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

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, sustaining crop production while navigating the climate change impact forms the greatest challenge facing mankind today, considering that an estimated 60 per cent more food will be needed to feed a world population of 9.3 billion, by 2050. Also, targeting higher crop production, through conventional agriculture 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 the municipality solid waste (MSW)/ 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 undertaken to study waste bio-conversion as well as GHG mitigation potential under Novcom Composting Technology, a validated, aerobic biodegradation process that can enable safe, stable and mature compost production within the shortest period of 21 days.

Analysis of the Novcom compost samples confirmed their stability and maturity as depicted by the CO_2 evolution rate (2 $mgCO_2$–C/ g OM/ day) and the safety/ non- phytotoxic effect as 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^{16} 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_2 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_2 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. The equations were consequently utilized to evaluate the GHG abatement potential of Novcom Composting Technology during recycling of landfill materials, MSW, legacy waste, press mud, coir pith, vegetable market waste, refuse from food processing industry and wheat mill waste. Assessment revealed that when compared with the reference value of GHG emission from landfill (calculated as per the IPCC guideline) adoption of Novcom Composing Technology can enable a GHG abatement of 5038 kg CO_2 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 crops and pests, and more frequent extreme weather events. On farms, climate change is reducing crop yields, the nutritional quality of major cereals, and lowering livestock productivity (The World Bank, 2022).

On the other hand, agriculture is the only sectors which acts as both source and sink for greenhouse gases (GHG). Emission enhances with industrial agriculture, when use of fossil fuel, chemical fertilizers (especially N), synthetic chemicals and involvement of machinery increases. According to an estimate by FAO, in 2018; global emissions due to agriculture was 9.3 billion tonnes of CO_2 equivalent (CO_2eqv.), which took a 14 percent growth since 2000 and accounted for 17 percent of global GHG emissions from all sectors. 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. 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.

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 and quality manure rich in self-generated microflora is prerequisite for ensuring time bound effectivity 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 and for GHG offsetting under the composting process towards making meaningful contribution in respect of climate change mitigation.

In this background, Novcom Composting Method, developed by Dr. P. Das Biswas, an Indian scientist and pioneer of sustainable organic tea cultivation; was taken under the study to evaluate its effectiveness for resource recycling along with its effectiveness towards GHG offsetting and attending the net zero objective.

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*. Calcutta University, Visva Bharati University, Energy Transition Commission, UK and i-NoCarbon Limited, UK.

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 (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 (Black, 1965). Stability tests for the compost (CO_2 evolution rate, phytotoxicity bioassay test/germination index) were performed according to the procedure suggested by Trautmann and Krasny (1997). Cress (Lepidiunsativum L.) seeds were used for the phytotoxicity bioassay test.

2.3 Protocol for greenhouse – gas measurement

For measurement of different greenhouse gas (GHG) *vis*. CO_2, N_2O, CH_4 and NH_3, eight Novcom compost heaps were made using different agro-waste *viz*. farmwaste, 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 Novcom composting with special perforated pipe for GHG estimation under IBM-IORF Sustainability Project.

2.31 Nitrous oxide (N_2O): Nitrous oxide (N_2O), 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_{100}). 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_2 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_2): CO_2 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_2 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. There were also four beakers containing 1% acetic acid and 1N NaOH at room temperature (Anderson, 1982).

Pic. 2 : Measurement of GHG emission from Novcom compost heap through closed chamber method under IBM-IORF Sustainability Project.

2.33 Methane (CH_4): An open bottom chamber was used to measure gas fluxes as per standard method (Anderson, 2010). Due to the flux ($F_{\text{Flux chamber}}$) of methane through the top of the compost material, the concentration of methane (C_{methane}) increased linearly inside the flux chamber over time, and the change in concentration over time (dC_{methane}/dt) was calculated.

2.34 Ammonia gas (NH_3): 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_2SO_4 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 (68^0 C) on 6th 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 7th and 14th day gradually decreased went below 44^0C from the 19th day and from 21st day onwards the temperature curve was almost parallel to X axis, which confirmed the completion of composting process or simultaneously compost maturity. Maintenance of a stable temperature of more than 145^0F (> 62.8 ^{0}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.

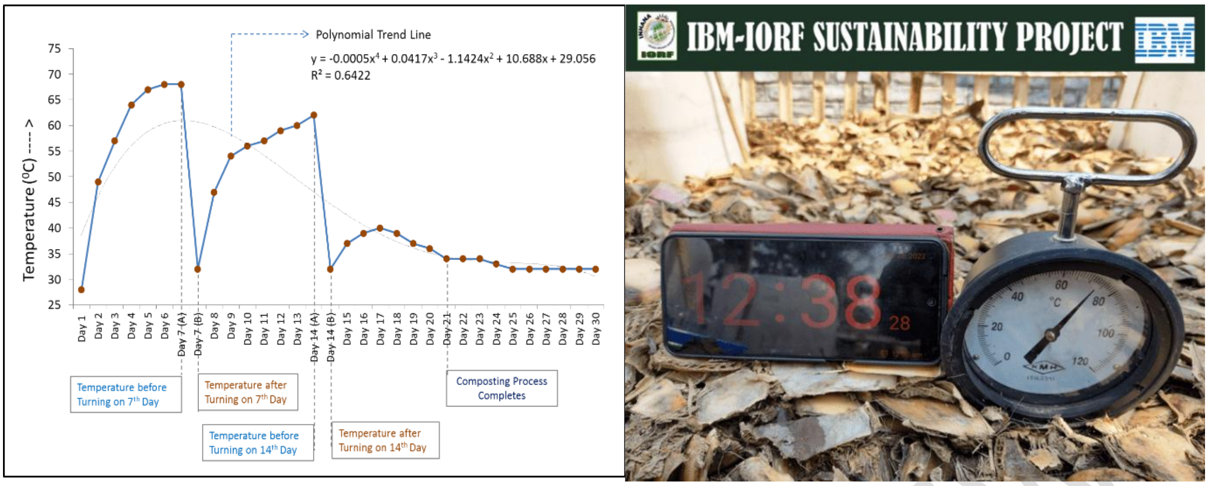

Fig. 1 : Variation in temperature generation during Novcom composting process underIBM-IORF Sustainability Project.

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 collected from the heap on the 21st 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 8.09 with mean of 7.80 (Table 1), which was well within the stipulated range for quality compost and indicated compost maturity (Jime`nez 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, however; with 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 (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.
Physicochemical Parameters				
1.	Moisture percent (%)	60.24 – 65.4	63.9	1.13
2.	pH_{water} (1 : 5)	6.09 – 8.09	7.80	0.21
3.	EC (1 :5) dSm^{-1}	1.24 – 3.30	1.70	0.27

4.	Total Ash Content (%)	29.56 – 65.50	55.1	2.62
5.	Total Volatile Solids (%)	34.50 – 70.44	44.9	2.13
6.	Organic Carbon (%)	21.20 – 27.14	24.9	1.03
7.	Compost Mineralization Index (CMI)	1.46 – 3.40	2.20	0.18

3.22 Fertility & 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. At the same time the very high microbial population (in order of 10^{16} in case of total bacteria, fungi and actinomycetes count) in compost samples, corroborated the uniqueness of its production method in terms of fastest conversion, high and balanced nutrient dynamics and desirable electrical conductivity etc., benefits which can be contributed only by the generation of high and diversified microbial population within the compost heap.

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

Sl. No.	**Parameter**	**Range Value**	**Mean value**	**(±) S.E.**
Fertility Parameters				
1.	Total Nitrogen (%)	1.69 – 2.01	1.89	0.04
2.	Total P_2O_5 (%)	0.86 – 1.10	0.97	0.03
3.	Total K_2O (%)	0.82 – 1.87	1.32	0.07
4.	C/N Ratio	12:1 – 17:1	13 : 1	0.52
Microbial Count (cfu per gm moist compost)				
5.	Total Bacteria	(34–68) x10^{16}	56 x10^{16}	-
6.	Total Fungi	(29 – 37) x10^{16}	33 x10^{16}	-
7.	Total Actinomycetes	(15–28) x10^{16}	19 x10^{16}	-

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_2 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.
Stability Parameters				
1.	CO_2 evolution rate (mgCO_2–C/g OM/day)	0.96 – 3.01	2.00	0.14
Maturity & Phytotoxicity Parameters				
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 that can enable reduction of fertilizer especially nitrogenous, further mitigating GHG 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_2O and CH_4 (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_4 emissions, whereas nitrogen transformation and loss (NH_3 and N_2O) 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) value of Green House gases

Global Warming Potential (GWP)[91] 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 1ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2) (EPA, 2022). Carbon dioxide (CO_2) was chosen as the reference gas to be consistent with the guidelines of the Intergovernmental Panel on Climate Change (IPCC 2008). Because CO_2 has a very long residence time in the atmosphere, its emissions cause increase in atmospheric concentrations of CO_2 that will last thousands of years (Vallero, 2019) The time period usually used for GWPs is 100 years. Nitrous Oxide (N_2O) has a GWP 273 times that of CO_2 for a 100-year timescale. N_2O 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_{100}, 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_{20} 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_2. 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_2 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_2 and CH_4. 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_{20} and GWP_{100} and how they perform, using methane as an example and explores how cumulative CO_2 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 (EFCTC2021). GSAT changes estimated with cumulative CO_2 equivalent emissions computed with GWP_{20} matches the warming trend for comparatively shorter time scale (a few decades) but quickly overestimates the response, whereas estimating emissions using GWP_{100} 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 $GWP_{1.50\ C}$ = 75 (Abernethy and Jackson, 2022).

In the study we used two different timescales for evaluating GHG emission in orderto estimate the maximum impact of the GHG gases on environment. In case of N_2O, we considered the usual 100 years' time frame. But in the case of methane we took the 24 years' timeframe because CH_4 is short-lived in atmosphere, this time horizon aligns with scenarios achieving a specific temperature goal as and to best align emission metrics with the Paris Agreement 1.5°C goal.

3.5 Emission of Carbon dioxide ($CO_{2)}$ under Novcom Composting Process: The CO_2 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. During biodegradation process the microbial communities' biodegrade the organic matter under aerobic condition and most of the carbon is lost as CO_2, such that a linear relation between carbon content and CO_2 emissions would be observed during the process (Qin, 2010). CO_2 emission measured on day basis during the Novcom composting process showed intense values in the 1st week (Avg. 114.6 gm CO_2/ ton wet waste), which gradually decreased with progression in the composting period and became minimum after 21 days (22.79 gm CO_2/ ton raw material) indicating completion of the biodegradation process (Fig.2).

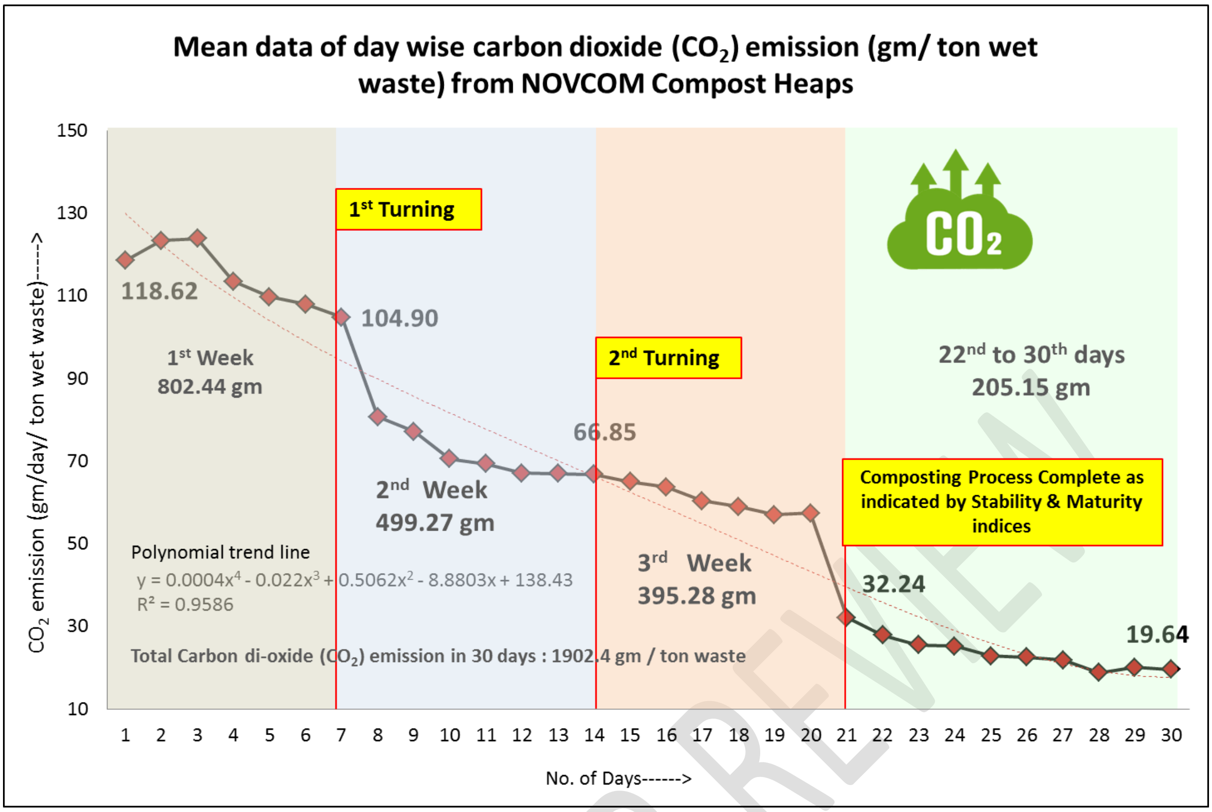

Fig. 2: Day wise carbon dioxide emission (gm/ton waste) during the biodegradation period under Novcom Composting Technology

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 order of 10^{16}cfu/ g or one trillion billion c.f.u. per ton moist compost) enabled higher carbon transformation from raw materials to the final end product leading to minimal CO_2 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_2, 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_2 emission during the process of biodegradation 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_4) under Novcom Composting Technology: Methane is the major contributor to non-biogenic greenhouse gas emissions from composting, and the majority of that CH_4 is emitted early in the composting process. Generally, the creation of anaerobic pockets in compost mixtures results in CH_4 emissions which is probably due to increase of moisture due to structural breakdown of organic materials. In the absence of oxygen (O_2), a succession of microbes converts carbohydrates in the organic waste to CO_2 and CH_4 (Bridgham and Richardson, 2014). Once CH_4 is produced, it may be emitted to the atmosphere or oxidized to CO_2 within the pile. The balance between CH_4 production and oxidation is likely controlled by redox potential (Conrad, 1996) and is affected by temperature and moisture, which control O_2 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 intense microbial activity within the 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_4 emission was nominal under Novcom Composting Technology in comparison to average reference value of CH_4 emission (0.03 – 8.0 kg CH_4 per ton wet waste) measured under the different composting processes), it was measured on regular basis during the entire 21 days biodegradation period. The highest value was observed on the 7th day before demolition/ churning of the heap, which might be due to the increased formation of anaerobic pocketswithin the composting heap; attributed to excess moisture generation due to structural breakdown of organic materials under intense microbial activity.CH_4 generation was found to be negligible after 14 days of composting and ceased completely after 21 days (Fig.3).

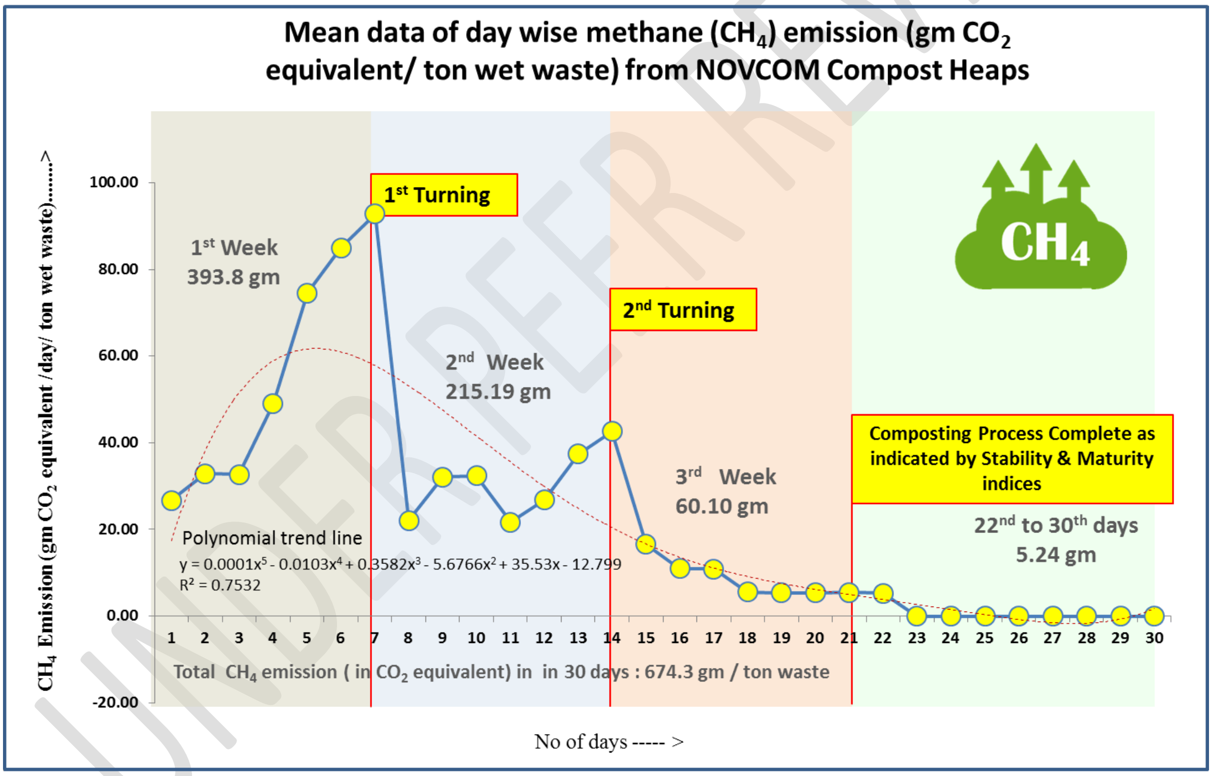

Fig.3 : Day wise methane emission (gm CO_2 equivalent /ton waste) during the biodegradation period under Novcom Composting Technology

3.7 Emission of Nitrous oxide (N_2O) under Novcom Composting Technology : Nitrification or the conversion of NH_4^+ to NO_3^-, and denitrification, the conversion of NO_3^- to nitrogen gas (N_2 and N_2O), are the major pathways leading to N_2O production and consumption (Firestone and Davidson, 1989). Net emission of N_2O is dependent on the controls on both processes.As biodegradation proceeds, the mineralization of organic nitrogen leads to formation of ammonia (NH_3), which could react with H^+ ions to form NH_4^+. The NH_4^+ to NH_3 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).

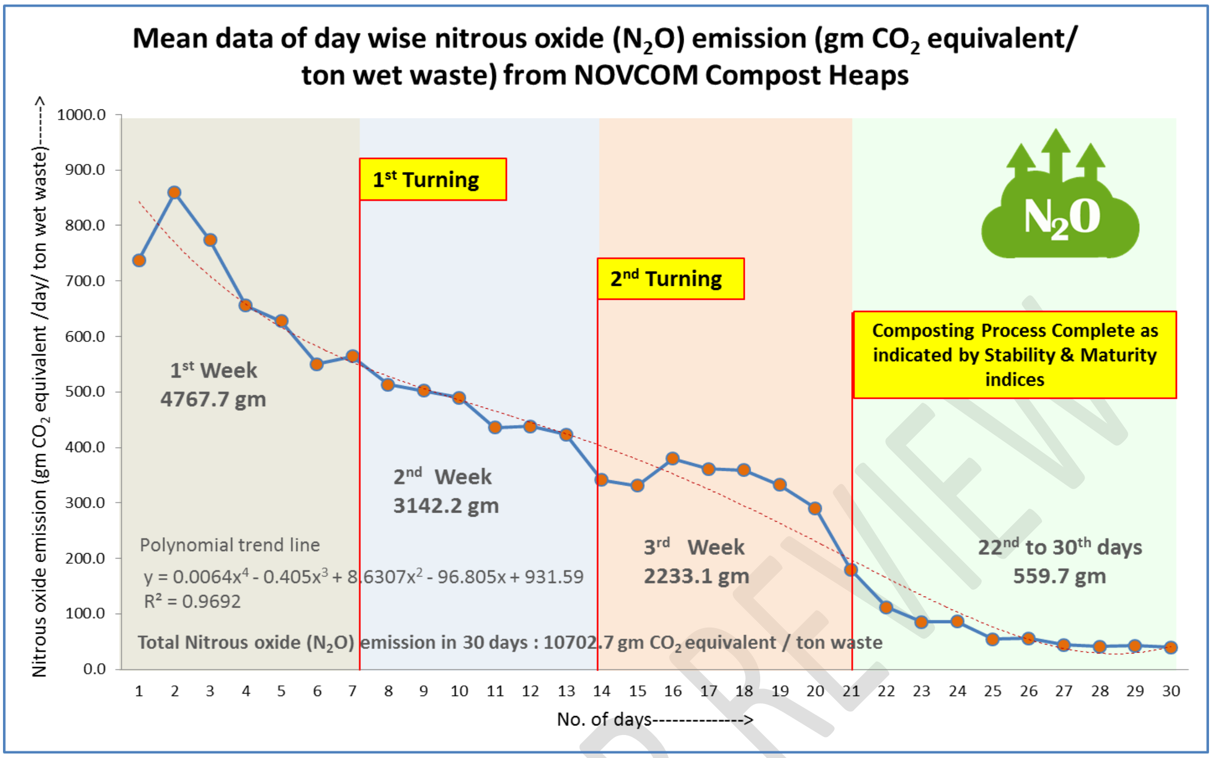

Fig.4 : Day wise nitrous oxide emission (gm CO_2 equivalent /ton waste) under Novcom composting method

In case of Novcom composting process, N_2O emission was highest in the 1stweek of biodegradation (Average N_2O emission 679.8 gm CO_2 equivalent/ ton wet waste), it reduced gradually with the advancement of the composting period became almost negligible post 21 days (Average N_2O emission 62.8 gm CO_2 equivalent/ day/ton wetwaste) (Fig. 4). Since high temperature (over 40^0C) can hinder the activity of nitrifiers, the considerable N_2O emissions in the thermophilic stage was possibly due to NH_4^+ oxidization by methanotrophs (Campbell *et al*. 2011 ; Jiang *et al*. 2016). Total N_2O emission under Novcom Composting Technology was about 1/10th of the average reference value (0.06 - 0.6 kg N_2O tonne 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^{16}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_2O during the process of organic matter breakdown.

3.8 Emission of Ammonia (NH_3) 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_3 emission decreased with progression of composting (Fig.5) which indicated intense microbial activity within compost heap that reduced the escaping chances of NH_3 during the biodegradation process. However, due it’s very low CO_2 equivalency, $NH_3$is generally not considered under the GHG calculation methodology, though it has a negative impact on environment and reduces the nutrient quality of compost.

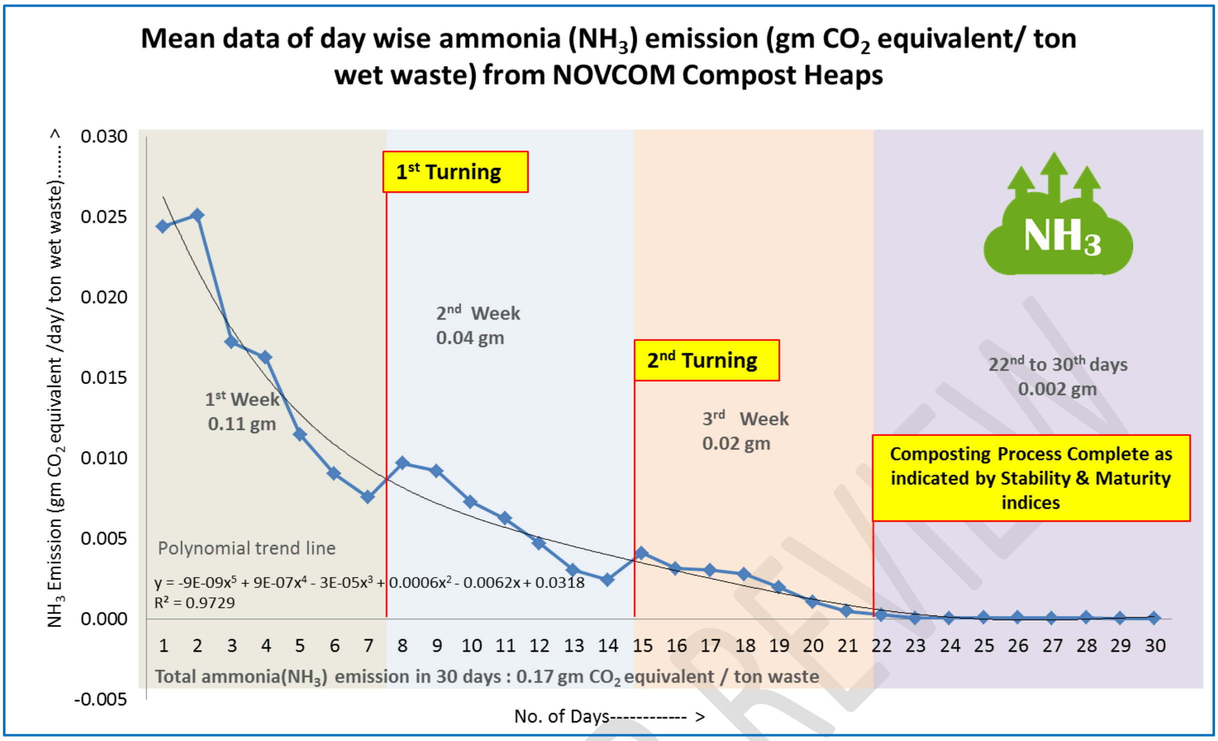

Fig.5 : Day wise ammonia emission (gm CO_2 equivalent /ton waste) under Novcom Composting Technology.

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

3.91 Regression equation to predict CO_2 emission

The following Equation

$Y = 11.37*X + 14.61$

Where,

Y = Expected CO_2 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.

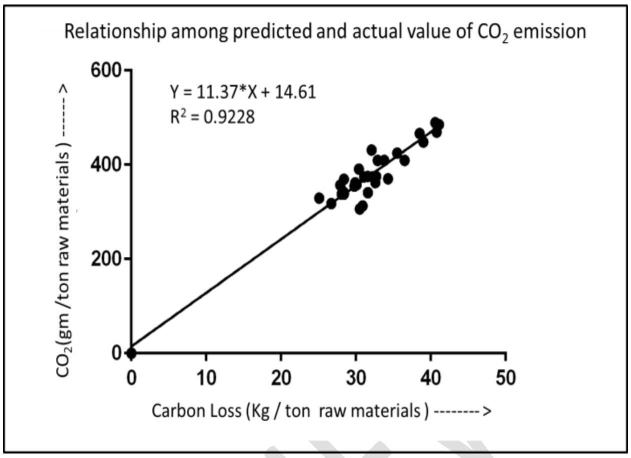

Fig 6 : Relationship among actual and predicted value of CO_2 emission

3.92 Regression equation to predict CH_4 emission

The following Equation

$Y = 0.06399*X - 0.2498$

Where,

Y = Expected CH_4 Emission (gm)

X = Actual Carbon loss during composting process (kg)

$R^2 = 0.8274$

Note: To find the expected emission in CO_2 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 75tonnes of carbon dioxide.

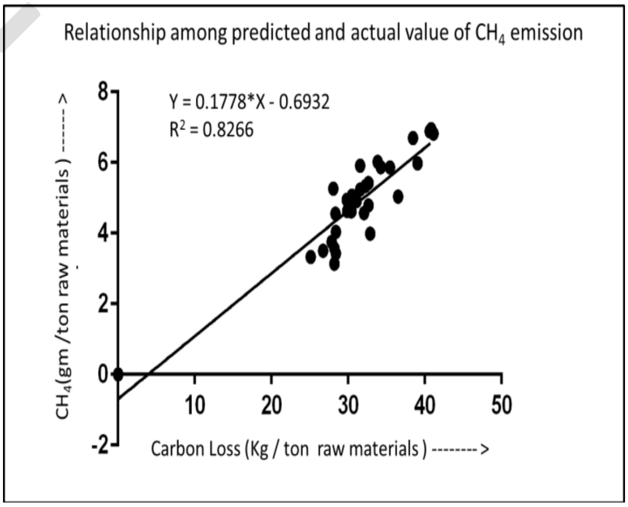

Fig 7 : Relationship among actual and predicted values of CH_4 emission

3.93 Regression equation to predict N_2O emission

The following Equation

$$Y = 39.31*X + 0.6338$$

Where,

Y = Expected N_2O 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_2O equivalent, Y value should by multiply with 273 (N_2O has GWP of 273over a 100 years period meaning that, one tonne of N_2Oemission is equivalent to emitting 273tonnes of carbon dioxide)

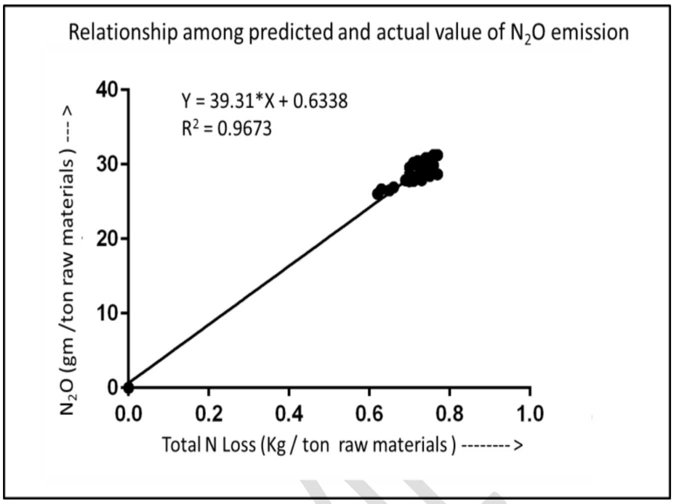

Fig 8 : Relationship among actual and predicted values of N_2O emission

3.94 Regression equation to predict NH_3 emission

The following Equation

$$Y = 0.07585*X - 0.003006$$

Where,

Y = Expected NH_3 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_3, has an Ozone Depletion Potential (ODP) rating of 0.

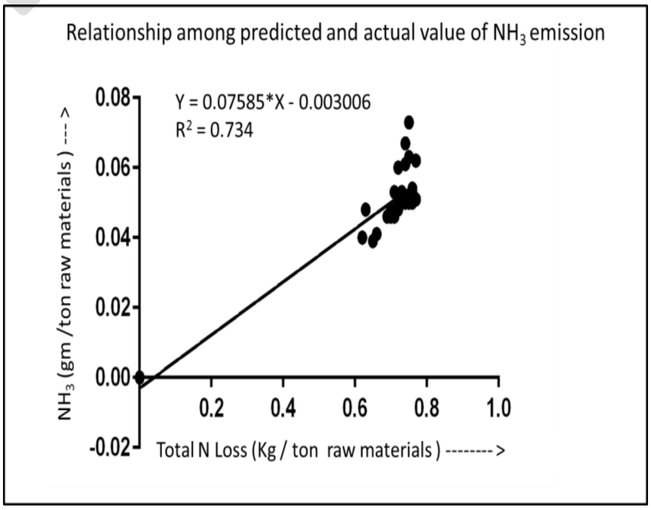

Fig 9 : Relationship among actual and predicted values of NH_3 emission

4.0 Assessment of GHG Offsetting 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 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_4 (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_2 equivalent) =

$$[(LM_T \times LF_F \times MC_F \times DOC \times DOC_F \times F \times 16/12 - R) \times (1 - OX)] * GWP_{CH4}$$

LM_T : Total Landfill Material(MT)

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

MC_F : 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_F : fraction DOC dissimilated (IPCC default is 0.77)

F : fraction of CH_4 in landfill gas (IPCC default is 0.5) 16/12 : conversion of C to CH_4

R : Recovered CH_4 (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)

$GWP_{CH4\ (24\ years)}$: 75

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

GHG Offsetunder Novcom Composting Technology	=	GHG Emission from untreated waste (Calculated as per IPCC Guideline)	-	GHG Emission during biodegradation under Novcom Composting Technology (Calculated as per emperical formula developed for GHG calculation under Novcom Composting Technology)

We used two different sets of emperical formula for calculation of GHG offsetunder bioconversion of any landfill waste utilizing Novcom Composting Technology. First we calculated the GHG emission potential of the selected landfill waste through the emperical 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.

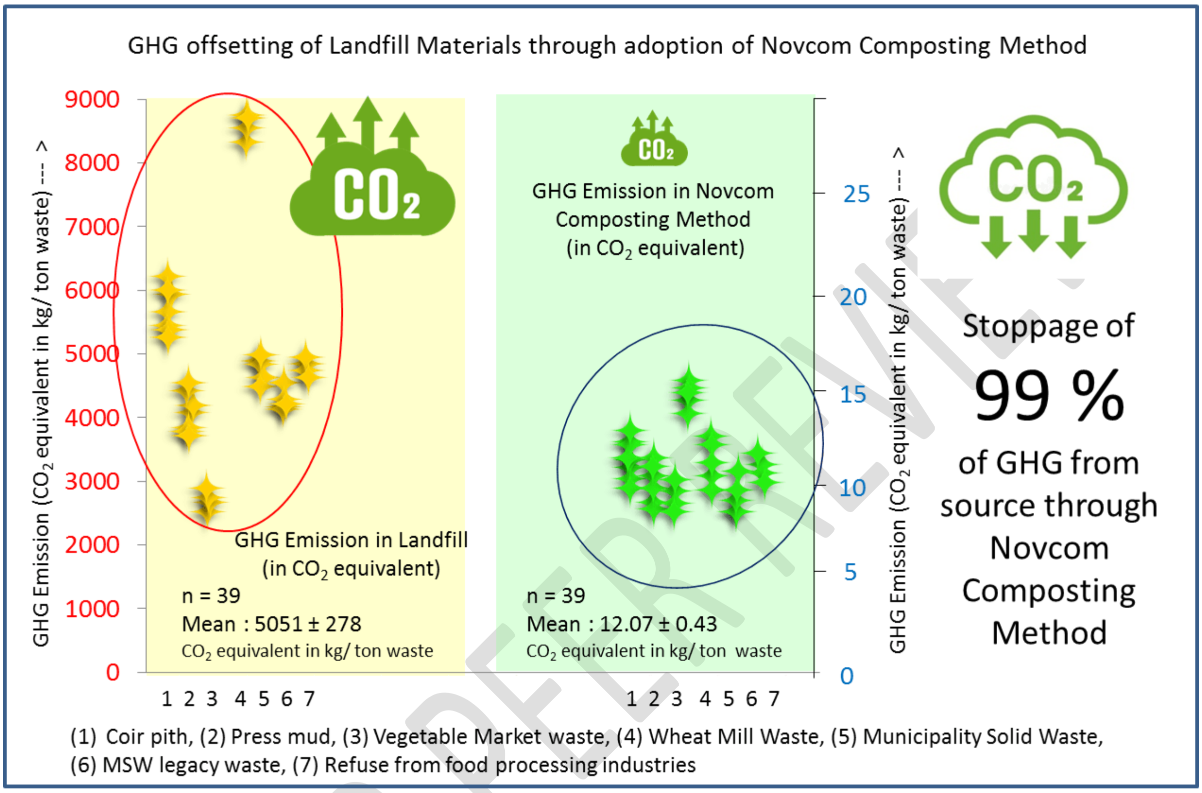

Fig. 10 : GHG offset from landfill waste through its bioconversion utilizing Novcom Composting Technology

We calculated the GHG offsetting potentials under Novcom Composting Technology in respect of eight different kinds of biodegradable waste and the average value generated through the emperical equations showed that Novcom Composting Technology has the potential to offset 99% of GHG from source (Fig. 10). 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_4 and N_2O 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 mater in the waste within a shortest period of 21 days, but did so with minimal emission, as indicated by 1/16th of the average reference emission values (total averaging 200 kg CO_2-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 Conclusion

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 16 times lower GHG emission as compared to the reference values under the other biodegradation processes.

Another aspect of this composting technology is that within a short period of 21 days it delivers quality compost that can support soil health regeneration towards the objective of sustainable crop production.

The dual premise of GHG abatement especially methane mitigation along with speediest generation of safe and quality compost 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 it's dual action mode i.e., lower CO_2 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, drive not only successful 'Waste to Wealth' programs but most importantly serve as an excellent tool towards attainment of the Net Zero GHG goal.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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