Perspectives on Waste Recycling in Indian Agriculture

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Edited by

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This land is to be increasingly cultivated according to the need of this hour, lest, half-fed, we die of fever or malnutrition, or exist as only living dead.

There are several examples that if proper attention and intelligence are invested, this land will yield much more than the total production of cultivated crops in our country.

Rabindranath Tagore (1918)

CONTENTS

Section III. Waste Recycling through Agriculture

Section IV. Composting as a Tool for Waste Recycling

PREFACE

India has made great strides to attain self-sufficiency in its food requirement recording a food grain production of 298 Mt during 2019-20, as against a value of merely 55 Mt during 1951-52. However, to feed the burgeoning population of the country in years to come, India had to fix a target of 377 Mt food grain production for the year 2050. With per capita arable land area declining consistently, such a high production can only be achieved through adoption of various proven and efficient production technologies. There is no need to mention that the success of such technologies in increasing the food production will depend largely on one major factor, sustenance of soil health. The present scenario of steadily declining fertilizer use efficiency under high productivity regimes owing to irrational uses of mineral fertilizers and inadequate levels of organic matter in most of the soils are presenting serious threats to sustainability of soil health and, thereby, food production in the country. It is now being realized that mineral fertilizers can only improve the nutrient status of the soils but they have little impact on various other physical, chemical and biological attributes of soil health. On the other hand, most of these soil health indicating properties can be improved substantially through use of organic materials. Therefore, it is the integrated use of mineral fertilizers and organic materials that can maintain the production sustainability through addition of the much-desired organic carbon to the soil for betterment of other soil health attributes. Under this context, regular use of good amount of organic matter to the soils is being advocated as a primary requisite for achieving sustenance in soil health and productivity. Since availability of traditional organic manures is gradually declining in the country while plentiful amount of wide ranges of biodegradable organic waste materials are being generated every day, growing attention is now being paid on judicious recycling of these wastes for improving the health conditions of our arable soils. These rural and urban waste materials are expected to play an important role in sustaining agricultural and environmental security. However, most of the organic wastes cannot be added directly to the soils due to some limitations in their chemical as well as biological properties and, therefore, effective pathways of managing these wastes need to be identified to achieve efficient organic waste recycling practices in agriculture.

With the present thrust and encouragement from the Government on waste recycling under the "*Swachh Bharat Yojna*", increasing efforts are being made to recycle different kinds of wastes for various productive purposes of which agriculture forms an important component. Since such activities have direct relevance on sustenance of soil health, the members of Sriniketan Chapter of Indian Society of Soil Science felt that there is a need to be associated with this endeavor by providing comprehensive information on recycling of wastes in agriculture. This book is an outcome of this effort and deals with various aspects of waste recycling in agriculture sector, discussed by eminent researchers working in this field in the country. We fervently hope that this publication will be useful in furthering the waste recycling practices in agriculture with a view to promote the soil health and productivity.

It was a difficult task to bring out the book contacting all the eminent researchers of the country during the unusual covid situation. We are indebted to Dr. H. Pathak, Director General, Indian Council of Agricultural Research (ICAR) and the President of Indian Society of Soil Science for his generous support and also for encouraging this effort by contributing an important chapter for this book. We are also grateful to Dr. S.K. Chaudhary, Deputy Director General (NRM) of ICAR for supporting our endeavor by writing a well knitted Foreword. Dr. A.K. Patra and Dr. D.R. Biswas , former Presidents of the Society, extended their valuable helps and suggestions during the preparation of the manuscript. The editors are thankful to both of them. This publication has been possible through active co-operation of all our contributors who have kindly accepted our invitation at a short notice and took all the initiatives to complete their articles within the time frame in spite of their busy schedules. We express our gratitude to all of them. We sincerely appreciate and thank the Associate Editors of this book for their helps and co-operations in making this endeavor a success.

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Foreword

By soil health, we generally mean for soil physical and chemical health (forgetting biological health) which largely rely on soil biodiversity and soil biological processes. Despite recognition of the fundamental role of soil biological health in maintaining sustainable and efficient agricultural systems, it is still largely neglected in the majority of agricultural development initiatives. The consequences of neglecting or abusing soil biological health weaken soil functions and lead to deterioration of soil health and loss of fertile lands.

The Government of India is implementing *Swachh Bharat Mission* for the safe management of solid and liquid bio-wastes in the country through recycling of these wastes into wealth. Burning of crop residue has emerged as one of the important issues in recent times which is adding to already high level of pollutants in the environment. It also leads to loss of soil carbon and nutrient elements. The surplus crop residue available from agricultural sector may be recycled through *in-situ* incorporation and/or *ex-situ* decomposition for improving soil health instead of burning. Similarly, the urban solid waste has to be recycled into city compost for agricultural use through proper treatments, segregation and decomposition. In this context, conversion of bio wastes through biogas technology may play a pivotal role in supplementing rural energy need besides generating biogas manure for agricultural use.

I am sure that the book entitled "Perspectives of waste recycling in Indian agriculture" authored by a group of professional experts will serve as a useful reference material for researchers, developmental officials, policy makers, and others engaged in soil health endeavours. I congratulate all the editors for their commendable job in bringing out this publication.

(S.K. Chaudhari)

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SECTION I

PROSPECTS OF WASTE RECYCLING IN INDIAN AGRICULTURE

Prospects and Problems of Organic Waste Recycling in Indian Agriculture

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Abstract

With the increase in food grain production to meet the demands of a growing population, along with fast urbanization and industrialization, the generation of organic wastes has significantly risen in recent years. Despite the evolution of various options and practices for recycling these wastes, effective management remains a challenge in India. This is primarily due to the substantial gap between the rate of generation and its management, resulting in the accumulation of vast piles that not only diminish the quality of the environment but also pose associated health hazards. In rural areas, the burning of crop residue has emerged as a major problem, causing environmental pollution and health concerns for both local and distant habitation. Numerous options for the effective management of these organic wastes are available, which can be adopted at the individual or community levels, including public welfare and urban development bodies, depending on their suitability to local conditions. This manuscript summarizes the status, challenges, and available options for organic waste management. The success of any such option depends on local participation, close monitoring, incentive options, legislative provisions, and the availability of adequate infrastructure required for the effective management of organic wastes in India.

1. Introduction

Industrialization coupled with accelerated urbanization and exponential population growth globally, has led to the generation of various types of organic wastes, including municipal solid wastes (Singh et al., 2011, 2014).

Increased food grain production has also resulted in a rise in crop residue generation, a significant organic waste in the country, alongside municipal solid waste from urban areas. India generates over 600 million tons of agricultural waste annually (Ravindra et al., 2019), holding the top position globally in terms of livestock population, contributing to a substantial portion of organic wastes through animal dung. Solid organic wastes, including sewage sludge, agricultural farm wastes, city and spoiled food waste, domestic kitchen waste, garden waste, agro-industrial waste, and animal waste, typically consist of an organic biodegradable fraction with moisture content below 85–90% (Mata-Alvarez et al., 2000). Unscientific management and dumping of these organic wastes in landfill sites lead to the generation of obnoxious and greenhouse gases (GHGs). The excessive use of agrochemicals, including pesticides and herbicides, as well as various organic chemicals, contributes to the accumulation of organic pollutants in the soil, adversely affecting soil biodiversity and leading to the accumulation of non-desirable chemical intermediates in the food chain (Lal, 2015).

With shrinking agricultural land area, there is tremendous pressure on fertile soil to produce more grain per unit area. This has led to crop intensification and overexploitation of such soils. Intensive agricultural practices, coupled with insufficient addition of organic manures, lack of proper crop rotation and management practices (such as tillage and fertilization), and on-farm crop residue burning, result in a decline in the organic carbon status of the soil (Bhan and Behera, 2014; Godde et al., 2016). Furthermore, soils are gradually depleting due to the loss of organic matter without adequate replenishment, and a deficiency of many other essential nutrients is surfacing. Conversely, a substantial quantity of organic wastes is being generated from various sources, which, if recycled effectively, may restore and enhance soil fertility, besides positively impacting environmental quality and human health. The major sources of organic wastes generated, and their nutrient potentials are detailed in the following section.

2. Status of organic waste generation in India

2.1 Crop Residue

India boasts the second-largest amount of agricultural land globally and produced more than 300 million metric tons of food grain during 2020-21 (https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1721692).
Considering the projected future demand, food grain supply, and past

growth trends, approximately 377 million tons of food grain will be required by 2050 (Manna et al., 2021). Consequently, crop productivity needs enhancement, and resource management must improve, as expanding the land area under cultivation is challenging. Therefore, the generation of crop residue is expected to increase in the future.

2.2 Animal Waste

India ranks first globally in livestock population, resulting in a substantial annual generation of animal excreta. These excreta hold great potential for manure preparation and energy (biogas) production. In 2014-15, India's estimated biogas production was around 20,757 lakh cubic meters, with Maharashtra state leading in biogas generation (3578 lakh cubic meters) compared to other states. The estimated production of animal excreta in 2012 (Manna et al., 2018) is presented in Table 1. Out of the total quantity of available cattle dung, approximately two-thirds are utilized to produce fuel cake in villages and only one-third is used as manure for agricultural land.

Table 1. Estimated Production of Dung/Excreta by livestock and poultry birds

Animal	Production of Dung/Excreta (Million Tons) in 2012
Cattle	209.996
Buffaloes	146.757
Yaks	0.077
Mithuns	0.330
Sheep and goats	30.01
Horses/ponies	0.317
Donkeys and mules	0.254
Camels	0.324
Pigs	2.574
Total (animals)	390.639
Poultry	1.029

Source: Adapted from Manna et al. (2018)

2.3 Municipal Solid Waste

Municipal solid waste (MSW) is the third-largest source of organic waste in India. India's cities are projected to generate around 82.2 million tons of waste in 2020, expected to rise to 107 million tons by 2030. Large cities, including Delhi, Mumbai, and Kolkata, are generating 4000–6000 tons of MSW daily, while smaller cities such as Bhopal, Nagpur, Chennai, and Bangalore produce approximately half of that quantity (1500–3000 tons of MSW/day) by 2030 (Manna et al., 2021). MSW is a heterogeneous mixture of biodegradable and non-biodegradable materials, with 35.2–47.1% compostable (biodegradable) materials, 2.1–5.4% plastics, 0.4–0.5% rubbers and leathers, and the remaining fraction containing non-degradable materials, especially heavy metals. Despite approximately 40% of the matter in MSW being considered biodegradable, only 14% (11.7 million tons) out of 82.2 million tons of MSW generated in 2020 were composted. Given the mixed nature of these wastes, material segregation is crucial for effective municipal waste management.

2.4 Horticultural (vegetables/fruit) waste:

The horticultural and plantation industries are estimated to generate approximately 263.4 million tons of by-products and wastes, of which 134 million tons are considered recyclable (Manna et al., 2018). Agro-processing industries produce a significant amount of waste and by-products, often exceeding the quantity of finished products. Quantifying the amount of organic waste from these industries is challenging due to the poorly organized nature of manufacturing operations and other factors. Agricultural processing waste was estimated to be 184.3 million tons in 2010, with approximately 95% of this waste resulting from sugarcane crushing (114 million tons of bagasse), paddy processing (56.7 million tons of husk and bran), and groundnuts processing (4.8 million tons of husk).

3. Management of organic wastes in India

3.1. *Off situ* management

Off situ management of organic wastes refers to the operations and practices which bring the residue away from their generation site to a suitable place where it can be converted to manure or composts or other products such as fuel briquette and animal feed after necessary processing and value addition.

3.1.1 Composting: Composting involves the decomposition of crop residue, farm wastes, and other organic materials. It is an environmentally sound practice that is gaining emphasis. Various factors, including composting techniques, substrate composition, use of decomposer organisms, moisture, temperature, techniques of enrichment, and turning, can affect the composting process. The composting process is mainly of two types: aerobic composting and anaerobic composting. In aerobic composting, gaseous oxygen is necessary to facilitate proper decomposition, leading to rapid decomposition and an earlier narrowing down of the C: N ratio than in the anaerobic process. Anaerobic decomposition results in only a partial breakdown of organic matter, producing foul gases due to the predominance of reduced sulphur compounds in the presence of anaerobic organisms. This process is very slow. While traditional composting procedures take as long as 6-8 months to produce finished compost, efficient composting techniques offer possibilities for completing the process within around 90 days. Some efficient technologies developed for recycling organic wastes into nutrient-enriched composts are presented here.

3.1.2. Vermicomposting: Vermicomposting is a method of composting using efficient epigeic earthworms. In vermicomposting, there is a saving of nearly two months of composting time compared to conventional composting. Vermicompost is also rich in plant nutrients and shows better microbial and biochemical activity. For the production of vermicompost, permanent pits of 10 feet length x 4 feet width x 3 feet deep are constructed above ground under shade. Partially decomposed dung (about 2 months old) is spread on the bottom of the pits to a thickness of about 3-4 cm. This is followed by the addition of a layer of litter/residue and dung in the ratio of 1:1 (w/w). A second layer of dung is then applied, followed by another layer of litter/crop residue in the same ratio up to a height of 2 feet. Two species of epigeic earthworms, namely *Eisenia foetida* and *Perionyx excavatus*, are introduced into the pit at a rate of 10 adult worms per kg of materials. Moisture content is maintained at 60-70% throughout the decomposition period. Vermicompost can be ready within 90-110 days.

3.1.3. Phospho-compost: Bio-solids produced in cities, agro-industries and at farms normally have low nutrient value, particularly the P content. Therefore, compost production from these bio-degradable wastes is commonly not an economically viable proposition. The traditional technology of composting, if improved in terms of nutrient content, may help in arresting trends of nutrient depletion to a greater extent. Under this context, the use of mineral additives such as rock phosphate and pyrites during composting has been found beneficial. A phospho-compost/N-enriched phosphor-compost technology has been developed using phosphate rock, pyrite and bio-solids along with phosphate solubilizing microorganisms, namely, *Aspergillus awamori*, *Pseudomonas striata* and

Bacillus megaterium to increase the manurial value compared to ordinary FYM and compost (Singh, 2003). Crop residues or farm wastes are common resources for the preparation of good quality compost having nutrient contents higher than FYM or ordinary compost. Cereal straw materials usually exhibit high C: N ratio. This can be narrowed down to favorable values either by using nitrogenous fertilizers or legume residues. Chopped rice straw, amended with phosphate rock (10-25% w/w); pyrite (5-10% w/w) and mixed with soil is composted either in pit or heap layer by layer. Sufficient water is added to each layer to bring its moisture content between 60-70%. Culture of decomposing microorganisms and phosphate solubilizing fungi like *Aspergillus awamori* are added to the decomposing material. The material is turned at 3-5 days interval initially and then at 15 days interval for enhancing decomposition process. Agriculturally beneficial microbes such as free living N_2-fixer (*Azotobacter chroococcum*), phosphorus solubilizers or microbial biocontrol agent can be added at the end of composting for further value addition of the prepared compost.

3.1.4. Biochar Production: Biochar is high carbon material, stable and relatively recalcitrant to degradation, produced through slow pyrolysis (heating in the absence of oxygen) of biomass. It can act as carbon sink or long-term storage of carbon in soil thus helping in C sequestration and reduction of GHG emission. However, production of biochar is an energy intensive process and its effect on crop productivity, nutrient dynamics, and its fate in soil needs to be explored in detail.

3.1.5. Energy production and fuel briquette making: Fuel briquettes are generated by the pressure compaction of agricultural waste, paper, sawdust etc. to serve as an alternative to firewood, wood pellets and charcoal. The energy content of briquettes ranges from 4.48 to 5.95 kilojoules per gram (kJ/g) depending on the material's composition whereas the energy content of sawdust, charcoal and wood pellets varies from 7.24 to 8.25 kJ/g (Yazdani and Ali, 2010). It has been observed that low-energy containing feedstocks can be compressed and combusted to produce higher energy containing fuels.

3.2. *In situ* Management

3.2.1 Conservation Agriculture (CA): The main principles of CA are minimal soil disturbance, retention of crop residue and a rational use of crops in rotations, along with profitability at the farm level. CA-based interventions such as zero tillage (ZT) or reduced tillage (RT) and crop residue retention on the soil surface are adopted for increasing soil organic matter content and reducing runoff water which eventually reduce loss of nutrients due to leaching and runoff. Most of the CA-based studies concluded that ZT and RT improved crop yields by 5% to 30% (Manna et al., 2018). Worldwide about 105 Mha of land is being cultivated using conservation agriculture practices which is increasing with time. Countries like the USA, Brazil, Argentina, Canada and Australia occupy about 90% of the land used for conservation agriculture in the world (IARI 2012).

3.2.2 *In situ* incorporation: The crop residue left after harvesting can be ploughed into the soil and left for decomposition. Irrigation and nitrogen are required to hasten the decomposition process by bringing C:N ratios to a favorable range for restricting the immobilization of nitrogen. *In situ* incorporation of crop residues enriches the soil with organic matter and also augments soil microbial diversity. Efficient microbial cultures can be applied to the residue before incorporation into soil to of further accelerate the decomposition process. The limitation of *in situ* decomposition process includes lack of irrigation water, short time gap between harvest of preceding crop and sowing of succeeding crop, extra labor and cost incurred on the use of farm machinery for incorporation of residues, use of nitrogen fertilizer and inoculants etc. (Thakur et al., 2021).

4. Potential and limitations of recycled organic waste

Recycling of organic waste as compost in agricultural field has several benefits such as supplementation of the use of chemical fertilizers, improvement in soil fertility status and nutrient profile, reduced GHG emissions from waste decomposition in open dumps, restricted soil erosion, conservation of land resource with less amounts of land filled waste and reduction in volume of wastes from dumpsites and minimized environmental pollution (Schulz and Römheld 1997). The benefits of recycling organic wastes and the associated limitations are summarized in Table 3. Utilization of organic waste may pose a threat of food chain contamination due to heavy metal toxicity (Sharma et al. 2018) and hazardous organic contaminants (Clarke and Cummins 2015). Therefore, prior to land application, proper sanitization and stabilization of organic wastes must be ensured. Compost/vermicompost prepared from organic wastes should be tested to avoid the possibility of any soil and food chain contamination.

Table 3. Benefits and limitations of using organic waste in agriculture

Benefits	Limitations
Improves soil structure and soil fertility	May increase heavy metal toxicity
Enhanced crop yield	Possibility of food chain contamination
Reduced GHGs emission	Risk of emerging contaminants or organic pollutants
Fosters biological diversity	Risk of pathogens
Reduced use of agrochemicals	Low in nutrient content

4.1 Pathogen content

One of the major issues of MSW composting is the possibility of the occurrence of pathogenic microbes in such wastes, which may be harmful to humans. Microbial contamination also arises from untreated manure or bio-solids. The presence of *Salmonella* and *Shigella*, as well as faecal contamination indicating bacteria such as faecal coliforms and faecal *Streptococci*, in compost from municipal solid waste (Hassen et al., 2001) constitutes a major threat to those handling these composts. Although the survival of these pathogenic microbes in the compost depends on the physical condition and is generally killed at higher temperatures of 55-60 °C during the composting process, testing and safe handling protocols still need to be observed. Information on survival time and threshold temperature is a priority research area for evaluating the safe use of manure in organic farming practices.

4.2 Heavy metals toxicity

The prolonged application of organic manure through compost, sewage sludge, and municipal solid waste may lead to the accumulation of various toxic heavy metals in the soil. This, in turn, could result in their transfer to different trophic levels of the food chain, causing health-related issues. When heavy metals surpass the permissible threshold limits, they have negative effects on existing organisms and the environment (Cebula et al., 1995). Additionally, heavy metals remain unaffected throughout the process of composting organic waste. The impact of organic amendments on metal bioavailability varies, depending on the nature of the metals, soil type, organic matter content, and the degree of humification (Walker et al., 2004).

Therefore, finished products must undergo examination for metal concentration before application.

5. Conclusion

The agricultural and city waste disposal systems in India still regard waste as a problem despite its potential. The recent trend of burning crop residues in agricultural fields is exacerbating the issue. Managing waste in a country like India, with high population density leading to substantial waste generation in both rural and urban areas, is a challenging task. City waste disposal has largely remained unsegregated at the source. Recycling organic waste generated from agriculture and municipal sectors holds enormous potential for its nutrient content, which can be harnessed through various composting techniques. The utilization of organic waste must be assessed based on organic matter quality, soil fertility, adverse effects on plant and human health, pathogens, heavy metals, and persistent organic pollutants before land application. As persistent organic pollutants and chemicals are known for their toxicity to soil-dwelling microbes and negative impact on human and animal health, great care and effort should be taken to prevent the transport of such substances to the soil to sustain biodiversity. Besides industrial regulation, the responsibility also lies with public bodies, regulatory organizations, scientists, and all individuals to work together to minimize environmental contamination. Lack of awareness and inadequate technology adoption by stakeholders hinder the success of the organic waste management strategy, which needs to be addressed through appropriate scientific or engineering interventions.

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MANAGING CROP RESIDUES FOR GREENHOUSE GAS MITIGATION IN AGRICULTURE

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Abstract

Organic residue management, through biochar, compost, vermicompost, crop-residue incorporation and mulching in agricultural systems, play an important role in regulating organic carbon dynamics and GHGs emissions. Crop residue type, soil and climatic variables are important factors that regulate carbon sequestration, carbon emissions, and overall carbon balance in agriculture. Specifically, research and experimentation on different crop-residue management practices revealed that direct incorporation of rice and wheat straw in soil increases carbon stock but at the same time causes higher carbon dioxide (CO_2) and methane (CH_4) emissions. On the other hand, if the residues are applied through composting, the CO_2 and CH_4 emission could be reduced by 10-12%, as compared to their direct incorporation. Again, the carbon sequestration was found to be more with crop residue incorporation than with compost application. Moreover, reduction in nitrous oxide (N_2O) emissions were observed due to crop residue application in different forms. The addition of residues like rice-straw with high C: N ratio could decrease the N_2O emissions by immobilizing the nitrogen present in the soil. Evidences showed that proper crop-residue management practices could increase

carbon sequestration and moderate the GHGs emissions along with higher nutrient and water use efficiencies in rice-based cropping systems.

1. Introduction

The portion of plants, encompassing stalks, leaves, and roots remaining after the harvest of the primary economic component (grain), is termed crop residues (OECD, 2001). These are valuable natural resources that could be used efficiently for getting other economic and environmental benefits. Crop residue management is key for the success of conservation agriculture (CA). Modern input-intensive agriculture generates a huge amount of crop residues. These crop residues can provide significant ecosystem services that improve soil health and supply necessary nutrient supplements to plants (Sarkar et al., 2020). These crop residues can be used as organic soil amendments, substrates for compost, manures, etc., for improving soil fertility, health, and enhancing the plant growth.

There are various kinds of usage of organic residues in agriculture which could be broadly classified as, (i) mulch; (ii) sewage-sludge; (iii) animal-origin manures; (iv) compost; (v) compost-fortified with beneficial microorganisms and enzymes; (vi) vermicompost; (vii) crop residue as such (e.g., rice straw), etc. Apart from that biomass like waste from agriculture, food, and municipal solids are also considered organic residues in agriculture and could be utilized as sustainable and alternative options to attain the demand for future fuel and energy supply (Paritosh et al., 2017). Annually, the worldwide production of renewable biomass is approximately 220 billion tons. Agricultural residues are categorized in a broad group in the form of agricultural biomass that incorporates the food-based parts of crops (corn and sugarcane) and non-food parts (rice husk, rice straw, pearl millet stalk, wheat straw, etc.), perennial grasses and biogenic wastes.

Rice, wheat, and corn are the three top cereal crops grown globally, and a huge quantity of residues are produced from those crops. The crop residues are primarily utilized as an energy source in Indonesia, China, Nepal, Nigeria, Thailand, and the Philippines. On the other hand, residues are commonly used for the generation of compost and animal feed in Pakistan, Syria, Lebanon, the Philippines, and a few parts of China. However, in South Asia, residue burning is a common practice for the last 3-4 decades in countries like Indonesia, India, China, Pakistan, Nepal, and Thailand.

India produces 650 million tons (mt) of crop residue annually, out of which wheat and rice contribute 27-36% and 51-57%, respectively (Dutta et al., 2022). In India, considerable quantities of residues from wheat, rice, and pearl millet are utilized as animal fodder, while the stubbles of cotton and red gram are generally used as firewood. Mustard husks are used as fuel for brick kilns. The major contributors to crop residues in India are rice, wheat, corn, sugarcane, millets, pulses, fiber, oilseed and coconut. So, a significant quantity of crop residues is generated along with those large quantities of harvested products. Unfortunately, around 16% of the crop residues is burnt in open fields (Bhattacharyya et al., 2021). The latest estimation indicated that the volume of rice-straw residue generation has increased with annual fluctuations based on the production of rice (grains). Among all the states, the maximum straw is generated in West Bengal (22.95 mt) followed by UP (20.63 Mt) and Punjab (17.38 mt) (MoA, 2012;Bhattacharyya et al. 2021)

The crop residues are the reservoir of essential plant nutrients. Based on the distinct crop seasons with varied soils and crops cultivated, various types of residues are generated at different periods in a year in India. Rice is cultivated primarily in the wet season and produces a significant quantity of residues (straw, husk, and stubble) after harvest (during October-December). Considering the huge amount of rice straw generated each year, it is indeed a major challenge to manage such a massive stock. Further, rice straw contributed the maximum (40%), followed by wheat straw (22%) and sugarcane trash (20%) to open field burning in India in last few years. The burning of straw polluted air and also emits GHGs. For example, during 2017, CO_2 (141.15 Mt), SOx (0.037 Mt), CO (8.57 Mt), NH_3 (0.12 Mt), and NOx (0.23 Mt) were emitted due to open-field straw burning in India (MNRE, 2018). Further, straw-burning could lead to the depletion of the stratospheric ozone layer and the release of particulate matter (PM) and various hydrocarbons into the air, causing human health hazards. It also causes the loss of plant-available nutrients and, decline in soil fertility, and crop productivity (Pandey, 2019). According to India's National Ambient Air Quality Standard, the permissible level for $PM_{2.5}$ is set at 40 µg m^{-3} (Pathak et al., 2017). But in 2017, the air pollution in Delhi reached the critical limit of $PM_{2.5}$ after straw burning, reporting a mean value of 98 µg m^{-3}, twice the Indian standard and ten times higher than the WHO standard (Zehra, 2017).

However, various studies suggested that there is good potential to *ex-situ* and *in-situ* management for rice residues (Bhattacharyya et al., 2021). Composting, biochar production, and mechanized farming are cost-effective sustainable techniques to retain nutrients and enhance carbon sequestration in the soil, which could reduce the gravity of the stubble burning issues (Bhuvaneshwari et al., 2019; Bhattacharyya et al., 2021). Therefore, it becomes a challenge to handle/manage organic crop residues effectively and profitably. However, using these residues for the purpose of animal feed, fodder, bioethanol, biochar, packaging, mushroom cultivation, composting, and conservation agriculture are alternative options to manage these residues, which can increase carbon sequestration in the soil as well as reduce GHGs emissions (Bisen and Rahangdale, 2017; Bhattacharyya et al., 2021). Thus, for the maintenance of soil health and the stability of the environment, there is an urgent need for the management of organic residues in agriculture.

2. Characterization of organic residues

For the effective utilization of organic residue, characterization of biomasses is necessary. The nutrient content and other properties of agricultural residues differentially affect crop yield and soil fertility. The percentage of nitrogen content in residues ranged from 0.38-2.0%, and carbon ranged from 15-50.76%. These organic residues, having higher carbon content (50.76%), could be used as a fuel-efficient feedstock (Table 1).

3. Management of organic residue and greenhouse gases emissions (GHGs) in agriculture

The three major GHGs in agriculture are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), contributing about 12% of emissions. Organic residues, in general, and crop residue, in particular, enhance carbon sequestration in the soil, contributing to methane emissions. On an annual basis, CH_4 emission was higher in rice straw incorporation. Compared with the recommended dose of fertilizers (RDF), higher emissions of CH_4 were noticed in rice straw incorporation. However, the addition of rice-straw compost enhanced methane emission only by 7.9% over RDF. So, it could be stated that straw incorporation could increase the seasonal CH_4 emissions from lowland rice ecology. However, rice straw provides carbon to microbes and nutrients to the crop. Although it facilitates CH_4 emission by providing labile carbon as a substrate to methanogens (Zou et al., 2005; Bhattacharyya et al., 2012), it also helps in carbon build-up in the soil.

Table 1. Characterization of organic residues.

Organic residue	Nutrient content (%) in organic residues				
	N	P	K	C	References
Compost	0.5-2.0	-	-	15-30	Bhattacharyya et al., 2021
Vermicompost	1.21	0.78	0.90	24.5	Chaudhary et al. (2020)
Maize straw	0.38	-	-	41.6	Rakesh et al. (2021)
Paddy straw-compost	0.62	-	-	50.76	Malik et al. (2021)

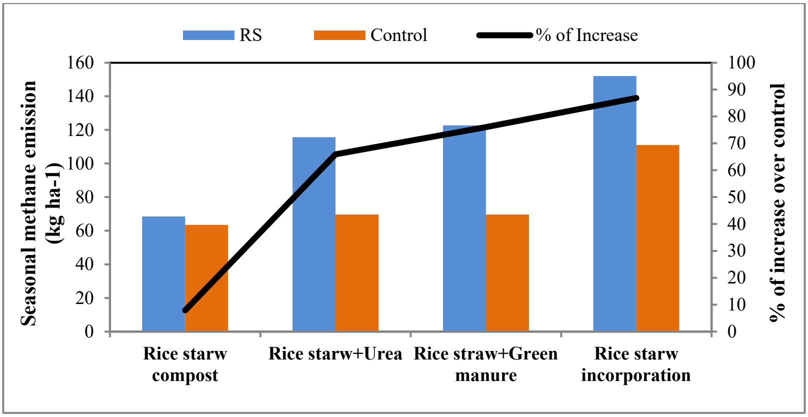

Figure 1. Annual methane emission as affected by the addition of different organic residues in rice

[Note: Rice straw compost (RDF 60:40:40 + RSC 5t ha^{-1}), Rice straw + urea (1:1 nitrogen basis), Rice Straw (RS)+ Green manure (GM) (1:1 nitrogen basis), Rice straw incorporation (RSI) 6t ha^{-1}]

In continuously flooded lowland rice systems, residue management rarely affects N_2O emissions. However, mid-season drainage, drainage before harvesting, and fallow periods do alter N_2O formation and emission in flooded rice. The peak of N_2O emissions is generally observed just after nitrogenous fertilizer application and rainfall, irrespective of crop residue addition (both time and amount) (Bhattacharyya et al., 2012, 2013). Further, no clear trend in the fluctuations of N_2O emissions was noticed due to the incorporation of crop residues or removal of residues from the field in rice. However, the annual N_2O emission was found lower in rice straw compost addition (1.59 kg ha^{-1}) compared to RDF (1.80 kg ha^{-1}) (Dash et al., 2021). Compared with the RDF (control), N_2O emissions increased by 11.7% when rice straw + urea was added to rice.

The N_2O emissions are often affected by soil water regime, surface mulch, and residue incorporation (Harada et al., 2007). Although, after nitrogen fertilizer and water management, the type of residue incorporated/mulched is the determinant factor for N_2O emissions.

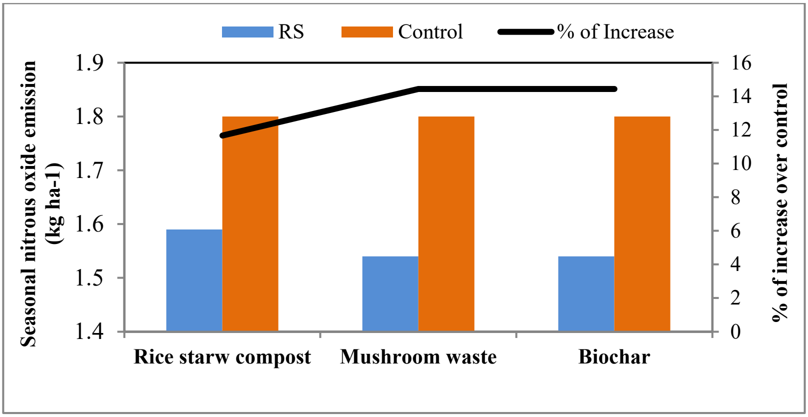

Figure 2. Annual nitrous oxide emissions as affected by different organic residues management in rice.

[Note: Rice straw compost (RDF 80:40:40 + RSC 5t ha^{-1}), Straw mushroom waste (5t ha^{-1}) and Biochar (5t ha^{-1})]

Application of organic products can affect mineralization rates of soil organic matter and contribute to increases in soil organic carbon content (Iqbal et al., 2009). At the same time, the supply of nutrients through organic residues affected soil CO_2 flux by increasing carbon input from enhanced plant productivity and crop residue (roots and stubbles) returned to the soil (Bhattacharyya et al., 2012). It was noticed that the annual CO_2 emission was higher in rice + green manure (1858.5 kg CO_2 ha^{-1}) followed by rice straw + urea (1680.6 kg CO_2 ha^{-1}) only (Figure 3). The higher CO_2