

## Recycling of Waste utilizing Novcom Composting Technology towards GHG Abatement from Source

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

### Abstract

Increased emission of greenhouse gases with enhanced industrialization, urbanization and conventional agriculture has accelerated the climate change which poses a fundamental threat to the environment, biodiversity and peoples' livelihoods. Moreover, targeting higher crop production, through conventional agriculture to feed a world population of 9.3 billion, by 2050; will entail higher GHG emission, considering that agriculture accounts for 17 percent of the global GHG emissions. But, agriculture is also the only sector, which can serve as a potential sink for GHG's, through regeneration of the Soil-C sequestration potentials. Application of stable and mature organic amendments is one of the effective ways, but for taking the program at scale, the raw material source for compost production has to be abundant and cost free. In this respect any type of biodegradable waste specially landfill/ legacy waste perfectly fits the bill, but the primary requirement is availability of effective and economic composting technology/ ies that can justify the dual premise of safe and effective waste bio-conversion as well as GHG abatement. The present study under IBM-IORF Sustainability Project was taken up to study waste bio-conversion as well as GHG mitigation potential under Novcom Composting Technology. The GHG's were measured using 'Closed Chamber Method' with daily reading for continuous 30 days.

Analysis of the Novcom compost samples confirmed their stability and maturity as depicted by the CO<sub>2</sub> evolution rate (2 mgCO<sub>2</sub>-C/ g OM/ day) and the safety/ non- phytotoxic effect was confirmed by the germination index value of 1.12. The total NPK value of 4.18% indicated a high nutrient content and the C:N ratio of 13:1 indicated an effective nutrient mineralization potential, post soil application. However, the significant finding was made in respect of the soil microflora population which was found in the order of 19 – 56 x 10<sup>16</sup> c.f.u., per gm or in other words 1 trillion billion c.f.u. per ton moist compost.

The study indicated a significantly low GHG emission (11.38 kg CO<sub>2</sub> equivalent/ ton treated waste) under Novcom Composting Technology, which was found to be 17 times lower in comparison to the reference values obtained in respect of the other biodegradation processes. Also, a very insignificant methane emission (0.67 kg CO<sub>2</sub> equivalent/ ton treated waste) was recorded under this technology. The generated database along with the initial and final data of moisture, carbon and nitrogen was utilized for development of empirical equations to predict GHG emission under Novcom Composting Technology. These empirical equations were consequently utilized to evaluate the GHG abatement potential of Novcom Composting Technology while recycling landfill materials, MSW, legacy waste, press mud, coir pith, vegetable market waste, refuse from food processing industry and wheat mill waste.

According to the assessment as per IPCC guideline, bioconversion of these wastes through Novcom Composing Technology can enable a GHG abatement of 5039 kg CO<sub>2</sub> eq per ton (*on an average*) of treated waste. Hence, this composting technology can facilitate an effective

model towards attainment of the Net Zero objective along with significant social and economic impacts.

**Keywords :**

*Greenhouse gases, waste recycling, Novcom Composting Technology, empirical equation, emission predictability*

**1.0 INTRODUCTION**

Human-induced climate change is causing widespread disruption in nature and affecting the lives of billions of people around the world, despite efforts to reduce the risks. (IPCC, 2022).

A 2020 report found that nearly 690 million people or 8.9 percent of the global population are hungry, and 149 million children are stunted because of under-nutrition (FAO *et al.* 2021). The food security challenge will only become more difficult, as the world will need to produce about 70 percent more food by 2050 to feed an estimated 9 billion people (The World Bank, 2022). The challenge is intensified by agriculture's extreme vulnerability to climate change. Climate change's negative impacts are already being felt, in the form of increasing temperatures, weather variability, shifting agro-ecosystem boundaries, invasive pests, and more frequent extreme weather events (NRDC, 2023). On farms, climate change is reducing crop yields, the nutritional quality of major cereals, and lowering livestock productivity (EPA, 2023).

On the other hand, agriculture is the only sector, which acts as both a source and sink for the greenhouse gases (Vetter *et al.*, 2017). Emission enhances with industrial agriculture, when use of fossil fuel, chemical fertilizers (especially N), synthetic chemicals and involvement of machinery increases (IAEA, 2023). According to an estimate by FAO, in 2018; global emissions due to agriculture was 9.3 billion tonnes of CO<sub>2</sub> equivalent (CO<sub>2</sub>eqv.), which took a 14 percent growth since 2000 and accounted for 17 percent of global GHG emissions from all sectors (FAO, 2020). However, agricultural ecosystems also have the potential to store a vast amount of soil carbon up to 1 billion metric tons per year, which would offset around 10% of the annual GHG emissions of 8–10 billion metric tons per year (IPCC, 2014). According to an estimate by Dr. Lal, the renowned Soil Scientist and the 2020 World Food Prize Winner, the carbon sink capacity of the world's agricultural and degraded soils is 50 to 66% of what it has been historically. This means our soil can hold 42 to 78 billion metric tons more carbon (Lal, 2001).

Increasing the amount of carbon in soil also makes it more productive for farmers which can only be through sustainable farming approaches. And for any sustainable farming, amelioration of soil is the most important criteria (AGRIVI, 2023) and quality manure, rich in self-generated microflora is prerequisite for ensuring time bound effectiveness irrespective of agro-ecological settings. Effective technology is the primary requirement towards effective bio-conversion of bio-resources, especially hard to biodegrade waste into quality manure (Wei, 2021) and for GHG offsetting under the composting process (Vergara and Silver, 2019) towards making meaningful contribution in respect of climate change mitigation. However, there have been limited studies in this direction especially in the Indian agriculture sector.

In this background, bioconversion of waste was taken up under Novcom Composting Technology, which is a validated, aerobic biodegradation process developed by Dr. P. Das Biswas (pioneer of sustainable tea production in India) that can enable safe, stable and mature compost production within the shortest period of 21 days. The objective was to evaluate the effectiveness of Novcom Composting Technology in respect of waste recycling and abatement of greenhouse gases from source, as compared to the GHG emission potential of waste under landfill conditions.

## 2.0 MATERIALS AND METHODS

The study was done as part of developing Clean Food ‘Net Zero’ Model under IBM-IORF Sustainability Project at Nadia, West Bengal, India during 2021-22 by Inhana Organic Research Foundation in collaboration with Nadia Krishi Vigyan Kendra, BCKV, ICAR. Technical help specially in terms of studying the GHG emission under Novcom composting process was provided by experts from other institutes viz. Visva Bharati University, Energy Transition Commission, UK and i-No Carbon Limited, UK and Agricultural & Ecological Research Unit, Indian Statistical Institute, Giridih

**2.1 Preparation of Novcom compost:** For preparation of Novcom compost, different agro waste and cow dung was taken in 80: 20 ratio and the compost was prepared as per standard methodology (Seal *et al.* 2012).

**2.2 Analysis of compost quality parameters:** Physicochemical properties of compost viz. moisture content, pH, electrical conductivity and organic carbon were analyzed according to the procedure of Trautmann and Krasny (1997). The total N, P and K in compost were determined using the acid digestion method (Tandon, 1993, Jackson 1973). Estimation of bacteria, fungi and actinomycetes was performed using Thornton’s media, Martin’s media and Jensen’s media respectively, according to standard procedure (Bottomley *et al.*, 1994; Black, 1965). Stability tests for the compost (CO<sub>2</sub> evolution rate, phytotoxicity bioassay test/germination index) were performed according to the procedure suggested by Trautmann and Krasny (1997). Cress (*Lepidiun sativum* L.) seeds were used for the phytotoxicity bioassay test.

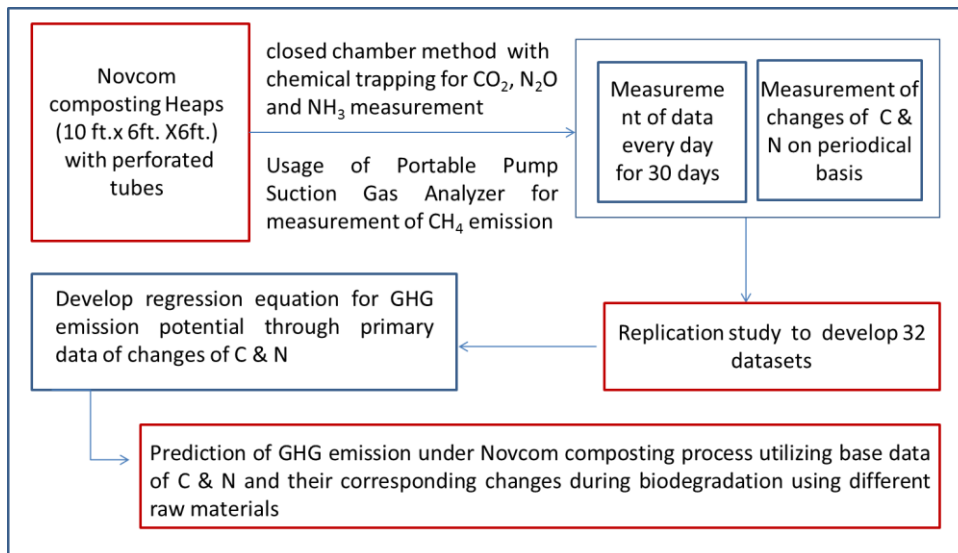
### 2.3 Protocol for greenhouse – gas measurement

For measurement of different greenhouse gas (GHG) viz. CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub> and NH<sub>3</sub>, eight Novcom compost heaps were made using different agro-waste viz. farm waste, banana stumps, water hyacinths, paddy straw, vegetable market waste, etc. during 2021 - 2022. To measure the GHGs, we inserted eight perforated tubes of 6.5’ length, placed equidistance in the compost heap of dimension 10 ft. x 6 ft. x 6 ft. as per pic 1 and 2; in order to trap all the greenhouse gases (Pic 1). We measured all the gases using ‘Closed Chamber Method’ with daily reading for continuous 30 days (compost matures in 21 days). This was done to estimate the total GHG on actual basis, not from any prediction model; as generally done in such case studies.



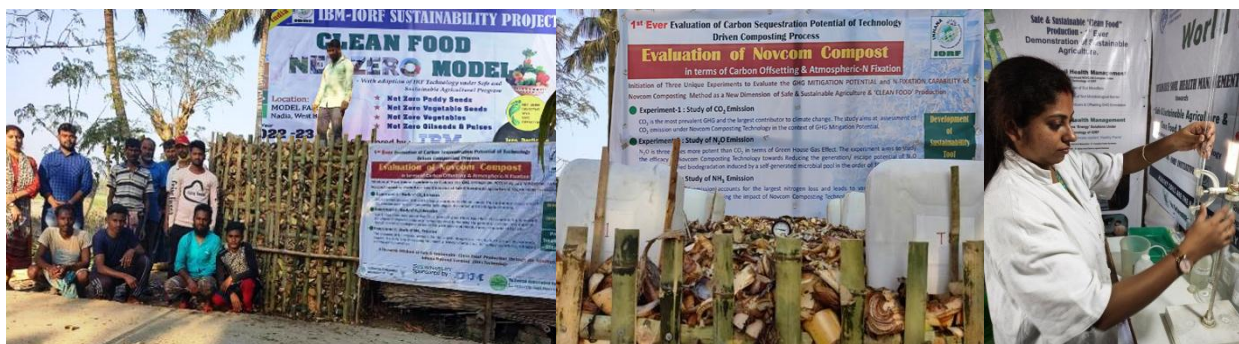
Pic. 1 : Structure for C with special perforated pipes for GHG estimation under IBM-IORF Sustainability Project.

### Flowchart of the Methodology Adopted for GHG estimation under Novcom Composting Technology



**2.31 Nitrous oxide (N<sub>2</sub>O):** Nitrous oxide (N<sub>2</sub>O), more commonly known as “laughing gas,” is a potent greenhouse gas, 273 times more powerful than carbon dioxide in terms of Global Warming Potential (GWP<sub>100</sub>). Nitrous oxide has a strong affinity to get absorbed in acetic acid (Sada *et al.* 1974). So we developed a chemical trapping mechanism using a closed chamber to measure Nitrous oxide emitted during compost biodegradation. However, the major difficulty is that CO<sub>2</sub> is also absorbed by acetic acid. So we used six different aqueous solution of acetic acid i.e., 0.05, 0.10, 0.30, 0.50, 1.0 and 2.0 percent. The solubility curve of carbon dioxide in aqueous acetic acid solution formed a parabola-like structure with maximum absorption in 1% acetic acid solution. Therefore, 1% acetic acid solution was used for the experiment.

**2.32 Carbon-di-oxide (CO<sub>2</sub>):** CO<sub>2</sub> gas is absorbed in 1N NaOH solution. Hence, 20 mL 1 N NaOH solution was taken in two beakers and placed on the heap under the specific jar selected for CO<sub>2</sub> absorption. These solutions each of 20 mL were taken in a 100 mL beaker and were placed according to requirement under a closed vessel. The head of the eight tubes were also covered by these vessels. Also four beakers, containing 1% acetic acid and 1N NaOH were kept at room temperature (Anderson, 1982).



**Pic. 2A :** Measurement of GHG emission from Novcom compost heap through ‘Closed Chamber Method’ under IBM-IORF Sustainability Project.

**2.33 Methane (CH<sub>4</sub>):** An open bottom chamber was used to measure gas fluxes as per standard method (Anderson, 2010). Due to the flux (F<sub>Flux chamber</sub>) of methane through the top of the compost material, the concentration of methane (C<sub>methane</sub>) increased linearly inside the

flux chamber over time, and the change in concentration over time ( $dC_{\text{methane}}/dt$ ) was calculated.



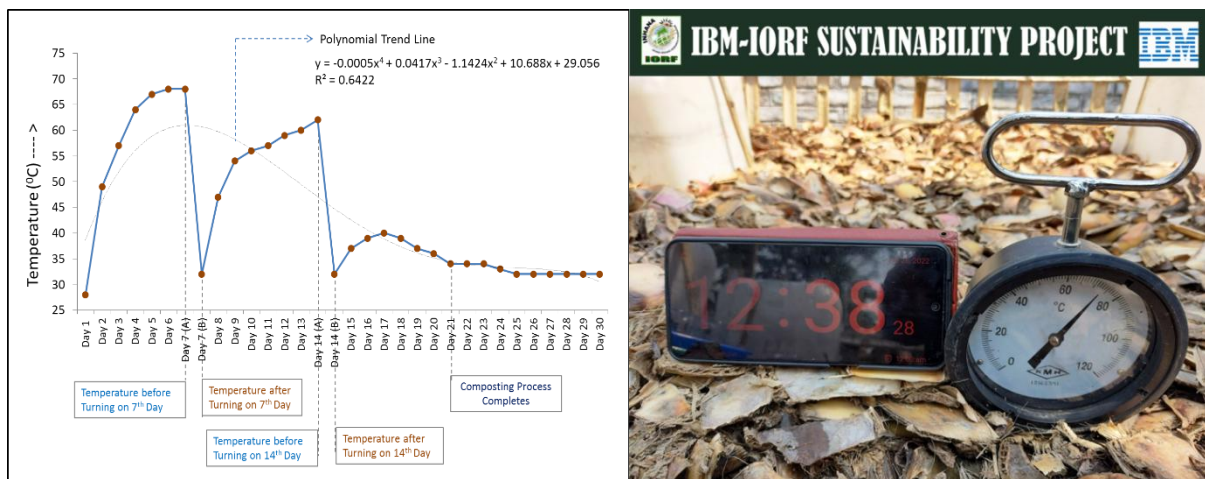
**Pic. 2B : Measurement of GHG emission from Novcom compost heap from 0 – 30 days under IBM-IORF Sustainability Project.**

**2.34 Ammonia gas (NH<sub>3</sub>):** Ammonia gas is absorbed in 5% boric acid. So, two beakers containing 20 mL 5% boric acid in each were placed under each jar selected for ammonia absorption. After 24 hours the boric acid was titrated against 0.05 N H<sub>2</sub>SO<sub>4</sub> using mixed indicator. This was done repetitively on each day for the entire period of composting.

### 3.0 Results and Discussion

#### 3.1 Variation in temperature generation during composting process

The temperature variation curve (Fig. 1) showed that there was steady rise of temperature within Novcom composting heap from day 2, which reached the peak (68<sup>o</sup> C) on 6<sup>th</sup> day. The steep rise of temperature indicated initiation of prolific microbial activity (*de Bertoldi et al. 1983*), which might be influenced by the energized Novcom solution. The average temperature between the successive turnings on 7<sup>th</sup> and 14<sup>th</sup> day gradually decreased went below 44<sup>o</sup>C from the 19<sup>th</sup> day and from 21<sup>st</sup> day onwards the temperature curve was almost parallel to X axis, which confirmed the completion of composting process or simultaneously compost maturity [Bera et al.\(2016\)](#). Maintenance of a stable temperature of more than 145<sup>o</sup>F (> 62.8<sup>o</sup> C) within the compost heap for more than 3 consecutive days has been found to be effective towards destruction of most of the human pathogens, insect larvae and weed seeds within the compost heap (*Rynk et al. 1992*), hence the temperature curve of compost heap suggests that the process could ensure a safe end product for application in soil as well as human handling.



**Fig. 1 : Variation in temperature generation during Novcom composting process under IBM-**

### 3.2 Evaluation of end product quality

Study was also taken up to evaluate the end product quality developed under Novcom Composting Technology. Under this study, compost samples were collected from the heap on the 21<sup>st</sup> day and analyzed for physicochemical, microbial, stability and maturity/phytotoxicity parameters.

**3.21 Physicochemical parameters:** All the compost samples appeared dark brown in colour with an earthy smell, deemed necessary for mature compost (Epstein, 1997). Average moisture varied from 60.24 to 65.4 percent (Table 1), which is slightly higher than the reference range (40 to 50) as suggested by Evanylo, (2006). pH of compost is an important criteria for consideration in respect of soil application, so that it can create a good growing medium for plants. pH value of Novcom compost samples ranged between 6.09 and 8.29 with mean of 7.70 (Table 1), which was well within the stipulated range for quality compost and indicated compost maturity (Jimenez and Garcia, 1989). Electrical conductivity value ranged between 1.24 and 3.30 with mean 1.70, indicating its high nutrient status. The organic matter of compost is a necessary parameter for determining the compost application rate to support sustainable agricultural production. Organic carbon content in compost samples ranged between 21.20 and 27.14 percent with mean value of 24.9, qualifying even the standard suggested value of >19.4 percent (AS 4454, 1999) for nursery application, with only few exceptions. Compost mineralization index (CMI) expressed as ash content/ oxidizable carbon indicated the ready nutrient supplying potential of compost for plant uptake (Bera *et al.* 2012). The CMI values of the compost samples varied from 1.46 to 3.40 indicating that all the values complied the standard range of 0.79 to 4.38 (Rekha *et al.* 2005)

**Table 1:** Physicochemical parameters of compost prepared under IBM-IORF Sustainability Project

Sl. No.	Parameter	Range Value	Mean value	(±) S.E.
<b>Physicochemical Parameters</b>				
1.	Moisture percent (%)	60.24 – 65.6	63.9	0.94
2.	pH <sub>water</sub> (1 : 5)	6.09 – 8.29	7.7	0.41
3.	EC (1 :5) dSm <sup>-1</sup>	1.24 – 3.30	1.86	0.37
4.	Total Ash Content (%)	49.56 – 65.50	55.1	2.69
5.	Total Volatile Solids (%)	34.5 - 50.44	44.9	2.69
6.	Organic Carbon (%)	19.2 - 28.0	24.9	1.52
7.	Compost Mineralization Index (CMI)	1.69 – 3.43	2.2	0.31

**3.22 Fertility and microbial parameters:** Although 36 different nutrients are required for plant growth, but the macronutrient (N, P, and K) contribution of compost is usually of major interest. The total nitrogen content in the compost samples ranged between 1.69 and 2.01 percent (Table 2), which was well above the reference range suggested by Alexander (1994) and Watson (2003). Mean value of total phosphate and total potash (0.86 and 1.10 percent respectively) were also higher than the minimum suggested standard. The ideal C/ N ratio of any mature compost should be about 10, as in humus; but it can be hardly achieved in composting (Mathur *et al.* 1991). However, of greater importance is its critical value (C/N ratio 20), below which further decomposition of compost in soil did not require soil nitrogen, rather released mineral nitrogen into the soil (Mathur *et al.* 1993). C/N ratio of the compost resembled the values obtained for any good quality compost.

Most organic substrates draw an indigenous population of microbes from the environment. In case of open-air composting processes, further colonization in compost material occurs naturally during heap construction as well as turning of heap. The microbial population, their biomass and activity, are key parameters that can also be used to elucidate the composting process (Tiquia *et al.* 2002). At the same time the very high microbial population (in order of 10<sup>16</sup> for total bacteria, fungi and actinomycetes count) in Novcom compost samples, corroborated the uniqueness of its production method which enables energy transfusion into the micro-environment within compost heap through application of potentized and energized Novcom solution. The process leads to generation of an ideal micro-atmosphere that facilitates self-generation of a high and diversified native microbial pool within the compost heap (Seal *et al.*, 2012), which in turn influences fastest bio-conversion, high and balanced nutrient dynamics and desirable electrical conductivity, etc. (Dolui *et al.*, 2014).

**Table 2:** Fertility and microbial parameters of compost prepared under IBM-IORF Sustainability Project

Sl. No.	Parameter	Range Value	Mean value	(±) S.E.
<b>Fertility Parameters</b>				
1.	Total Nitrogen (%)	1.69 – 2.01	1.89	0.04
2.	Total P <sub>2</sub> O <sub>5</sub> (%)	0.86 – 1.10	0.97	0.03
3.	Total K <sub>2</sub> O (%)	0.82 – 1.87	1.32	0.07
4.	C/N Ratio	12:1 – 17:1	13 : 1	0.52
<b>Microbial Count (c.f.u. per gm moist compost)</b>				
5.	Total Bacteria	(34–68) x10 <sup>16</sup>	56 x10 <sup>16</sup>	-
6.	Total Fungi	(29 – 37) x10 <sup>16</sup>	33 x10 <sup>16</sup>	-
7.	Total Actinomycetes	(15–28) x10 <sup>16</sup>	19 x10 <sup>16</sup>	-

**3.33 Stability, Maturity and Phytotoxicity parameters:** Compost maturity and phytotoxicity rating are the most important criteria for ensuring soil safety post compost application. Immature compost may contain high level of free ammonia, specific organic acids or other water soluble compounds which can limit seed germination and root development (Thompson *et al.* 2002). Many studies have shown that the application of immature compost in soil caused severe damage to plant growth (Jimenez and Garcia, 1989). Stability of compost sample indicates the status of organic matter decomposition and is a function of biological activity. Hence, microbial respiration forms an important parameter for determination of compost stability. Mean respiration or CO<sub>2</sub> evolution rate of all compost samples (1.98 to 3.92 mg/day) were more or less within the stipulated range (2.0 - 5.0) for stable compost (Trautmann and Krasny, 1997). The values obtained were in close conformity to the respirometry stability class rating of U.S Composting Council (2002) for compost stability (Thompson *et al.* 2002).

**Table 3:** Stability, Maturity and Phytotoxicity parameters of compost prepared under IBM - IORF Sustainability Project

Sl. No.	Parameter	Range Value	Mean value	(±) S.E.
<b>Stability Parameters</b>				
1.	CO <sub>2</sub> evolution rate (mgCO <sub>2</sub> -C/g OM/day)	0.96 – 3.01	2.00	0.14
<b>Maturity &amp; Phytotoxicity Parameters</b>				
2.	Seedling emergence (% of control)	89 – 157	104	4.21
3.	Root elongation (% of control)	87 – 128	123	3.05
4.	Germination index (phytotoxicity bioassay)	0.95 – 1.37	1.12	0.08

Assessment of phytotoxicity revealed that percent seed germination and root elongation over control ranged from 89 to 157 and 87 to 128 respectively (Table 3), which was well above the USCC guideline (> 90) for 'very mature compost with no phytotoxic effect'. Germination index (phytotoxicity bioassay) value ranged between 0.78 and 1.60 (mean 1.12), which was

well above the highest order of rating (1.0) and indicated not only the absence of phytotoxicity (Tiquia *et al.* 1996) in the compost samples but moreover, it confirmed that the compost enhanced rather than impaired germination and radical growth (Trautmann and Krasny, 1997).

### 3.3 Measurement of different greenhouse gas (GHG)

In the context of global warming, composting is one of the best waste management options that can offset GHG gases on one hand, while also contributing towards sustainable agriculture through the utilization of end product (compost) for soil health management; which in turn can enable the reduction of chemical fertilizers *vis-a-vis* GHG mitigation from source. However, implementation of a reliable technology to deal with these wastes is considered as a pillar for sustainable development of any nation (Iqbal, 2020). The amount of emitted gases under any composting process is highly influenced by the type of treated wastes and operational conditions, but most importantly the adopted composting technology, which would have a direct impact in reducing the rate of emissions, mainly N<sub>2</sub>O and CH<sub>4</sub> (Dhamodharan *et al.* 2019, Sayara and Sánchez, 2021). At the same time apart from being environment friendly the technology needs to be cost-effective as well, in order to ensure large scale adoptability.

Emissions are formed due to inadequate aerobic conditions of composting (Dhamodharan *et al.* 2019). Generally, the creation of anaerobic zones in compost mixtures results in CH<sub>4</sub> emissions, whereas nitrogen transformation and loss (NH<sub>3</sub> and N<sub>2</sub>O) are linked to ammonification, nitrification, and de-nitrification during the composting process (Jiang *et al.* 2015; Wang *et al.* 2016; Yang *et al.* 2015). The rate of gaseous emissions generally vary as per the adopted composting method, but the emitted amount is still less than that recorded from the landfill sites and under waste-to-energy processes (Friedrich and Trois, 2011; Saer *et al.* 2013; Wang and Nakakubo, 2020).

### 3.4 Global Warming Potential (GWP) values of Green House Gases

Global Warming Potential (GWP) has been developed as a metric to compare (relative to another gas) the ability of each greenhouse gas to trap heat in the atmosphere. Specifically, it is a measure of how much energy the emission of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO<sub>2</sub>) (EPA, 2022). CO<sub>2</sub> was chosen as the reference gas to be consistent with the guidelines of the Intergovernmental Panel on Climate Change (IPCC 2008). Because CO<sub>2</sub> has a very long residence time in the atmosphere, its emissions cause increase in atmospheric concentrations of CO<sub>2</sub> that will last thousands of years (Vallero, 2019) The time period usually used for GWPs is 100 years. Nitrous Oxide (N<sub>2</sub>O) has a GWP 273 times that of CO<sub>2</sub> for a 100-year timescale. N<sub>2</sub>O emitted today remains in the atmosphere for more than 100 years, on an average (EPA, 2022). Now in case of methane, there is an emerging debate whether, GWP of methane will be taken on 100 year's basis (as IPCC recommended) or on a shorter scale. Because, GWP hides trade-offs between short- and long-term policy objectives inside a single time scale of 100 or 20 years (Plattner *et al.* 2009). The most common form, GWP<sub>100</sub>, focuses on the climate impact of a pulse emission over 100 years, diluting near-term effects and misleadingly implying that short-lived climate pollutants exert forcing in the long-term, long after they are removed from the atmosphere (Allen *et al.* 2016). Meanwhile, GWP<sub>20</sub> ignores climate effects after 20 years (Ocko *et al.* 2017).

Now, the challenge is majorly related to methane, which is a powerful greenhouse gas with a 100-year global warming potential 28-34 times that of CO<sub>2</sub>. But when measured over a 20-year period, that ratio grows 84-86 times. Despite methane's short residence time, the fact

that it has a much higher warming potential than CO<sub>2</sub> and that its atmospheric volumes are continuously replenished make effective methane management a potentially important element in countries' climate change mitigation strategies (UNECE,2022) .

According to J. Trancik, an MIT associate professor at the Institute for Data, Systems, and Society, more scientists are beginning to model the warming effects that today's methane emissions will have over the next 20 or 30 years, in order to predict more accurately whether humanity can avoid overshooting targets such as stopping global warming at 1.5 degrees Celsius. (Moseman and Trancik, 2021).

Pérez-Domínguez *et al.* (2021) also indicated that methane's short atmospheric life has important implications for the design of global climate change mitigation policies in agriculture. Results also showed that the choice of a particular metric for methane's warming potential is the key to determine optimal mitigation options, with metrics based on shorter-term impacts leading to greater overall emission reduction. Most importantly, when the ambition is to reduce warming in the next few decades, a shorter time horizon might be applied in comparing the effects of CO<sub>2</sub> and CH<sub>4</sub>. Thus a two-value approach, which indicates the effect over two different time horizons, is suggested by a number of studies (Ocko *et al.* 2017)

In the Sixth Assessment Report of IPCC (AR6) (IPCC, 2021) , there is discussion regarding the use of a range of emission metrics, including GWP<sub>20</sub> and GWP<sub>100</sub> and how they perform, using methane as an example and explores how cumulative CO<sub>2</sub> equivalent emissions estimated for methane vary under different emission metric choices and how estimates of the global surface air temperature (GSAT) change deduced from these cumulative emissions compare to the actual temperature response computed with the two-layer emulator (EFCTC, 2021). GSAT changes estimated with cumulative CO<sub>2</sub> equivalent emissions computed with GWP<sub>20</sub> matches the warming trend for comparatively shorter time scale (a few decades) but quickly overestimates the response, whereas estimating emissions using GWP<sub>100</sub> underestimate the warming potential (IPCC ARC 6, 2021). So the moot point is we do not have another 100 years to achieve our 2050 climate neutrality and net zero targets and whatever we need to change, have to be done now.

Now, according to Abernethy and Jackson, emission metrics, a crucial tool in setting effective exchange rates between greenhouse gases, currently require an arbitrary choice of time horizon. So they propose a novel framework to calculate the time horizon that aligns with scenarios achieving a specific temperature goal and to best align emission metrics with the Paris Agreement 1.5 °C goal. They recommend a 24 year time horizon, using 2045 as the endpoint time, with its associated GWP<sub>1.50 C</sub> = 75 (Abernethy and Jackson, 2022).

In the study we used two different timescales for evaluating GHG emission in order to estimate the maximum impact of the GHG gases on environment. In case of N<sub>2</sub>O, we considered the usual 100 years' time frame. But in the case of methane we took the 24 years' timeframe because CH<sub>4</sub> is short-lived in atmosphere, this time horizon aligns with scenarios achieving a specific temperature goal and to best align emission metrics with the Paris Agreement 1.5°C goal.

**3.5 Emission of Carbon dioxide (CO<sub>2</sub>) under Novcom Composting Technology:** The CO<sub>2</sub> released during composting is considered biogenic, not anthropogenic, so it is not considered in greenhouse gas calculation (USCC, 2008). Good composting practices that balance the carbon: nitrogen ratio and provide adequate moisture will minimize GHG emissions (Talt, G. 2020) During biodegradation process the microbial communities' biodegrade the organic matter under aerobic condition and most of the carbon is lost as CO<sub>2</sub>, such that a linear

relation between carbon content and CO<sub>2</sub> emissions would be observed during the process (Qin, 2010). CO<sub>2</sub> emission measured on day basis under Novcom Composting Technology showed intense values in the 1<sup>st</sup> week (Avg. 114.6 gm CO<sub>2</sub>/ ton wet waste), which gradually decreased with progression in the composting period and became minimum after 21 days (22.79 gm CO<sub>2</sub>/ ton raw material), indicating completion of the biodegradation process (Fig.2).

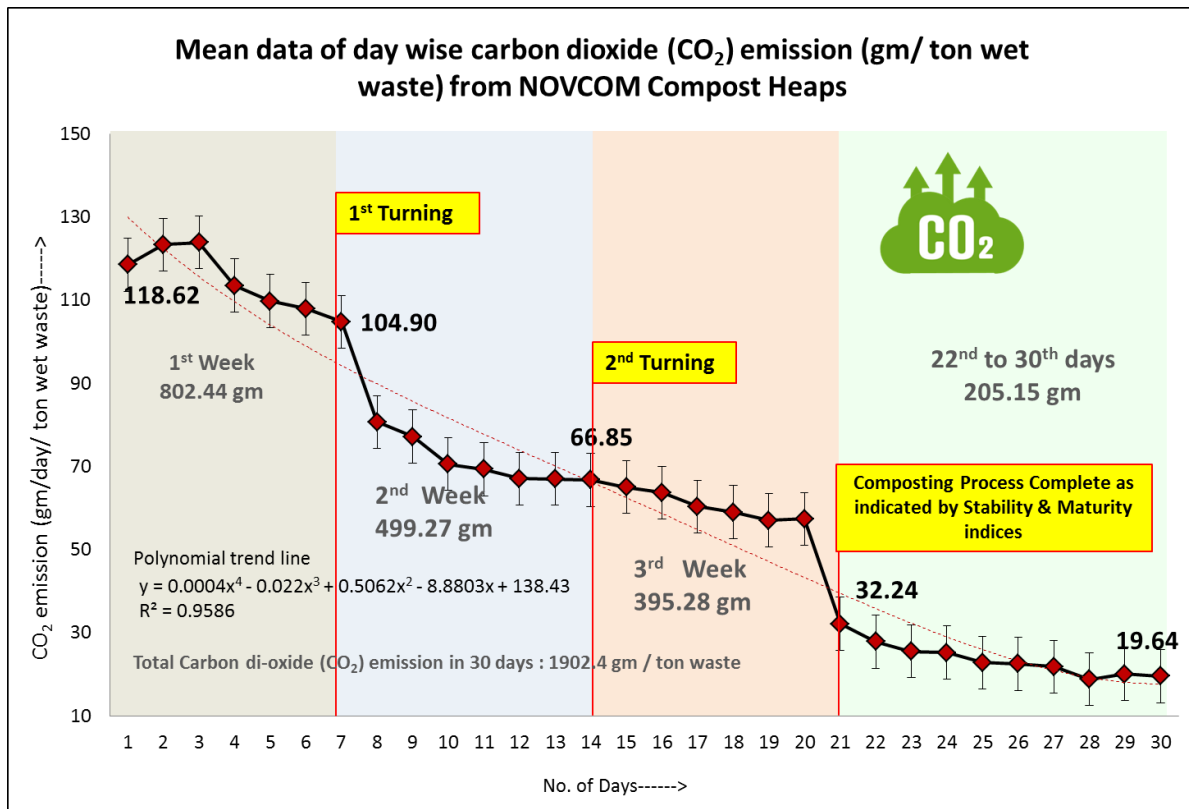


Fig. 2: Day wise carbon dioxide emission (gm/ton waste) during the biodegradation period under Novcom Composting Technology

In case of Novcom Composting Technology, the faster biodegradation (within 21 days) and presence of a very high, self-generated and diversified microbial pool in the order of 10<sup>16</sup>cfu/gm moist compost (Bera *et al.* 2016); perhaps enabled higher carbon transformation from raw materials to the final end product leading to minimal CO<sub>2</sub> emissions. A case study from FAO-CFC-TBI Project (2009-11) relating to end product (compost) quality assessment (made using similar raw materials) under four different composting processes including Novcom Composting Technology, indicated the highest percent of organic carbon in Novcom compost as compared to the rest other studied compost samples (Seal *et al.* 2015c). The result further indicated that on an average 8 – 10 kg more organic carbon was saved from being lost in the environment as CO<sub>2</sub>, per ton of compost; during the process of biodegradation under Novcom Composting Technology. Hence, Novcom Composting Technology demonstrated a higher GHG mitigation potential due to lower CO<sub>2</sub> emission during the process of biodegradation (Datta *et al.*, 2022) as well as better opportunity towards regeneration of the soil carbon sink through Novcom compost application due to transformation/ preservation of the organic carbon as humus by the high, self-generated and diversified microbial pool within Novcom Compost.

**3.6 Emission of Methane (CH<sub>4</sub>) under Novcom Composting Technology:** Methane is the major contributor to non-biogenic greenhouse gas emissions from composting, and the

majority of that CH<sub>4</sub> is emitted early in the composting process. Generally, the creation of anaerobic pockets in compost mixtures results in CH<sub>4</sub> emissions which is probably due to increase of moisture due to structural breakdown of organic materials. In the absence of oxygen (O<sub>2</sub>), a succession of microbes convert carbohydrates in the organic waste to CO<sub>2</sub> and CH<sub>4</sub> (Vergara and Silver, 2019). Once CH<sub>4</sub> is produced, it may be emitted to the atmosphere or oxidized to CO<sub>2</sub> within the pile. The balance between CH<sub>4</sub> production and oxidation is likely controlled by redox potential (Conrad, 1996) and is affected by temperature and moisture, which control O<sub>2</sub> solubility and biological activity (Treat *et al.* 2014; Olefeldt *et al.* 2013). Methane emission under Novcom Composting Technology was found to be negligible in comparison to other processes, as also documented by several research workers (Hermann *et al.* 2011; Lou and Nair, 2009; IPCC, 2006). This might be attributed to the aerobic process (EPA, 2020) and the intense microbial activity within Novcom Composting heaps accelerated by the creation of favourable environment through the application of subtle energy forms in the form of Novcom solution.

Though the CH<sub>4</sub> emission was nominal under Novcom Composting Technology in comparison to average reference value of CH<sub>4</sub> emission (0.03 – 8.0 kg CH<sub>4</sub> per ton wet waste) measured under the different composting processes), it was measured on regular basis during the entire biodegradation period. The highest value was observed on the 7<sup>th</sup> day before demolition/ churning of the heap, which might be due to the increased formation of anaerobic pockets within the composting heap; attributed to excess moisture generation due to structural breakdown of organic materials under intense microbial activity. CH<sub>4</sub> generation was found to be negligible after 14 days of composting and ceased completely after 21 days (Fig.3).

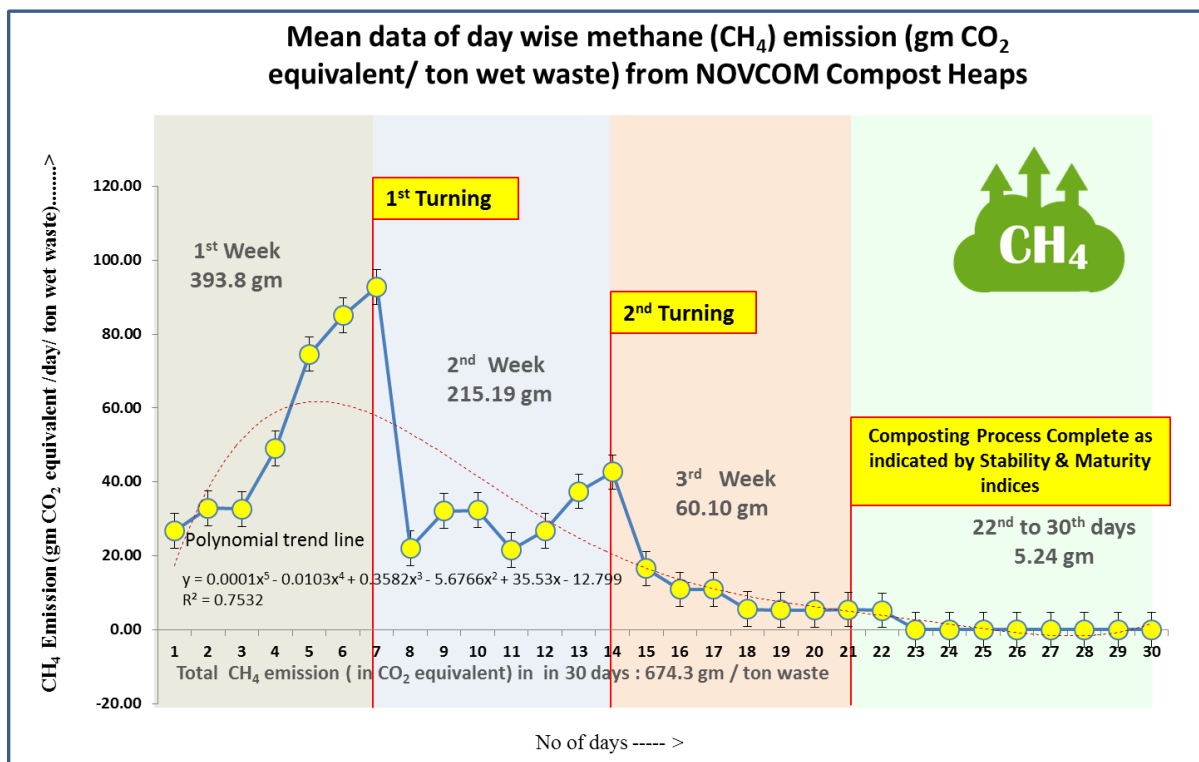
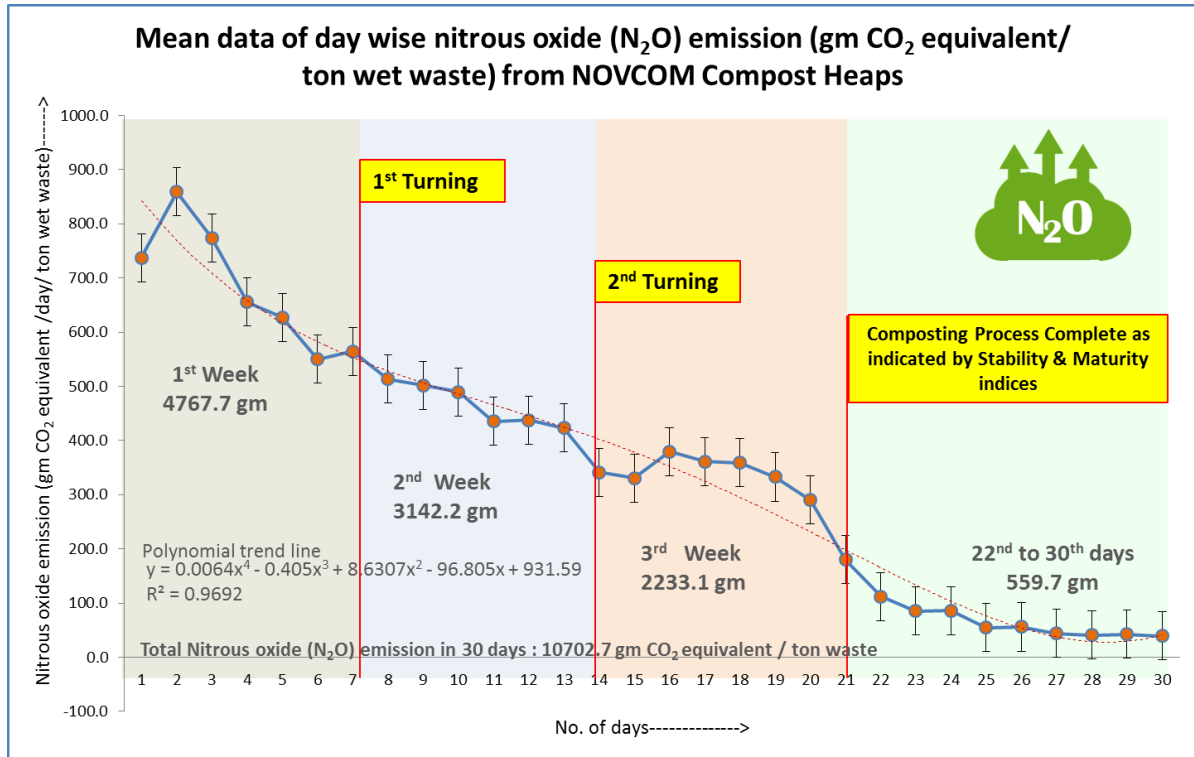


Fig.3 : Day wise methane emission (gm CO<sub>2</sub> equivalent /ton waste) during the biodegradation period under Novcom Composting Technology

**3.7 Emission of Nitrous oxide (N<sub>2</sub>O) under Novcom Composting Technology:** Nitrification or the conversion of NH<sub>4</sub><sup>+</sup> to NO<sub>3</sub><sup>-</sup>, and denitrification, the conversion of NO<sub>3</sub><sup>-</sup> to nitrogen gas (N<sub>2</sub> and N<sub>2</sub>O), are the major pathways leading to N<sub>2</sub>O production and consumption (Firestone and Davidson, 1989). Net emission of N<sub>2</sub>O is dependent on the controls on both processes. As biodegradation proceeds, the mineralization of organic nitrogen leads to formation of ammonia (NH<sub>3</sub>), which could react with H<sup>+</sup> ions to form NH<sub>4</sub><sup>+</sup>. The NH<sub>4</sub><sup>+</sup> to NH<sub>3</sub> equilibrium is governed mainly by pH value and temperature within the compost heap (Zhu *et al.* 2020; Wang *et al.* 2019). Ammonia-oxidizing bacteria or archaea and nitrite oxidizing bacteria convert part of the nitrogen to nitrate through the nitrification process which is used by the microbial community (Ma *et al.* 2022).



**Fig.4 : Day wise nitrous oxide emission (gm CO<sub>2</sub> equivalent /ton waste) under Novcom composting method**

In case of Novcom composting process, N<sub>2</sub>O emission was highest in the 1<sup>st</sup> week of biodegradation (Average N<sub>2</sub>O emission 679.8 gm CO<sub>2</sub> equivalent/ ton wet waste), it reduced gradually with the advancement of the composting period and became almost negligible post 21 days (Average N<sub>2</sub>O emission 62.8 gm CO<sub>2</sub> equivalent/ day/ton wet waste) (Fig. 4). Since high temperature (over 40<sup>0</sup>C) can hinder the activity of nitrifiers, the considerable N<sub>2</sub>O emissions in the thermophilic stage was possibly due to NH<sub>4</sub><sup>+</sup> oxidization by methanotrophs (Campbell *et al.* 2011 ; Jiang *et al.* 2016). Total N<sub>2</sub>O emission under Novcom Composting Technology was about 1/10<sup>th</sup> of the average reference value (0.06 - 0.6 kg N<sub>2</sub>O ton wet waste treated) documented in case of various composting piles by several research workers (Adhikari *et al.* 2013, Lou and Nair, 2009; IPCC, 2006). The lower values under Novcom Composting Technology might be due to the fact that the higher speed of biodegradation under this method was induced by the self- generated diversified microbial pool (in order of 10<sup>16</sup>c.f.u. per gm moist compost) and not through any mechanization or artificial induction. The high microbial pool quickly immobilized the nitrogen released due to organic matter breakdown thereby reducing the escaping chances of N<sub>2</sub>O during the process of organic matter breakdown.

**3.8 Emission of Ammonia (NH<sub>3</sub>) under Novcom Composting Technology:** Key factors that control ammonia emission during composting are: pH, temperature, moisture content, aeration rate, carbon-to-nitrogen ratio and presence of microbial pool within the compost heap (Palashikar *et al.* 2016). In case of Novcom Composting Technology, NH<sub>3</sub> emission decreased with progression of composting (Fig.5) which indicated intense microbial activity within compost heap that reduced the escaping chances of NH<sub>3</sub> during the biodegradation process. However, due to its very low CO<sub>2</sub> equivalency, NH<sub>3</sub> is generally not considered under the GHG calculation methodology, though it has a negative impact on environment and reduces the nutrient quality of compost.

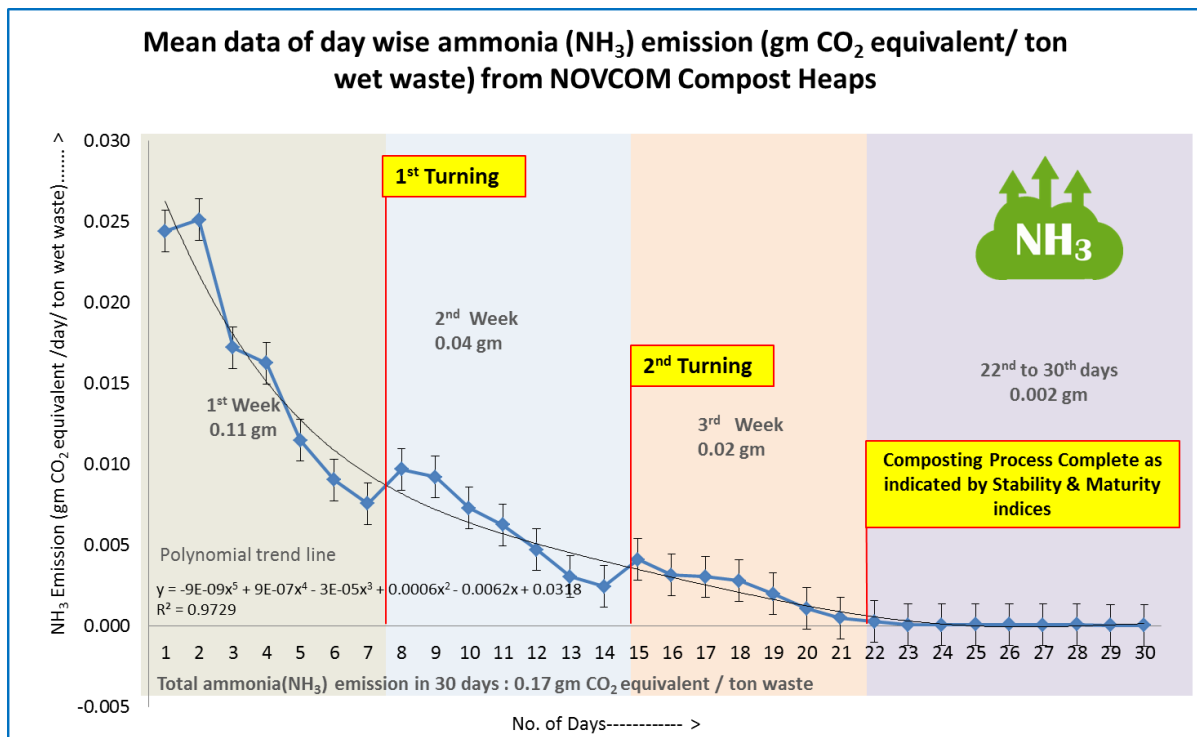


Fig.5 : Day wise ammonia emission (gm CO<sub>2</sub> equivalent /ton waste) under Novcom Composting Technology.



Pic. 3: Utilization of Novcom compost for ‘Clean Vegetable’ production and development of ‘Clean Food Net Zero’ Model under IBM-IORF Sustainability Project.

### 3.9 Development of equation for prediction of GHG emission under Novcom Composting Technology:

Regression equations were developed using the 32 generated data sets from the study of 8 Novcom Composting heaps, made with different agro waste, under IBM-IORF Sustainability Project, during the period 2021 – 22.

#### 3.9.1 Regression equation to predict CO<sub>2</sub> emission

The following Equation

$$Y = 11.37 * X + 14.61$$

Where,

Y = Expected CO<sub>2</sub> Emission (gm)

X = Actual Carbon loss during composting process (kg)

$$R^2 = 0.9228$$

Note: R-squared ( $R^2$ ) is a statistical measure that represents the proportion of the variance for a dependent variable and explains the strength of the relationship between an independent and dependent variable.

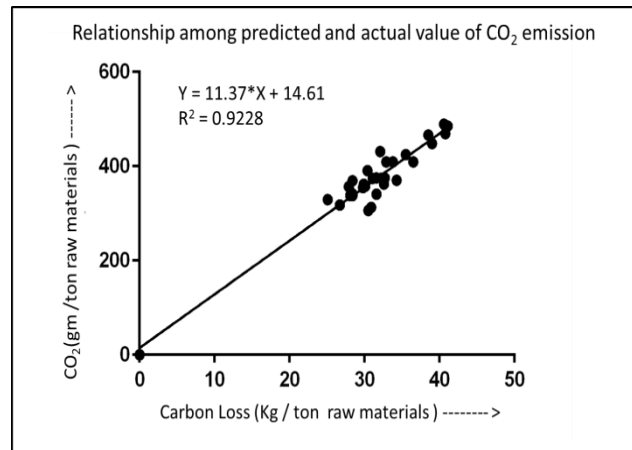


Fig 6 : Relationship among actual and predicted value of CO<sub>2</sub> emission

#### 3.9.2 Regression equation to predict CH<sub>4</sub> emission

The following Equation

$$Y = 0.06399 * X - 0.2498$$

Where,

Y = Expected CH<sub>4</sub> Emission (gm)

X = Actual Carbon loss during composting process (kg)

$$R^2 = 0.8274$$

Note: To find the expected emission in CO<sub>2</sub> equivalent, Y value should be multiplied with 75 (GWP of methane is 75 over a period of 24 years, meaning that one tonne of methane emission is equivalent to emitting 75 tonnes of carbon dioxide).

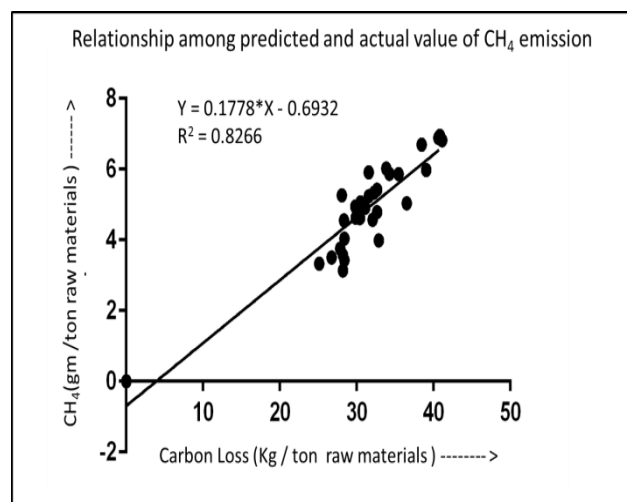


Fig 7 : Relationship among actual and predicted values of CH<sub>4</sub> emission

### 3.93 Regression equation to predict N<sub>2</sub>O emission

The following Equation

$$Y = 39.31 * X + 0.6338$$

Where,

Y = Expected N<sub>2</sub>O Emission (gm)

X = Actual N loss in first 14 days during composting process (kg)

$$R^2 = 0.9673$$

Note : To find the expected emission in N<sub>2</sub>O equivalent, Y value should be multiplied by 273 (N<sub>2</sub>O has GWP of 273 over a 100 years period meaning that, one tonne of N<sub>2</sub>O emission is equivalent to emitting 273 tonnes of carbon dioxide)

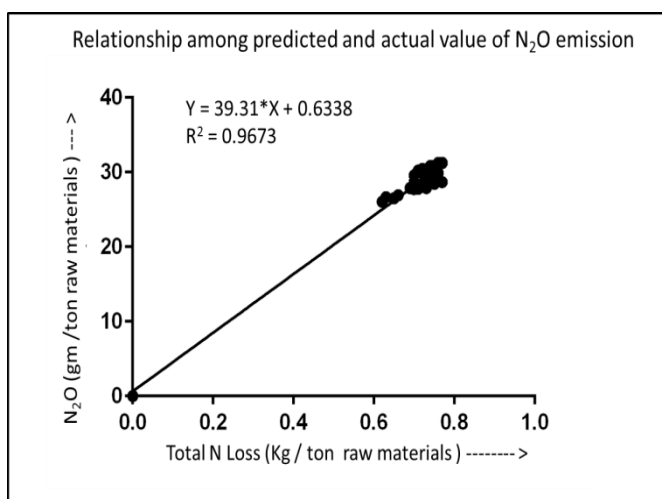


Fig 8 : Relationship among actual and predicted values of N<sub>2</sub>O emission

### 3.94 Regression equation to predict NH<sub>3</sub> emission

The following Equation

$$Y = 0.07585 * X - 0.003006$$

Where,

Y = Expected NH<sub>3</sub> Emission (gm)

X = Actual N loss in first 14 days during composting process (kg)

$$R^2 = 0.734$$

Note: Ammonia is generally not considered as GHG during any evaluation process as NH<sub>3</sub> has an Ozone Depletion Potential (ODP) rating of 0.

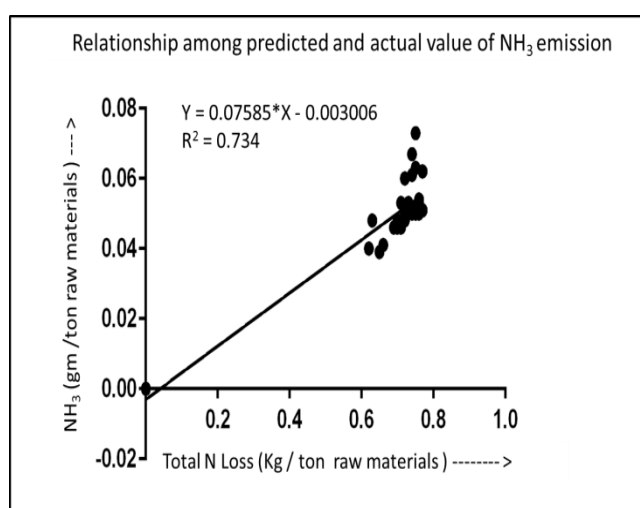


Fig 9 : Relationship among actual and predicted values of NH<sub>3</sub> emission

#### 4.0 Assessment of GHG abatement from landfill materials utilizing Novcom Composting Technology as per IPCC Guideline

Novcom Composting Technology can be utilized for bioconversion of any type of waste from (1) coir pith (Seal *et al.* 2015), (2) Press mud (Seal *et al.* 2016), (3) Water hyacinth (Dolui *et al.* 2014), (4) Poultry litter (Seal *et al.* 2015b), (5) Municipality solid waste (Bera *et al.* 2012), (6) Crop residues, (7) Banana stumps (Mukhopadhyay *et al.* 2015), (8) Refuse from food processing industries etc.; which in general are high GHG emitting sources especially under unplanned dumping at landfill sites. Estimation of the potential GHG emission from these waste materials was based on the document prepared by the IPCC National Greenhouse Gas Inventories Program to support the development of *Good Practice Guidelines* for estimation of greenhouse gas emissions from the waste sector and to manage the associated uncertainties. The document is a background paper for the IPCC expert meeting on Waste in Sao Paulo. The document concentrates on the anaerobic degradation process generating landfill gas (LFG). The existing *IPCC Guidelines* for national Greenhouse Gas Inventories have been reviewed, and an upgraded basis has been proposed for a worldwide good practice framework to carry out as accurately as possible national inventories of emissions of CH<sub>4</sub> (IPCC, 2018). We took the default IPCC methodology that is based on the theoretical gas yield (a mass balance equation) for calculating all potential methane released at a time.

#### 4.1 Formula for Calculation of GHG emission from biowaste (primarily landfill materials)

GHG emission (MT in CO<sub>2</sub> equivalent) =

$$[(LM_T \times LF_F \times MC_F \times DOC \times DOC_F \times F \times 16/12 - R) \times (1 - OX)] *GWP_{CH_4}$$

LM<sub>T</sub> : Total Landfill Material(MT)

LF<sub>F</sub> : Fraction of Landfill Material disposed at Disposal Sites (if 100 % landfill material which is generated is deposited in Disposal sites, then LF<sub>F</sub> value will be 1.0 (default value))

MC<sub>F</sub> : Methane correction factor (fraction) (IPCC default value is 0.6, when there is no specific information)

DOC : Degradable organic carbon (fraction) (kg C/ kg landfill material)

DOC<sub>F</sub> : fraction DOC dissimilated (IPCC default is 0.77)

F : fraction of CH<sub>4</sub> in landfill gas (IPCC default is 0.5) 16/12 : conversion of C to CH<sub>4</sub>

R : Recovered CH<sub>4</sub> (MT) (in general value is 0 if not any specific treatment plants in disposal sites to recover methane)

OX : oxidation factor (fraction – IPCC default is 0)

GWP<sub>CH<sub>4</sub></sub> (24 years) : 75

Therefore, GHG Offset under Novcom Composting technology (credit calculation upto compost development, credit for compost application in soil is not included)

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GHG Offset under Novcom Composting Technology	=	GHG Emission from untreated waste (Calculated as per IPCC Guideline)	-	GHG Emission during biodegradation under Novcom Composting Technology (Calculated as per empirical formula developed for GHG calculation under Novcom Composting Technology)
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We used two different sets of empirical formula for calculation of GHG abatement under bioconversion of any landfill waste utilizing Novcom Composting Technology. First we calculated the GHG emission potential of the selected landfill waste through the empirical formula developed by IPCC. Then we used our formulation, developed from the extensive field experiments (as described in this article); to calculate the GHG emission potential of the same landfill waste when biodegraded under Novcom Composting Technology.

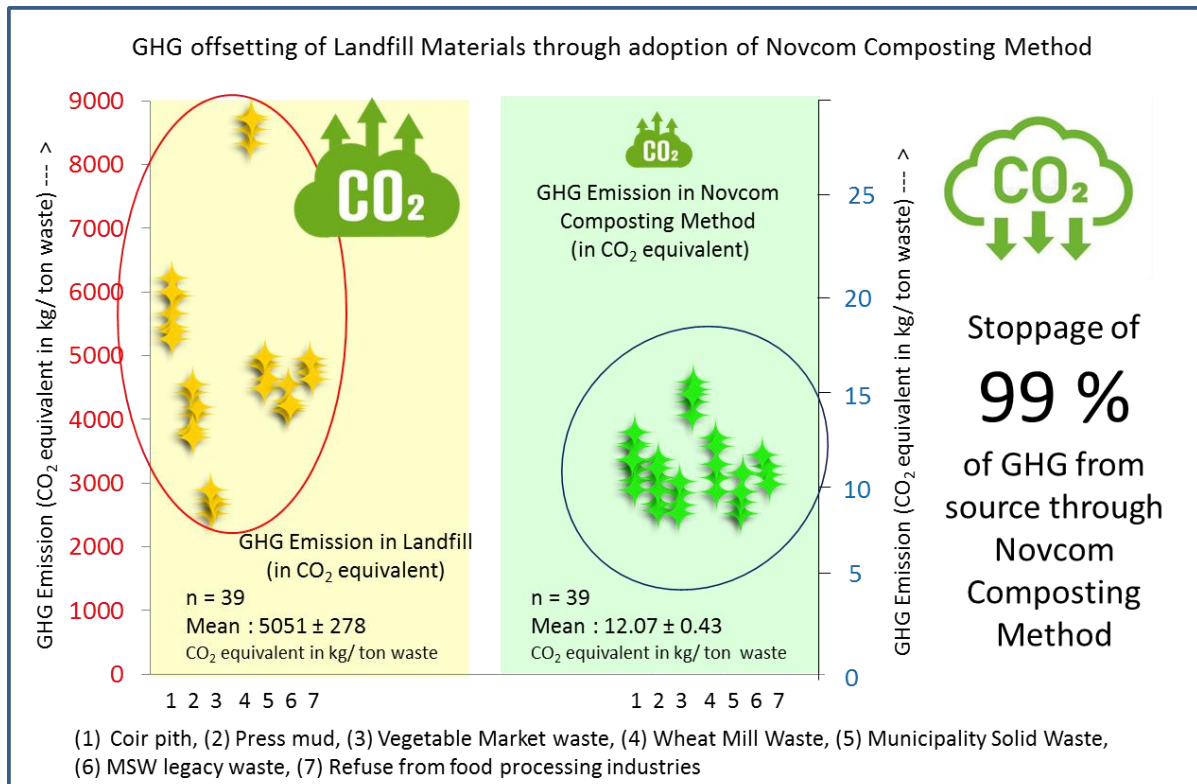


Fig. 10 : GHG offset from landfill waste through its bioconversion utilizing Novcom Composting Technology

We first calculated the GHG emission potentials of eight different kinds of biodegradable waste viz. coir pith, press mud, vegetable market waste, wheat mill waste, municipality solid waste, MSW legacy waste and refuse from food processing industries; under landfill conditions as per the IPCC methodology described above. GHG emission potential in terms of CO<sub>2</sub> equivalent in kg/ ton waste varied in between 2549 to 6187 kg CO<sub>2</sub> equivalent/ ton waste (Fig 10). The highest GHG emission was in case of wheat mill waste (average 8828 kg CO<sub>2</sub> equivalent/ ton waste) followed by coir pith (average 6014 kg CO<sub>2</sub> equivalent/ ton waste) and municipality solid waste (average 4722 kg CO<sub>2</sub> equivalent/ ton waste). The GHG emission potentials of these eight different kinds of biodegradable waste when recycled under Novcom Composting Technology was recalculated as per the developed empirical formula described above. The required database for calculating the probable GHG emission during biodegradation was sourced from our previous studies (Seal *et al*, 2016, Seal *et al* 2016a, Bera *et al*, 2011, Bera *et al*, 2022). The Calculation using empirical equations indicated that biodegradation under Novcom Composting Technology leads to non significant GHG emission (average 12.07 kg CO<sub>2</sub> equivalent/ ton waste) and thus has the potential to offset 99% of GHG from source.

The phenomenal achievement under this aerobic composting process is primarily due to minimization of the escape potential of two major GHG's i.e. CH<sub>4</sub> and N<sub>2</sub>O during the process of biodegradation; primarily attributed to the generation of high self-generated and diversified microbial pool within the Novcom composting heap. Thus, Novcom Composting Technology not only stabilized the organic matter in the waste within a shortest period of 21 days, but did so with minimal emission, as indicated by 1/16<sup>th</sup> of the average reference emission values (total averaging 200 kg CO<sub>2</sub>-eq per tonne wet waste treated) as documented under various composting processes (Adhikari *et al.* 2013; Friedrich and Trois, 2011; Hermann *et al.* 2011; Rogger *et al.* 2011; Martínez-Blanco *et al.* 2010; Lou and Nair, 2009; IPCC, 2006).

## 5.0 Conclusions

Composting programs are one of the most effective and economic means of reducing, eliminating and reversing GHG emissions towards the objective of climate change mitigation. In this respect, Novcom Composting Technology—a technological innovation can serve as an effective tool for climate action (GHG abatement from source) due to 17 times lower GHG emission as compared to the reference values under other biodegradation processes.

The dual premise of speediest biodegradation as well as GHG abatement, especially methane mitigation, under this composting process is primarily attributed to the self-generated and very high population of microflora which minimized the generation and escaping chances of the GHG's resulting from organic matter breakdown and nitrogen mineralization. Hence, the very high climate action potential of this Technology is driven by its dual action mode i.e., lower CO<sub>2</sub> emission during waste recycling as well as speedy regeneration of the soil- C sequestration potential; through transformation/preservation of organic carbon as humus by the very high, self-generated and diversified microbial pool within Novcom Compost.

Thus Novcom Composting Technology can, serve as an effective tool for bioconversion of waste especially the high GHG emitters like landfill materials. It provides a fresh perspective in respect of large scale waste management especially in a country like India which continues to be a ticking time bomb of waste. Moreover, generation of safe and quality compost from waste, a raw material source, which is both abundant and cost free; that too within the shortest time period, provides the choice especially for the resource poor marginal and small farmers to undertake sustainable soil health management that is essential for present as well as future crop security. Thus Novcom Composting Technology can, drive not only successful 'Waste to Wealth' programs but most importantly serve as an excellent tool for GHG Mitigation.

## Acknowledgement

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## Reference

- Abernethy S and Jackson RB. Global temperature goals should determine the time horizons for greenhouse gas emission metrics. *Environ. Res. Lett.* 2022; 17: 024019
- Adhikari BK, Trémier A, Barrington S, Martinez J. and Daumoin M. Gas emissions as influenced by home composting system configuration. *Journal of Environmental Management.* 2013;116 : 163 -171
- Alexander RA. Standards and guidelines for compost use. *BioCycle.* 1994; 35(12):37–41.
- Allen M, Fuglestvedt J, Shine K, Reisinger A, Pierrehumbert RT, Forster PM. New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change.* 2016; 6: 773–776.
- Andersen JK, Boldrin A, Samuelsson J, Christensen TH, and Scheutz, C. Quantification of Greenhouse Gas Emissions from Windrow Composting of Garden Waste. *Journal of Environmental Quality.* 2010; 39(2): 713-724.
- Anderson, JPE. Soil respiration *in* Methods of soil analysis. Part 2. Chemical and microbiological properties. Agronomy no. 9. American Society of Agronomy, Inc., Madison, WI. 1982. 831–871p
- Australian Standards. 4454:1999. Composts, soil conditioners and mulches. Standards Association of Australia, Homebush, NSW(1999).
- Bera R, Datta A, Bose S, Barik AK, Mallick R, Das A, Ganguli M, Narasimhan VL, Quah E and Seal A. Induction of Novcom Composting Technology for Highest GHG Mitigation under ‘Waste to Wealth Program’– A Case Study from IBM-IORF Sustainability Project, West Bengal, India. *Waste Management and Circular Economy. Proceedings of 12<sup>th</sup> International Conference on Sustainable Waste Management and Circular Economy and IPLA Global Forum, 2022.*
- Bera R, Datta A, Saha S, Dolui AK, Chatterjee AK, Sarkar RK, Mazumdar D, Bhattacharyya P, and Seal A. An Effective Road Map Through Resource Recovery Output Approach for Municipality Solid Waste Management A Success Story from North Barrackpore & Garulia Municipalities, North 24 Parganas, West Bengal, India. *Proceeding of 2<sup>nd</sup> International Conference on Solid Waste Management, Nov 9-11, 2011, pp. 337-345.*
- Bera R, Datta A, Saha S, Dolui AK, Chatterjee AK, Sarkar RK, Sengupta K, Bhattacharyya A, and Seal A. New Concept in Municipality Solid Waste Management- A Case Study from Garulia& North BarrackporeMunicipalities, North 24 Parganas, West Bengal. *Journal of Crop and Weed.* 2012; 8(1):60-64.
- Bera R, Seal A, Datta A, Saha S, Dolui AK, Sarkar RK, Chatterjee AK, Barik AK, De GC and Mazumdar D. Self-generated microbial population or cultured microflora –an important criterion toward development of an effective and economically viable road map for organic soil management. *Archives of Agronomy and Soil Science.* 2017;63(5):674-686.
- Black CA. Methods of soil analysis, Part 1 and 2. Madison (WI): American Society of Agronomy. 1965.
- Bottomley PS, Angle JS and Weaver RW. Methods of Soil Analysis: Part 2— Microbiological and Biochemical Properties. Madison, WI: Soil Science Society of America. 1994.

- Campbell MA, Nyerges G, Kozlowski JA, Poret-Peterson AT, Stein LY, Klotz MG. Model of the molecular basis for hydroxylamine oxidation and nitrous oxide production in methanotrophic bacteria. *FEMS Microbiol. Lett.* 2011. 322 : 82–89.
- Conrad R. Soil Microorganisms as controllers of atmospheric trace gases (H<sub>2</sub>, CO, CH<sub>4</sub>, OCS, N<sub>2</sub>O, and NO) *Microbiol. Rev.* 1996. 60: 609–40
- Datta A, Bera R, Bose S, Dutta S, Mukherjee K, Goswami KK, Debnath M, Barik AK, Mallick R, Das A, Ganguli M, Narasimhan VL, Quah E. and Seal A. Induction of Novcom Composting Technology for Highest GHG Mitigation under ‘Waste to Wealth Program’– A Case Study from IBM-IORF Sustainability Project, West Bengal, India. Waste Management and Circular Economy. Proceedings of 12<sup>th</sup> International Conference on Sustainable Waste Management and Circular Economy and IPLA Global Forum. 2022.
- de Bertoldi M, Vallini G and Pera A. The biology of composting: a review. *Waste Manage Res.* 1983. 1:157–176.
- Dhamodharan K, Varma VS, Veluchamy C, Pugazhendhi A and Rajendran K. Emission of volatile organic compounds from composting: A review on assessment, treatment and perspectives. *Sci. Total. Environ.* 2019. 695:133725.
- Dolui AK, Som A, Mukhopadhyay K, Mukherjee S, Bera R and Seal A. Evaluation of a Novcom Composting Method towards Speedy Biodegradation of Water Hyacinth for Effective Bio-resource Utilization in Farmers Level. *Journal of Natural Product and Plant Resource.* 2014. 4(3): 44-47.
- Dolui, AK, Goura P, Bera R and Seal A. Evaluation of Different On-farm Compost Quality and their Role in Made Tea Productivity and Development of Acid Tea Soils. *International Journal of Innovation and Applied Studies.* 2014. 6(3): 549-571
- EFCTC. IPCC AR6 Discusses the use of 100-Year and 20-Year GWPs and Other Emission Metrics, European Fluoro Carbons Technical Committee. 2021. Available at <https://www.fluorocarbons.org/news/ipcc-ar6-discusses-the-use-of-100-year-and-20-year-gwps-and-other-emission-metrics/> (Accessed on 28.10.22)
- EPA Climate Impacts on Agriculture and Food Supply, United States Environmental Protection Energy. 2023. Available at <https://climatechange.chicago.gov/climate-impacts/climate-impacts-agriculture-and-food-supply> (Accessed on 27.1.23)
- EPA. Composting Food Waste: Keeping a Good Thing Going. Southeast New England program. 2020. <https://www.epa.gov/snep/composting-food-waste-keeping-good-thing-going> (Accessed on 28.10.22)
- EPA. Understanding Global Warming Potentials, United States Environmental Protection Energy. 2022. Available at <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials> (Accessed on 19.12.22)
- Epstein E. The science of composting. Lancaster (PA): Technomic, 1997. 383–415.
- Evanylo G. Compost maturity and indicators of quality: laboratory analyses and on farm tests. 2006. [http://www.mawaterquality.org/industry\\_change/compost\\_school/Compost%20quality\\_Evanylo.pdf](http://www.mawaterquality.org/industry_change/compost_school/Compost%20quality_Evanylo.pdf) (Accessed on 19.12.22)
- FAO. Emissions due to agriculture. Global, regional and country trends 2000–2018. FAOSTAT Analytical Brief Series No 18. Rome. 2020.

- FAO. The State of Food Security and Nutrition in the World 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all. Rome, FAO. 2021.
- Firestone MK and Davidson EA. Microbiological basis of NO and N<sub>2</sub>O production and consumption in soil Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere ed M O Andreae and D S Schimel (Chichester: Wiley). 1989. 7–21
- Friedrich E and Trois C. Quantification of greenhouse gas emissions from waste management processes for municipalities—A comparative review focusing on Africa. Waste Manag. 2011. 31:1585–1596.
- Hermann, BG, Debeer L, De Wilde B, Blok K, Patel MK. To compost or not to compost: carbon and energy footprints of biodegradable materials' waste treatment. Polymer Degradation and Stability. 2011. 96 : 1159-1171.
- IAEA. Greenhouse gas reduction, International Atomic Energy Agency. 2023. Available at <https://www.iaea.org/topics/greenhouse-gas-reduction> (Accessed on 27.01.23).
- IPCC AR6 WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity. (2021. Available at [https://report.ipcc.ch/ar6wg1/pdf/IPCC\\_AR6\\_WGI\\_Chapter\\_07.pdf](https://report.ipcc.ch/ar6wg1/pdf/IPCC_AR6_WGI_Chapter_07.pdf) (Accessed on 19.12.22)
- IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories – A primer, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Miwa K., Srivastava N. and Tanabe K. (eds). Published: IGES, Japan. 2008.
- IPCC. Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future. 2022. Available at <https://www.ipcc.ch/2022/02/28/pr-wgii-ar6/> (Accessed on 19.12.22)
- IPCC. IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories 5.1, 2018. Available at [https://www.ipcc.ch/site/assets/uploads/2018/03/5\\_Waste-1.pdf](https://www.ipcc.ch/site/assets/uploads/2018/03/5_Waste-1.pdf)(Accessed on 19.12.22)
- IPCC. IPCC Guidelines for National Greenhouse Gas Inventories. In: Waste. Intergovernmental Panel on Climate Change, vol. 5. 2006. [www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html](http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html). (Accessed on 19.12.22)
- IPCC. Summary for policymakers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Arahani E, Kadner S, Seboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlomer S, van Stechow C, Zwickel T, Minx JC, editors. Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014
- Iqbal A, Liu X and Chen G. Municipal solid waste: Review of best practices in application of life cycle assessment and sustainable management techniques. Sci. Total Environ. 2020. 729: 138622.
- Jackson ML Soil chemical Analysis, Prentice Hall of India Pvt. Ltd., New Delhi, 1973.
- Jiang T, Li G, Tang Q, Ma X, Wang G and Schuchardt F. Effects of aeration method and aeration rate on greenhouse gas emissions during composting of pig feces in pilot scale. J. Environ. Sci. 2015. 31: 124–132.

- Jiang T, Ma X, Tang Q, Li G and Schuchardt, F. Combined use of nitrification inhibitor and struvite crystallization to reduce the NH<sub>3</sub> and N<sub>2</sub>O emissions during composting. *Bioresour. Technol.* 2016. 217 :210–218.
- Jime`nez IE and Garcia PV. Evaluation of city refuse compost maturity: A Review. *Biological Wastes.* 1989. 27 : 115-142.
- Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science.* 2004 Jun 11;304(5677):1623-7.
- Lou XF and Nair J. The impact of landfilling and composting on greenhouse gas emissions a review. *Bioresource Technology.* 2009. 100:3792-3798
- Ma Q, Li Y, Xue J, Cheng D and Li Z. Effects of Turning Frequency on Ammonia Emission during the Composting of Chicken Manure and Soybean Straw. *Molecules.* 2022. 27, 472.
- Martínez-Blanco J, Colón J, Gabarrell X, Font X, Sánchez A, Artola A and Rieradevall J. The use of life cycle assessment for the comparison of biowaste composting at home and full scale. *Waste Management.* 2010. 30 : 983-994.
- Mathur SP, Dinel H, Levesque MP, Brown A and Butler A. The role of methane gas in peat land hydrology: A new concept. *Proceedings Symposium 89. Canadian Society for Peat and Peat lands.* 1991. 153-157.
- Mathur SP, Owen G, Dinel H and Schnitzer M. Determination of compost biomaturity. *BiolAgrHortic.* 1993. 10:65–85.
- Moseman A and Trancik J. Why do we compare methane to carbon dioxide over a 100-year timeframe? Are we underrating the importance of methane emissions? (2021). Available at <https://climate.mit.edu/ask-mit/why-do-we-compare-methane-carbon-dioxide-over-100-year-timeframe-are-we-underrating> (Accessed on 27.10.22).
- Mukhopadhyay K, Mukherjee S, Seal A, Bera R and Dolui AK. Effective soil resource recycling with a new biodegradation method towards organic soil management – A case study from Howrah KrishiVigyan Kendra, ICAR. *Central European Journal of Experimental Biology.* 2015. 4 (2):17-23.
- NRDC Are the Effects of Global Warming Really that Bad? *Natural Resources Defense Council.* 2023. available at <https://www.nrdc.org/stories/are-effects-global-warming-really-bad> (Accessed on 27.1.23)
- Ocko IB, Hamburg SP, Jacob DJ, Keith DW, Keohane NO, Oppenheimer M, Roy-Mayhew JD, Schrag DP and Pacala SW.. Unmask temporal trade-offs in climate policy debates, *Science.* 2017. 356(6337):492-493.
- Olefeldt D, Turetsky MR, Crill PM and McGuire AD. Environmental and physical controls on northern terrestrial methane emissions across permafrost zones *Glob. Change Biol.* 2013. 19 : 589–603
- Palashikar G, Ranade A and Veerappapillai S. A Brief Review on Emission of Gaseous Ammonia from Composting of Various Waste Materials, *Int. J. Pharm. Sci. Rev. Res.,* 38(2), May – June 2016; Article No. 18, Pages: 97-101.
- Pérez-Domínguez I, del Prado A, Mittenzwei K, Hristov J, Frank S, Tabeau A, Witzke P, Havlik P, van Meijl H, Lynch J, Stehfest E, Pardo G, Barreiro-Hurle J, Koopman JFL and Sanz-Sánchez MJ. Short- and long-term warming effects of methane may affect the

- cost-effectiveness of mitigation policies and benefits of low-meat diets. *Nature Food*. 2021. 2, 970–980.
- Plattner GK, Stocker T, Midgley P. and Tignor M. “IPCC expert meeting on the science of alternative metrics: Meeting report,” Oslo, 18 to 20 March 2009 (IPCC Working Group, Technical Support Unit, Bern, Switzerland, 2009).
- Qin L, Shen, Y, Li G and Hu, J. C matter change of composting with different C/N. *J. Agro-Environ. Sci.* 2010. 29: 1388–1393.
- Rekha P, Suman-Raj DS, Aparna C, Hima-Bindu V, Anjaneyulu Y. Bioremediation of contaminated lake sediments and evaluation of maturity indices as indicators of compost stability. *Int J Environ Res Public Health*. 2005. 2(2):251–262.
- Rogger C, Beaurain F and Schmidt TS. Composting projects under the Clean Development Mechanism: sustainable contribution to mitigate climate change. *Waste Management*. 2011. 31:138-146.
- Rynk R, van de Kamp M, Willson GB, Singley ME, Richard TL, Kolega JJ, Gouin FR, Laliberty L Jr., Kay D, Murphy DW, Hoitink HAJ and Brinton WF. *On farm composting handbook*. New York: Cornell University. 1992.
- Sada E, Kito S. and Ito Y. Solubility’s of Gases in Aqueous Solutions of Weak Acids, *Journal of Chemical Engineering of Japan*. 1974. 7(1): 57-59
- Saer A, Lansing S, Davitt NH and Graves RE. Life cycle assessment of a food waste composting system: Environmental impact hotspots. *J. Clean. Prod.* 2013. 52: 234–244.
- Sayara T and Sánchez A. Gaseous Emissions from the Composting Process: Controlling Parameters and Strategies of Mitigation, *Processes* 2021, 9:1844. <https://doi.org/10.3390/pr9101844>.
- Seal A, Datta A, Saha S, Chowdhury R Roy, Chatterjee AK, Barik AK, Mazumdar D, Bera R. Evaluation of Compost Quality under Novcom Composting Method Using Wheat Flour Mill Waste as Raw Material, *Journal of Crop Science and Technology*. 2016; 5(2):1-6.
- Seal A, Bera R, Chatterjee AK and Dolui AK. Evaluation of a new composting method in terms of its biodegradation pathway and assessment of the compost quality, maturity and stability. *Archives of Agronomy and Soil Science, Germany*. 2012. 58(9):995-1012.
- Seal A, Bera R, Datta A, Saha S, Chatterjee AK, Barik AK, Nath R and Mazumdar D. Successful Biodegradation of coir pith waste using Novcom Composting Method : A Case Study from Vaniampara Rubber Estate, India. *Journal of Pharmaceutical and Scientific Innovation*. 2015. 4(1) : 73-77.
- Seal A, Bera R, Datta A, Saha S, Chowdhury R Roy, Chatterjee AK, Barik AK. Utilization of Press Mud for Quality Compost Generation under Waste to Wealth Programme through Adoption of Novcom Composting Programme: A Case Study from BalarampurChini Mills, Uttar Pradesh, India, *Research & Reviews: Journal of Agricultural Science and Technology*. 2016. 5(3): 1–11.
- Seal A, Bera R, Datta A, Saha S, Chowdhury RR, Chatterjee AK, and Barik AK. Utilization of Press Mud for Quality Compost Generation under Waste to Wealth Programme through Adoption of Novcom Composting Programme: A Case Study from Balarampur Chini Mills, Uttar Pradesh, India. *Research & Reviews: Journal of Agricultural Science and Technology*. 2016. 5(3): 1-11.

- Seal A, Bera R, Mukhopadhyay K and Mukherjee S. Recycling of Poultry Litter Through Novcom Composting Method : A case Study from Howrah KrishiVigyan Kendra, West Bengal, India. *Journal of Pharmaceutical and Scientific Innovation*. (2015b). 4(3) : 176-179.
- Seal A, Datta A, Saha S, Chatterjee AK, De GC, Barik AK, Mazumdar D, Dolui AK, Sarkar RK and Bera R. Importance of Compost Quality Towards Effective Organic Soil Management: A Case Study under FAO-CFC-TBI Project at Maud Tea Estate, Assam, India. *Research & Reviews: Journal of Agriculture Science and Technology*, 2015c. 4(1) : 16 – 26.
- Talt, G. The ComPOSTer: How much can composting help in solving the climate challenge? [UPDATED]. Sustainable Composting Research At Princeton (S.C.R.A.P LAB). © 2023 The Trustees of Princeton University. 2020. <https://scraplab.princeton.edu/2020/03/the-composter-how-much-can-composting-help-in-solving-the-climate-challenge/> (Accessed on 27.10.22).
- Tandon H.L.S. *Methods of Analysis of Soils, Plants, Waters and Fertilizers*. Publ. Fertilizer Development and Consultation Organization. New Delhi. 1993. 1-143p.
- The World Bank CLIMATE-SMART AGRICULTURE. 2022. Available at <https://www.worldbank.org/en/topic/climate-smart-agriculture> (Accessed on 27.10.22).
- Thompson WH, Leege PB, Millner P. and Watson ME. Test methods for the examination of composting and compost. U.S. Composting Council. [Online]. 2002. Available at <http://www.tmecc.org/tmecc/> (posted 1 May 2002; verified 15 Oct.2002).
- Tiqua, S.M., Tam, N.F.Y. and Hodgkiss, I. J. (1996). Effects of composting on phytotoxicity of spent pg manure sawdust litter. *Env. Pollut.* 93 : 249 – 296.
- Tiquia SM, Wan JHC and Tam NFY. Microbial population dynamics and enzyme activities during composting. *Compost Sci Util.* 2002.10:150–161.
- Trautmann NM and Krasny ME. Composting in the classroom. 1997. Available from: <http://www.cfe.cornell.edu/compost/schools.html> (Accessed on 27.10.22).
- Treat CC, Wollheim WM, Varner RK, Grandy AS, Talbot J and Froelking S. Temperature and peat type control CO<sub>2</sub> and CH<sub>4</sub> production in alaskan permafrost peats *Glob. Change Biol.* 2014. 20: 2674–86
- UNECE Methane Management - The Challenge, The United Nations Economic Commission for Europe (UNECE). 2022. Available at <https://unece.org/challenge> (Accessed on 28.10.22)
- US Composting Council. 2002. Available from <http://www.compostingcouncil.org> (Accessed on 12.02.11)
- USCC Greenhouse Gases and the Role of Composting: A Primer for Compost Producers, USCC Factsheet, 2008. Available at <https://www.sanjoseca.gov/home/showpublisheddocument?id=198> (Accessed on 28.10.22)
- Vallero DA Air pollution biogeochemistry, Chapter 8, in book *Air Pollution Calculations*, Edited by D. A. Vallero, Elsevier. 2019. Pages 175-206, ISBN 9780128149348,
- Vergara SE and Silver WL. Greenhouse gas emissions from windrow composting f organic wastes: Patterns and emissions factors. *Environ. Res. Lett.* 2019. 14.
- Vetter, SH, Sapkota TB, Hillier J, Stirling CM, Macdiarmid JI, Aleksandrowicz L, Green R, Joy EJM, Dangour AD and Smith P. Greenhouse gas emissions from agricultural food

- production to supply Indian diets: Implications for climate change mitigation. *Agric Ecosyst Environ.* 2017. 16; 237: 234–241.
- Wang J, Liu Z, Xia J and Chen Y. Effect of microbial inoculation on physicochemical properties and bacterial community structure of citrus peel composting. *Bioresour. Technol.* 2019. 291: 121843.
- Wang K. and Nakakubo T. Comparative assessment of waste disposal systems and technologies with regard to greenhouse gas emissions: A case study of municipal solid waste treatment options in China. *J. Clean. Prod.* 2020. 260: 120827.
- Wang X, Selvam A and Wong JW. Influence of lime on struvite formation and nitrogen conservation during food waste composting. *Bioresour. Technol.* 2016. 217 : 227–232.
- Watson ME. Extension Fact sheet. Ohio State University. 2003. <http://ohioline.osu.edu>. (Accessed on 15.2.10)
- Wei Y, Wang N, Lin Y, ZhanY, Ding X, Liu Y and Gu AZ. Recycling of nutrients from organic waste by advanced compost technology- A case study. *Bioresource Technology.* (2021). Vol. 337.
- Yang F, Li G, Shi H and Wang Y. Effects of phosphogypsum and superphosphate on compost maturity and gaseous emissions during kitchen waste composting. *Waste Manag.* 2015. 36 : 70–76.
- Zhu F, Hong C, Wang W, Lyu H, Zhu W, Xv H. and Yao Y. A microbial agent effectively reduces ammonia volatilization and ensure good maggot yield from pig manure composted via housefly larvae cultivation. *J. Clean. Prod.* 2020. 270: 122373.