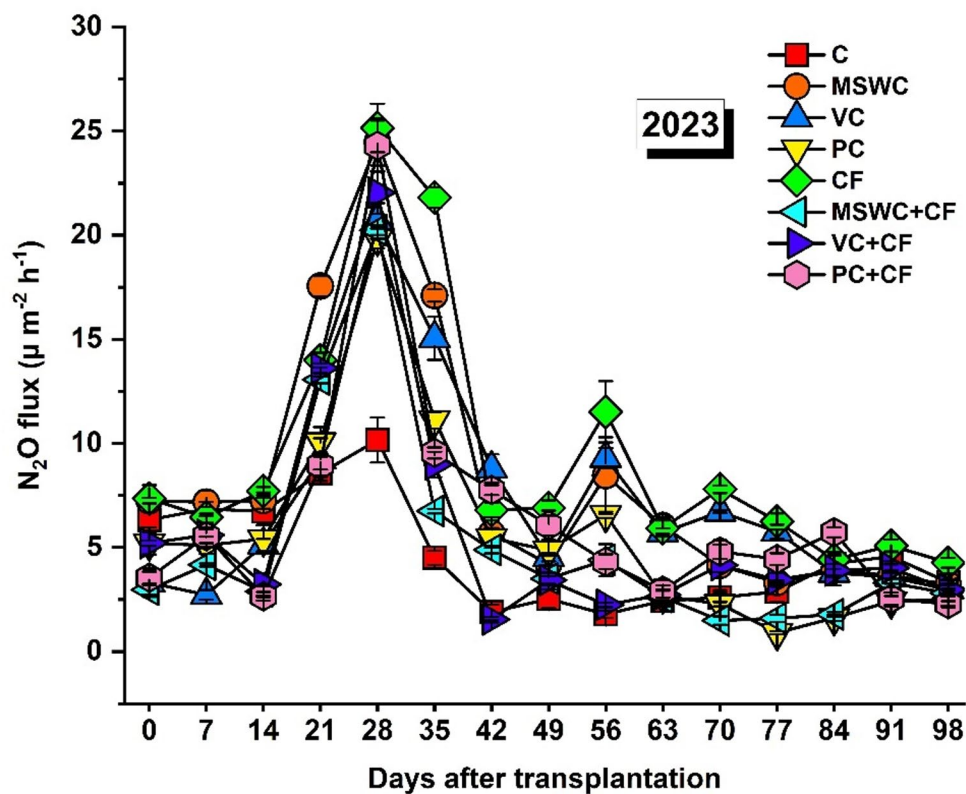


Fig. 7 Cumulative N_2O emission in the two years under different treatments in the rice field (mean $\pm$ SD). Bars with different letters at each year are significantly different in Tukey's HSD test ($p < 0.05$)

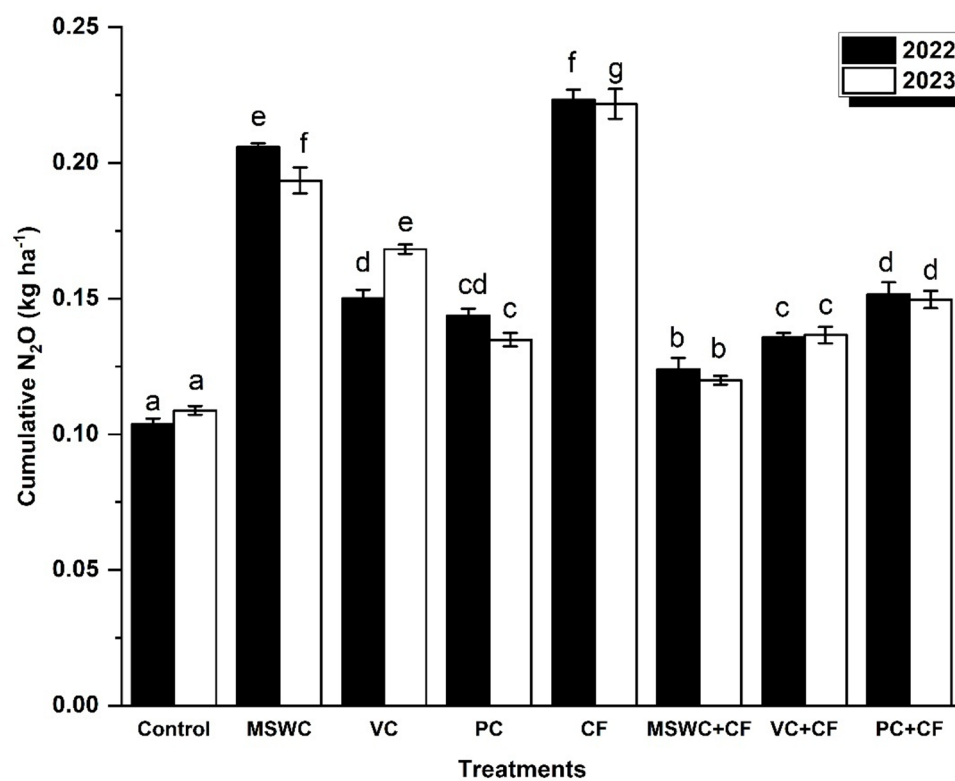


Table 2 Global warming potential and greenhouse gas intensity in different treatments in rice field in the two years

In a column, the means followed by the same letter are not significantly different in Tukey's HSD test ($p < 0.05$). *C* Control, *MSWC* municipal solid waste compost, *VC* Vermicompost, *PC* Phumdi compost, *CF* Chemical fertilizer. Values are mean $\pm$ standard error

Treatments	GWP (kg CO ₂ eq. ha ⁻¹)		GHGI (kg CO ₂ eq. t ⁻¹)	
	2022	2023	2022	2023
C	1587.22 $\pm$ 14.54 a	2497.21 $\pm$ 22.37 b	509.37 $\pm$ 49.52 a	682.00 $\pm$ 50.61 cde
MSWC	3843.58 $\pm$ 162.00 c	5709.54 $\pm$ 120.51 d	916.01 $\pm$ 58.64 d	1102.81 $\pm$ 63.89 f
VC	2879.48 $\pm$ 106.71 b	2645.75 $\pm$ 171.56 b	755.90 $\pm$ 27.28 bcd	533.26 $\pm$ 43.82 bcd
PC	3187.38 $\pm$ 214.67 bc	4421.46 $\pm$ 119.60 c	800.58 $\pm$ 34.51 cd	885.61 $\pm$ 23.67 e
CF	2610.04 $\pm$ 246.36 b	3998.70 $\pm$ 174.49 c	638.59 $\pm$ 87.08 abc	728.97 $\pm$ 47.11 de
MSWC+CF	2865.46 $\pm$ 100.26 b	2764.97 $\pm$ 138.66 b	633.72 $\pm$ 36.44 abc	483.46 $\pm$ 18.30 abc
VC+CF	2473.46 $\pm$ 209.43 b	1750.98 $\pm$ 74.00 a	510.04 $\pm$ 29.71 a	296.74 $\pm$ 39.42 a
PC+CF	3015.95 $\pm$ 75.54 b	2661.44 $\pm$ 41.28 b	561.32 $\pm$ 2.36 ab	357.79 $\pm$ 29.18 ab

Table 3 Grain yield, carbon efficiency ratio and nitrogen use efficiency in different treatments in the rice field

Treatments	Grain Yield (t ha ⁻¹)	CER	NUE (%)
C	3.44 $\pm$ 0.37a	2.70 $\pm$ 0.18	–
MSWC	4.71 $\pm$ 0.70a	1.54 $\pm$ 0.00	76.49 $\pm$ 1.78c
VC	4.39 $\pm$ 0.82a	2.21 $\pm$ 0.48	28.85 $\pm$ 3.29a
PC	4.48 $\pm$ 0.71a	1.81 $\pm$ 0.06	38.11 $\pm$ 0.74b
CF	4.83 $\pm$ 0.97b	2.30 $\pm$ 0.08	22.87 $\pm$ 15.01a
MSWC+CF	5.12 $\pm$ 0.83b	2.55 $\pm$ 0.45	57.67 $\pm$ 0.56ab
VC+CF	5.44 $\pm$ 0.84b	3.40 $\pm$ 0.90	42.09 $\pm$ 1.61bb
PC+CF	6.45 $\pm$ 1.52c	3.14 $\pm$ 0.87	93.64 $\pm$ 15.30bc

Values are mean $\pm$ (standard deviation). *C* Control, *MSWC* municipal solid waste compost, *VC* Vermicompost, *PC* Phumdi compost, *CF* Chemical fertilizer. In a column, the means followed by the same letter are not significantly different in Tukey's HSD test ($p < 0.05$)

The average EF of N₂O in treated plots ranged from 0.16 to 1.23 g N₂O-N (kg N)⁻¹, maximum was recorded in CF while minimum in MSWC+CF in both years ($p < 0.05$) (Table 1). No significant variation of EF of N₂O was recorded between the two years.

GWP and GHGI

The GWP in all treatments ranged from 1587.22 to 3843.58 kg CO₂ eq. ha⁻¹ in first year ($p < 0.05$) and 1750.98 to 5709.54 kg CO₂ eq. ha⁻¹ in second year ($p < 0.05$) (Table 2). Application of MSWC recorded maximum GWP and VC+CF recorded minimum among the treatments in both years. GWP of MSWC was 44.55% more than GWP of CF when averaged over the two years. In the first year GWP in VC+CF treatment only recorded lesser than CF among treatments whereas, in second year the treatments VC, MSWC+CF, VC+CF and PC+CF recorded lesser GWP compared to CF. The average GWP of the two years decreased by 17.37%, 56.44% and 16.40% in MSWC+CF, VC+CF and PC+CF, respectively compared to CF.

The GHGI which measures GWP for the treatments in relation to the amount of grain yield ranged from 509.37 to 916.01 kg CO₂ eq. t⁻¹ of grain yield and 296.74 to 1102.81 kg CO₂ eq. t⁻¹ of grain yield in the first year ($p < 0.05$) and

second year ($p < 0.05$) respectively (Table 2). The integrated treatment of composts and CF showed a declining trend in GHGI compared to CF. The average GHGI reduced by 69.49% in VC+CF followed by 48.75% in PC+CF and 22.35% in MSWC+CF compared to CF. GHGI was in the order of VC+CF < PC+CF < MSWC+CF < C < VC < CF < P < C < MSWC when averaged over the two years. However, there was no significant variation of GHGI between the two years.

Grain yield, CER and NUE

The average grain yield was maximum in PC+CF and minimum in C ($p < 0.05$) (Table 3), with the integrated treatments recording more grain yield than CF treatment. The CER does not show significant variation between the different treatments. On an average maximum CER was recorded in VC+CF followed by PC+CF and MSWC+CF, while minimum was recorded in MSWC. The average NUE varied from 22.87 to 93.65% in the treatments. The NUE of all the treatments was found to be more than CF ($p < 0.05$), with PC+CF treatment showing maximum average increase of 309.44% relative to CF. The average NUE of VC+CF and MSWC+CF was also 75.94% and 152.18% more than CF respectively.

Discussion

The CH₄ flux showed prominent peaks during active tillering and reproductive stages, corresponding to the time of application of composts and inorganic fertilizers. Moreover, during the reproductive phase of plants, rate of photosynthesis is higher, leading to the release of more organic substrates in the form of root exudates causing more activities of methanogenic bacteria emitting more CH₄ [30]. The application of both composts and chemical fertilizers also resulted in increased availability of substrates for methanogenic bacteria. Similar results of peak emission during these stages were reported by Ali et al. [3] and Bharali et al.

[5]. Application of composts as sole nutrient source, especially MSWC and PC stimulates CH_4 emission from the rice field compared to CF. The reason could be attributed to the presence of more C-rich materials providing high amount of labile C under anaerobic conditions, thereby increasing population of C-turnover bacteria. Similar increase in emission of CH_4 due to 100% application of compost compared to 100% application of chemical fertilizer was reported by Bhatia et al. [6] and Yuan et al. [59]. Under such application type, CH_4 emission is not only regulated through direct C inputs but also by the availability of rice photosynthate C in rhizosphere [53]. However, the sole application of VC recorded an average of 19.28% lesser CH_4 emission compared to CF. It indicates that vermicompost can be an efficient nutrient source in reducing the activities and population of methanogenic bacteria in rice fields. However, it could not be confirmed as study on microbial population was not conducted in the present work. Similar finding was reported by Singh et al. [46], where VC fertilized plot generates lesser CH_4 emissions than synthetic chemical fertilizer treatment plots.

The integrated treatments MSWC + CF, VC + CF and PC + CF also reduced emission of CH_4 with an average of 16.65%, 56.37% and 16.65% respectively compared to CF showing a high reducing rate in VC + CF treatment. However, when considered for each year, VC + CF was the only treatment that recorded a reduced rate of CH_4 emission in both the years compared to CF. According to IPCC [25], the default EF of CH_4 from rice cultivation without organic amendment is $0.85 \text{ kg ha}^{-1} \text{ d}^{-1}$ for South Asia. In the present study, EF of CH_4 in VC + CF was $0.784 \text{ kg ha}^{-1} \text{ d}^{-1}$, which was the only treatment recording lesser than the IPCC value. The result implies that incorporation of 50% vermicompost along with 50% chemical fertilizer can be a viable strategy for mitigating CH_4 emission from rice fields in the present study area. The present rate of cumulative emission of CH_4 from the composts amended plots in the present study is higher when compared to compost amended rice fields reported by Bharali et al. [5], although both the studies were conducted in two different states of north-east India, both in monsoon rainfed conditions. The reason could be attributed to the difference in the quality of the substrate used in preparing composts. However, the present rate is lower than the reports on composts amendment in rice fields of Yi-huet al. [58] and Triahet al. [51]. A study in Bangladesh identified that application of municipal solid waste compost tends to increase soil bacterial population of the rice field compared to kitchen waste compost and farm waste compost. Consequently, it produced the highest CH_4 ($51.20 \text{ mg m}^{-1} \text{ h}^{-1}$) at the active tillering stage, which was higher than the present emission rate [15]. The significant positive correlation of CH_4 flux with SOC, air temperature

and soil pH indicated that more activities of the methanogenic bacteria occur when the temperature is increased, leading to higher rate of decomposition under anaerobic conditions. Similarly, Sun et al. [50] observed a significant positive correlation between ambient air temperature and CH_4 emission. The increased temperature accelerated the mineralization process of SOC [41], thereby making more C available for methanogens.

Regardless of treatments, the N_2O emission showed similar trend of peak emission after application of composts and chemical fertilizer. The reason could be attributed to nitrification and denitrification of N contained in the fertilizer. The N_2O flux was lower in all the treatments compared to CF in both years, and even CF treatment recorded more emission of N_2O compared to C. It indicates that the supply of N to the N_2O -producers in the chemical fertilizer treatment takes place at a faster rate compared to the compost treatments. When chemical fertilizer was added to the paddy soil, it readily released, accelerating the mineralization process and hence increasing the gas emission [39]. The present study identified that the integrated application of compost and chemical fertilizer emitted lesser N_2O compared to the sole application of chemical fertilizer. Several studies have also reported that partial substitution of chemical fertilizer with organic sources reduces N_2O emission [35, 49, 59, 61]. Addition of organic substrate like vermicompost, reduced emission of N_2O by increasing the immobilization of N in soil and reduced nitrification intensity by enhancing anaerobic conditions [44, 60]. The cumulative emission of N_2O in the present study was lower than Das and Adhya [10], Mohanty et al. [34] and Triahet al. [51]. A study in Southeast China also revealed that N_2O emission was higher in chemical fertilizer application rice field compared to the organic fertilizer addition rice field [38]. In contrast, the study of Wu et al. [56] revealed that application of vermicompost in higher dose significantly increased N_2O emission from paddy soil. The lower EF of N_2O in the present study could be attributed to less rate of N application, as emission of N_2O from rice fields depends on the amount of N applied [62]. Moreover, in flooded rice fields, most of the N gas is released in the form of N_2 , therefore, high emission of N_2O is not generally observed in rice fields [19].

Among all the treatments, the integrated treatments reduced average GWP and increased grain yield compared to CF. The VC + CF recorded lesser GWP and GHGI compared to other integrated treatments, with maximum CER of 3.40. In agreement with our findings, a simulation study conducted by Abbbhishek et al. [1], predicted that in long run vermicompost based treatments has the potential to substantially reduce GWP and GHGI. The maximum grain production in PC + CF treatment with 33.54% increase from CF treatment, could be due to maximum record of NUE

in PC + CF, which indicated that the substrate in *Phumdi* compost is highly beneficial in rice production. However, the GHGI was lower in VC + CF treatment despite having lower grain yield than PC + CF. This could be attributed to the substantial reduction of CH₄ and N₂O in VC + CF treatment. Vermicompost contained more stable organic carbon [40], resulting in less CH₄ emission when applied in rice field. The availability of readily mineralizable C is one of the main drivers affecting CH₄ emissions from rice fields [57]. The type of dominant microbial population in the VC + CF and PC + CF could also play an important role in reducing more GHG emission in VC + CF while producing lesser grain yield compared to PC + CF. The three types of integrated treatments VC + CF, PC + CF and MSWC + CF recorded lower GHGI and higher CER compared to the CF treatment; therefore, these integrated treatments are highly beneficial in reducing the GWP from rice fields in the present study area. Similar low GHGI and high CER due to treatment of compost compared to chemical fertilizer treatment in rice field was also reported by Das and Adhya [10].

The selection of shorter duration rice variety in the present study might also contribute to lesser GWP. As crop growth was faster, it can lead to intensive utilization of the nutrients supplied. Similar studies conducted by Bhattacharyya et al. [7] and Win et al. [54] also showed longer growth duration rice variety emitted more CH₄ than shorter growth duration variety. Moreover, rainfed rice cultivation also produced lesser GHG compared to irrigated rice fields [42]. Overall, 98.5% of the GWP was contributed by CH₄ emission alone, while the remaining 1.5% was contributed by N₂O. Similar range of GWP was reported by Das and Adhya [10], where CH₄ contributed 96.14% and the remaining 3.86% by N₂O.

The effect of fresh or green organic substrate application on GHG emission from rice fields was documented in previous studies [23, 29, 32], however, reports on amendment of different types of composts and their effect on GWP, EF of GHG, and GHGI are very less, especially in the present study area. Therefore, the findings of the present study could be a helpful measure in reducing emission of GHG from rice fields. The limitations of the present study was estimation of microbial population and nutrient content of grain for all the treatments could not be carried out due to unavoidable constraints.

Conclusions

From the findings, it can be concluded that 50% substitution of chemical fertilizer with vermicompost, *phumdi* compost and municipal solid waste compost in rice fields leads to a reduction of GHG emission and production of more grain

yield compared to 100% application of chemical fertilizer. Among the three composts used in the present study, application of vermicompost integrated with chemical fertilizer has exerted a profound impact on mitigating GHG emissions with 36.02% reduction compared to the sole application of chemical fertilizer. Similarly, the treatment VC + CF could reduce GWP and GHGI while improving CER. Moreover, the EF of CH₄ in VC + CF treatment plot was lower than the default IPCC [24], suggesting that this could be the most effective fertilizer management strategy to mitigate GHG emissions from the inceptisol type of rice field of Northeast India. Since microbial population cannot be estimated in the present work in depth future work should focussed on such studies. The present study provides first-hand data of GHG emissions from rice fields of Manipur, which may aid in understanding the mitigation potential of GHG emissions in different environmental conditions of rice fields. The farmers are recommended to adopt such integrated nutrient management practice as a climate smart agriculture strategy to have higher net returns with lesser GHG emission.

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Declarations

Conflict of Interest The authors declare no competing financial interests or conflict of interest to influence the work reported in this paper.

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ABSTRACT

COMPARATIVE ACCOUNT ON INFLUENCE OF ORGANIC AND CHEMICAL FERTILIZERS ON GROWTH AND YIELD OF RICE AND METHANE EMISSION IN FIELD CONDITIONS

**An abstract submitted in partial fulfillment of the requirement for
the Degree of Doctor of Philosophy**

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People grow rice as it is a staple food for half of the world's population. As the population increases, the demand for rice increases. In order to feed the increasing population, agricultural production is expected to increase by 60% by 2050. And to ensure the food demand of the increasing population, intensive production of crops in a sustainable manner is needed. Generally, chemical fertilizers are used to supply the essential nutrients to the crop; however, their injudicious use could increase greenhouse gas emissions (GHG), and cause several soil-related issues such as acidification, loss of organic matter, which affect the soil fertility, leading to a decline in crop yield. Therefore, attention needs to be shifted towards the use of alternatives, like organic fertilizer.

Compost is a stable humus-like product that can increase the organic matter content of the soil and improve the overall properties of the soil. The application of compost in agriculture protects the land from depletion due to intensive use of chemical fertilizer. Compost provides slow-released nutrients, retains the nutrients longer in the soil, which helps in reducing leaching and runoff, improves soil quality and ensures crop development. However, while applying organic fertilizer in the field, total mineralizable N (N) should be considered because the growth and development of plants significantly depend on the rate of N mineralization and availability. Moreover, compost application in rice fields has been known to enhance the nutrient content and microbial communities.

Rice fields are one among the important anthropogenic sources of GHG emissions. It contributes around 10 to 17% of the total global GHG emissions. The water-saturated condition of rice field soil creates an anoxic environment and accelerates the methane (CH_4) emission from the paddy field. And under aerobic conditions, the microbial activities decompose the organic matter content in the soil and produce CO_2 into the atmosphere. Moreover, the nitrification and denitrification processes by microbial transformation of N produce N_2O . In India, rice cultivation is associated with the food security of the country. However, its increasing demand has raised concern and become a threat to sustainable agriculture as it impacts global climate change by emitting GHG. At the same time, the emission of GHG from rice fields depends on

the soil type, climatic conditions of the region and agricultural management techniques.

The increased urbanization process generated massive amounts of municipal solid waste (MSW) and created haphazard to the environment. *Phumdi*, a floating vegetative mat found in the Loktak Lake of Manipur, provide a unique ecosystem to the beautiful largest freshwater lake of the Northeast. However, its rapid proliferation poses a threat to the lake. The harvested biomass of *phumdi* and municipal solid waste can be turned into a resource by composting. Recycling of these waste will not only help in the management of waste but also its application in soil provides multiple benefits such as improving soil nutrients, water holding capacity, *etc.*

Many investigations were carried out earlier to identify the significant relationship between organic fertilizer amendment and GHG emissions from rice fields; however, the results were different due to the utilization of various raw materials while making organic fertilizer. Therefore, it is essential to study the potential of locally produced organic fertilizers on the yield of rice production as well as the changes in the emission of GHG.

The study was carried out with the main objectives of estimating the effect of the three locally available composts on the growth and yield of rice and quantifying the GHG emissions influenced by the applied fertilizers. The study also compared the growth and yield of rice and methane emission with organic fertilizers and chemical fertilizer treatments. The study further aimed to evaluate the effect of organic and chemical fertilizer on soil properties under rice cultivation.

Three types of compost made from different feedstock, *viz.* municipal solid waste (MSW) compost, vermicompost made from cow dung and rice straw, and *phumdi* compost made from floating mats consisting of aquatic macrophytes and soil found in Loktak Lake of Manipur were selected. The initial qualities of the three composts were analyzed before applying them in the field. A short-duration rice variety, RCM Maniphou 12 was selected and cultivated in rainfed conditions during kharif season of 2022 and 2023. The experiment plots were laid out in a randomized block design (RBD) method in the Rice Research Station, Wangbal, with eight treatments and three

replicates. The eight treatments comprise of (i) control (no fertilizer); (ii) municipal solid waste compost at the rate 3.7 t ha^{-1} (MSWC, 100%); (iii) vermicompost at 3.5 t ha^{-1} (VC, 100%); (iv) *phumdi* compost at 3.0 t ha^{-1} (PC 100%) (v) chemical fertilizer (CF, 100%); (vi) municipal solid waste compost plus chemical fertilizer in the ratio 1:1 *i.e.* 1.85 t ha^{-1} MSWC + 0.06 t ha^{-1} CF(MSWC+CF); (vii) vermicompost plus chemical fertilizer in the ratio 1:1 *i.e.* 1.76 t ha^{-1} VC + 0.06 t ha^{-1} CF (VC+CF); (viii) *phumdi* compost plus chemical fertilizer in the ratio 1:1 *i.e.* 1.5 t ha^{-1} PC + 0.06 t ha^{-1} CF (PC+CF). The compost and chemical fertilizer were applied based on the N content of the fertilizers.

Plant growth and yield characteristics were measured from the 30 random rice plants inside each plot. Grain yield and straw yield were determined from the total area of the plots. Plant N-uptake, nitrogen use efficiency (NUE) and agronomic nitrogen efficiency (ANE) were calculated. The quantification of GHG was carried out using a closed chamber technique established by Hutchinson and Moiser (1981). Gas samples were collected in a weekly interval starting from the day of transplantation (DAT) till one week after rice harvesting. Soil samples were also collected at four different stages of the rice crop (active tillering, panicle initiation stage, flowering and post-harvesting) and analyzed for various parameters.

Statistical analyses such as analysis of variance (ANOVA) followed by Tukey's HSD test, principal component analysis, and Pearson's correlation were performed using SPSS Statistics 25.0. And figures were drawn in *OrginPro*.

The application of different fertilizer treatments significantly influenced the growth characteristics of rice. Plant height was found to be at its highest at 60DAT and decreased at the maturity stage, irrespective of treatments. The application of PC+CF treatment recorded maximum plant height in the two years of study, with 8.7% and 5.94% higher than the application of CF treatment. The TNPP and ETNPP were also higher in the PC+CF treatment plots compared to other fertilizer treatments.

The yield characteristics of rice, including panicle length, number of spikelets per panicle, number of filled spikelets per panicle, and 1000-grain weight, were maximum in the PC+CF treatment, resulting in the maximum grain yield of rice, during the two

years of study. The positive correlation between grain yield and panicle length, spikelets per panicle, filled spikelets per panicle, and 1000-grain weight found in the present study supported our hypothesis. The application of PC+CF treatment produced 33.6% more grain yield relative to the CF treatment. The integrated fertilizer treatments, VC+CF and MSWC+CF, also recorded higher grain yield compared to the sole application of composts and chemical fertilizer. Furthermore, the study observed higher grain yield in the second year compared to the first year.

The straw yield was found to be maximum in PC+CF treatment, followed by VC+CF treatment, and the minimum was observed in PC treatment. Compared to the CF treatment, PC+CF and VC+CF treatments produced 26.44% and 12.86% higher straw yield. The HI of rice was found between the range of 0.44 to 0.48 in all the fertilizer application plots. HI was higher in MSWC+CF treatment and PC treatment compared to other treatments, with values of 0.48 and 0.47, respectively. The positive correlation between HI and soil available K, total N, and SOC indicated that application of compost with chemical fertilizer could supply nutrients to the plant and enhance the economic yield of rice plant.

The plant N uptake was higher in the combined application of compost and chemical fertilizer and the sole application of compost compared to the CF treatment. The application of PC+CF, MSWC+CF, and VC+CF increased the N uptake by an average of 79.35% compared to the CF treatment. It was further found that the application of different fertilizer treatments remarkably influenced the NUE and ANE. The application of PC+CF, VC+CF, and MSWC+CF treatment significantly increased the NUE and ANE compared to the sole application of chemical fertilizer. However, the application of compost alone resulted in lower ANE by an average of 29.89% compared to the chemical fertilizer treatment.

The study measured the magnitude of GHG emissions from the rice field to determine the effect of the composts on GHG emissions from rice fields cultivated under rainfed conditions. In the two years of study, it was observed that CH₄ flux followed a similar trend of increased gas flux with the development of the crop from the initial growth stage. The CH₄ flux reached its peak at the active tillering stage and reproductive stage

of rice growth. And then decline at the maturity stage in all the treatments. The CH₄ flux was emitted higher in the sole application of MSW compost and *phumdi* compost, with a maximum in MSWC treatment. Meanwhile, the VC+CF, MSWC+CF, PC+CF and VC treatment recorded lower CH₄ flux compared to the CF treatment. The present study identified that the application of different fertilizer treatments significantly influenced the seasonal cumulative CH₄ emission. The application of integrated fertilizer treatments reduced the CH₄ emission from rice fields by 3.63 to 42.17% compared to the CF treatment.

The N₂O flux accelerates after N fertilizer application and then decreases sharply until the next fertilization. The application of fertilizers influenced the nitrification and denitrification process, which in turn increased the gas flux after fertilizer application. The highest cumulative N₂O emission was recorded in the CF treatment (0.223±0.001 kg ha⁻¹) and the minimum in the control (0.106±0.003 kg ha⁻¹). The integrated fertilizer treatments reduced N₂O emissions by a margin of 65% compared to the CF treatment.

The measurement of CO₂ flux from the rice field under eight different fertilizer treatments indicated that the gas flux was higher in the sole application of compost compared to the application of chemical fertilizer alone and integrated treatments of compost and chemical fertilizer. The availability of more C-substrate from the sole application of compost could result in higher CO₂ flux. Higher CO₂ flux was recorded during the reproductive stage of rice growth, which could be explained by the release of more root exudates from the increased root biomass, and stimulates the activities of soil microorganisms. The increased CO₂ flux in the MSWC, VC, and PC treatments led to higher seasonal CO₂ emissions. At the same time, the application of integrated fertilizer treatment resulted in lower CO₂ emissions, with the lowest emission in VC+CF treatment (2372.52 kg ha⁻¹) compared to the CF treatment.

The study found a significant positive correlation between GHG emissions (CH₄ and CO₂) and SOC content, indicating that higher content of organic C led to higher CH₄ and CO₂ emissions. The CH₄ and CO₂ emissions were also found to be positively correlated with air temperature.

In the present study, more than half of the GWP from rice field was contributed by CH₄ emission. It was followed by CO₂ emission and N₂O emission. Since rice cultivation is mostly done in flooded conditions, it creates oxygen-deprived environment and enhances the formation of CH₄ by the process of methanogenesis. However, there were times when adequate rainfall was not received, such conditions favour CO₂ emissions, contributing 47% of the total GWP. The maximum GWP was recorded in MSWC treatment, followed by PC treatment, with 32.93% and 14.38% higher compared to the CF treatment. And the application of VC+CF treatment recorded minimum GWP among the fertilized plots.

The GHGI of the rice field was decreased with the application of combined composts and chemical fertilizer treatments. The higher grain yield with lesser GHG emissions in the MSWC+CF, VC+CF, and PC+CF treatments resulted in lower GHGI. The application of MSWC treatment recorded maximum GHGI, 35.41% higher compared to the application of chemical fertilizer alone.

In the two years of study, there was a distinct variation in SOC content among the four stages of rice. In the first year, maximum SOC was found in the active tillering stage in the treatments of control, MSWC, CF, and MSWC+CF treatment, but in the second year, maximum SOC was found in the panicle initiation stage in all the treatments except for control and PC treatments. Over the four stages and two years, the addition of MSWC treatment resulted in maximum SOC content. The positive correlation between SOC and soil total N and available P indicates that SOC content of soil significantly influences the nutrient availability of soil.

The CF treatment recorded maximum C-stock at the end of the cropping season. However, the result was at par with the value of MSWC+CF treatment. Among the three composts used in the present study, the application of MSW compost with or without chemical fertilizer accumulates more C in the soil due to its low C:N ratio compared to vermicompost and *phumdi* compost. Moreover, the C-sequestration rate was higher in MSWC treatment, followed by CF treatment and the lowest was found in control.

The pH of soil was found to range from 6.29 to 7.38 in the first year and 6.12 to 6.98 in the second year. It falls within the ideal range of pH for rice cultivation. The highest pH was found in MSWC treatment. The EC of soil found in the present experimental field was included in the category of very low saline soil. The application of PC+CF treatment resulted in higher total N and available K in soil. Moreover, the integrated treatments MSWC+CF, VC+CF, and PC+CF increased N content of soil by 21.78%, 12.38%, and 32.28%, respectively, over the sole application of chemical fertilizer. However, the available P was maximum in CF treatment compared to other fertilizer treatments.

The findings of the study concluded that substitution of 50% chemical fertilizer by composts produces more grain yield compared to the sole application of chemical fertilizer. The addition of *phumdi* compost combined with chemical fertilizer produced a maximum grain yield with 33.6% higher than the application of chemical fertilizer alone. It was followed by integrated treatment of vermicompost with chemical fertilizer and MSW compost with chemical fertilizer. Even though the same required amount of N was added, the application of composts alone could not be able to supply the essential amount of nutrients needed for optimal yield. Moreover, the integrated treatments of compost and chemical fertilizer significantly reduced GHG emissions from rice fields, resulting in lower GWP and GHGI. Among the three composts, application of vermicompost integrated with 50% chemical fertilizer becomes the most effective fertilizer management strategy to tackle the GHG emissions from rice field cultivated under rainfed conditions of Northeast India with greater crop production. The treatment has lower EF of CH₄ than the IPCC 2019 default EF OF CH₄. The study also found that the addition of integrated fertilizer treatments improved the total N and available K concentration of the soil. A positive impact on soil C stock due to the application of fertilizers was observed in the present study, where soil C stock increased over time. However, the composts used in the present study were made from different feedstocks which resulted in different nutrients released.

The results of the present study indicate that application of balanced chemical and organic fertilizer could improve NUE and hence increase crop productivity. The adoption of such integrated fertilizer treatments, especially vermicompost with

chemical fertilizer and *phumdi* compost with chemical fertilizer has emerged as a more substantial solution to mitigate the emissions of GHG from rice fields by maintaining the soil health.

Further study on microbial population due to the application of different composted materials with or without chemical fertilizer has been recommended. Additional research on vermicomposting of *phumdi* and evaluating its effect on grain yield and GHG emissions from the paddy field may be carried out.