PHYSICAL AND CHEMICAL PROPERTIES DURING COMPOSTING OF *Hydrilla verticillata* AND ITS APPLICATION IN SOIL

A thesis submitted
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

Submitted
By

MAYUR SHIRISH JAIN

Department of Civil Engineering
Indian Institute of Technology Guwahati
Guwahati, Assam
India – 781039
March – 2019

Acknowledgements

I am indebted to many people who helped me during my research work and it is my privilege to acknowledge them.

At first I express my deepest sense of gratitude and reverence to my supervisor Dr. Ajay Kalamdhad, Professor, Environmental Engineering division, Department of Civil Engineering who is always available for discussing as teacher and as a friend. He contributed a great deal to my understanding the research area through valuable discussions, ideas, useful comments and monthly presentation, which were a great source of inspiration. His affectionate concern for students and his in-depth appreciation of the problem and timely suggestions for its solutions keeps him on a unique pedestal as an outstanding supervisor.

I express my sincere thanks to the members of my Doctoral Committee Dr. A Mishra, Dr. B Kumar and Dr. S Senthilkumar, for their valuable suggestions, eternal encouragement, and timely help provided at various stages of the research work. I also thank to Prof. M. Jawed, Prof. P K Ghosh and Dr. B Hazra for their help during my course work.

I thank the former Head of the Department, Professor S. Dutta and present Head Professor C Mahanta for providing facilities for conducting the research. I gratefully acknowledge the unstinted help provided by Mr. P. Pathak and Mr. C Medhi during all phases of my research work. Furthermore, I would like to thank the office staff of the department for their support in administrative works.

I wish to put on record my gratitude to the Editors and Reviewers of all my manuscript published in the respective Journals and Conference proceedings for their valuable comments to upgrading my research study.

I would like to thank to my senior Dr. K Dhamodharan, Dr. S Varma, Ms. Jayeeta Hazarika, for giving their precious time related to my research work.

I would like to thank to my colleagues Mr. K R Singh, Ms. Heena Kauser and other WMRG members for giving their precious time related to my research work. I also thank to my juniors Mr. Mohit Daga, Mr. Rohit Jambhulkar, and Mr. Siddhartha Paul for helping me during my experimental work.

One other special friend, i.e., my wife I must mention is Rohini for her constant encouragement, communication, love and respect throughout my stay and during my research work and most importantly I consider her as my close friend.

I am very thankful to Mr. Nayan, and Mr. Rantu for the collection of raw materials from different places in adverse conditions and preparation for composting process.

At last I would also like to thank to my parents Mr. S P Papalkar and Mrs. J S Papalkar, brother Mr. R S Papalkar, his wife Mrs. R R Papalkar and nephew Arham for their love and support during study.

Above all, I owe it all to Almighty God for granting me the wisdom, health and strength to undertake this research task and enabling me to its completion.

Mayur Shirish Jain

ABSTRACT

Hydrilla verticillata (*L.f. Royle)* is a troublesome aquatic weed and is found globally. It is also called as noxious aquatic weed due to its rapid growth rate and significant uptake of nutrients. The complete removal of *Hydrilla verticillata* from the aquatic bodies by biological, chemical or mechanical means are still unsuccessful. Composting is the best alternative method to manage this weed but its high moisture levels and lower carbon: nitrogen ratio is the limiting factors that may affect the composting process and thus the quality of the final product. The presence of high moisture content during the process negatively impacts microbial activity as well as hinders aeration, and in the compost, it affects the porosity of the soil after agricultural land application.

Similarly, lower carbon: nitrogen ratios in the wastes are susceptible to higher nitrogen loss due to the ammonia volatilization. Thus the moisture content and carbon: nitrogen ratios of wastes play an essential role in the composting process as well as the quality of the end product. Therefore, studies were carried out on the utilization of *Hydrilla verticillata* as a substrate in a rotary drum composter mixed with fresh cow dung and sawdust. Five different proportions (Trials 1 (5:4:1), 2 (6:3:1), 3 (7:2:1), 4 (8:1:1) and 5 (10:0:0)) of *Hydrilla verticillata*, cow dung and sawdust were prepared for the composting process. Rotary drum composter operated in a batch mode for 20 days. The best proportion of the mixtures during rotary drum composting (Trial 4) selected due to attainment of higher temperature, lower moisture content, volatile solids, soluble BOD and COD, oxygen uptake and CO_2 evolution rate, and higher nutrients concentration.

But the end product still possessed high moisture content (nearly 80%) more than the recommended values and thus cannot be applied on agricultural land. The hypothesis was made that moisture content not only impacts biological activity and chemical properties, but the specific physical properties may get affected. The physical properties are equally important and should be evaluated before compost application. But very limited information is available on such studies during the composting process. Therefore, the composting physics were studied with the best trial (Trial 4) and the other wastes that include water hyacinth, vegetable wastes, sewage sludge and paper mill sludge. Their best ratios were selected from the past studies carried out in the rotary drum composter. The comparative studies showed that moisture content strongly affects the temperature rise, bulk density, free air space and porosity during the composting process. Bulk density and free air space are the prime physical properties during soil application of the compost.

To obtain the better quality compost and to minimize the effect of moisture content and the nitrogen loss an impact of locally available various carbon-rich agents (dry leaves, grass clippings, and wood chips were added 10%) and biochar (2.5, 5 and 10%) were studied with the (Trial 4) in the rotary drum composter. Based on the chemical, the physical and nutritional status of the end product the trial with biochar (5%) was selected as the best trial with the recommended moisture content and higher nitrogen content.

The quality compost so obtained was applied to the two sandy soils (viz. alluvial and laterite) that were characterized with poor nutritional, physical and chemical health. The compost was applied at varying proportion (10, 20 and 30%) in both soil and pot study was conducted. This study investigated the influence of parameters such as soil organic matter, soil organic carbon, pH, total nitrogen, available phosphorus, water-holding capacity, cation-exchange capacity, bulk density and total porosity. The study indicated the rise in the soil organic matter, organic carbon, total nitrogen phosphorus, water-holding capacity, cation-exchange capacity and porosity and lower bulk density immediately after application. The alluvial soil (20%) and laterite soil (30%) of compost application showed the best results compared to the other trials and was very useful for remediating the poor soil.

From this study, it can be concluded that the appropriate proportion of *Hydrilla verticillata*, cow dung and sawdust (Trial 4) could produce quality compost in the rotary drum composter. The moisture content has the substantial impact on the physical properties along with the biological and chemical properties and should not be neglected during compost application. An appropriate proportion of biochar (5%) addition during the composting process enhanced the organic matter degradation, reduced the moisture content and improved overall physical quality of the compost. The compost prepared from *Hydrilla verticillata* + biochar is useful to improve the overall soil health. This study further recommends compost application at the rate of 20 and 30% to the alluvial and laterite soil, respectively.

Keywords: *Hydrilla verticillata*; moisture content; bulk density; biochar; alluvial and laterite soil; water-holding capacity.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATIONS

AAS	Atomic absorption spectrophotometer
ANOVA	Analysis of variances
AP	Available phosphorus
APHA	American public health association
AS	Alluvial soil
BC	Biochar
C/N	Carbon/ Nitrogen
CA	Carbon-rich agents
CD	Cow dung
CEC	Cation exchange capacity
Cmol	centimole
DL	Dry Leaves
EC	Electrical Conductivity
FAS	Free air space
g	Gram
GC	Grass clippings
h	Hour
HV	*Hydrilla verticillata*
kcal	Kilo calories
kg	Kilogram
L	Liter
LS	Laterite soil
M	Molar
Mg	Milligram
MSW	Municipal solid waste
NH_3	Ammonia
NH_4-N	Ammonical nitrogen
p	Probability
SD	Sawdust
SOC	Soil organic content
SOM	Soil organic matter

TKN	Total kjeldahl nitrogen
TOC	Total organic carbon
VS	Volatile Solids
WC	Wood chips
WHC	Water holding capacity

Chapter 1

INTRODUCTION

This chapter mainly deals with the problems associated with the invasive weeds, impact of *Hydrilla Verticillata* on the lakes. It also includes the scope of composting of *H. verticillata*, importance of carbon-rich agents and biochar addition during composting of *H. verticillata*, insight of composting physics for agricultural application and its effect on alluvial and laterite soil. Finally, the chapter illustrates the objectives, the need of the study, and the organization of the thesis.

1.1 OVERVIEW

Aquatic weeds/plants are an essential part of the aquatic ecosystem due to their mitigating pollution capacity. They are beneficial as they take part in altering the chemistry of the water, and are one of the sources of oxygen supply in the water. Aquatic weeds are rich in essential nutrients that act as the food source for aquatic fauna. But if their importance is so crucial in the aquatic ecosystem, then why they are considered to be troublesome for aquatic bodies. According to Hussner et al. (2017) the disposal of the wastes from the various industries, use of the chemical fertilizers, and other human activities has polluted many aquatic bodies that have lead to the eutrophic condition in the aquatic bodies. It is a leading cause of damage to many freshwaters and other marine ecosystems in the world (Chislock et al., 2013). The decomposition of the enormous mass of aquatic weeds depletes the oxygen levels and also affects the structural and functional properties of the aquatic bodies. They interfere with navigation and irrigation channels thus hampering the trade businesses (Holm et al., 1969; Gallagher 2007). The eutrophic condition also invites some troublesome invasive species. The E.O. 13112 (1999) has defined an "Invasive species" are the alien species to the aquatic ecosystem under consideration and whose introduction cause economic or environmental harm or harm to the human health and possess various mechanisms of vegetative reproduction that enable it to spread rapidly. These species tend to alter the environmental conditions as well as physical or chemical properties of water and sediments (Zehnsdorf et al., 2015). The United States Congress declared *Arundo donax* (giant reed), *Eichhornia crassipes* (water hyacinth), *Hydrilla verticillata* (water thyme), *Pistia stratiotes* (Family: Araceae), etc. as the most troublesome invasive plant species in the United States and they are listed as federal noxious weeds (USDA, 2012).

1 *INTRODUCTION*

Northeast India is one of the global hot spot regions for biodiversity as the associated natural wetlands and forest support valuable bio-diversity (Kalita et al., 2007). *H. verticillata* is one of the dominant invasive submerged weed that is present globally, which covers the large area of the wetland (Langeland, 1996; Schardt, 1997; Williams et al., 2007; Jha et al., 2015). *H. verticillata* plays an important role in the ecological processes and functions of the wetland and also possess essential mineral composition (Langeland, 1996). But unfortunately overgrowth of the weed pose a severe threat to the ecosystem of the wetland. Haller (2002) reported problems for fishing due to the infestation of *H. verticillata*. It adversely affects the ecologically important submersed species such as *Potamogeton spp.*, tape grass (*Vallisneria Americana*) and coontail (*Ceratophyllum demersum*) (Van, 1985). It interferes with both recreational and commercial shipping (Colle and Shireman, 1980). Some drowning cases were also reported due to infestation of the *H. verticillata* (Getsinger, 2014). Various types of control measures (biological agents, chemical treatment and mechanical harvestors) on the growth of *H. verticillata* are reported in the earlier studies but none of them were successful due to the greater difficulties and also been costlier.

Evans and Wilkie (2010) reported the life cycle assessment approach to quantify significant energy, material and monetary flows associated with the mechanical harvest of *H. verticillata* and the subsequent use of harvested biomass for bioenergy and organic fertilizer production. The authors further reported composting of *H. verticillata* is one of the ways to recycle and utilize the aquatic weed. It can be established as an economical, natural and eco-friendly approach to use this organic solid waste. It possesses several essential nutrients such as nitrogen, phosphorus, potassium, calcium, sodium, and magnesium that makes it fit for composting and its application to agricultural land (Meier et al., 2014; Lu et al., 2015). Composting process involves a natural biological decomposition of organic matter, which is carried out by naturally occurring microbes such as bacteria, fungi, actinomycetes thus converting into humus product i.e. compost (Pan et al., 2012). It is an entirely aerobic biological process that occurs under certain conditions, which allow development of thermophilic temperatures to produce compost that is free from pathogens and plant seeds and can be applied to land (Haug, 1993). The compost acts as a soil conditioner in agricultural applications. Therefore, disposal of these wastes can be avoided by proper utilization of the wastes, thus reducing demand for landfill sites (Gabhane et al., 2012).

1.2 BACKGROUND OF THE PROBLEM

The scope for converting *H. verticillata* biomass into compost requires an understanding of its initial characterization to achieve proper degradation. The concentration of mineral and nutrients varies from wetlands to wetlands, which depends on the extent of the pollution. Initial characterization is also essential to assess their performance and its efficacy in a particular composting method. It is also beneficial as it provides information on the requirement of different wastes materials (inoculum or carbon-rich agents or both) during the composting process. The microorganisms in the composting process require four essential ingredients for the decomposition of the wastes. These ingredients include carbon for energy, nitrogen as food, oxygen for the oxidation of carbon as well as to avoid anaerobic condition and water to maintain the metabolic activities. The appropriate ratios of these ingredients in the initial feedstock provide microorganism to work effectively that aid in heating up of the feedstock, which is the critical parameter of the composting process. The achievement of thermophilic temperatures (45-70°C) during composting indicates standard sterilization of the process. Ever-increasing generation of solid wastes leads to increase in the duration required for its management and to achieve compost maturity. Therefore, it is essential to the design proper composting technologies to manage huge mass of organic wastes in less time. According to Haug (1993), the final product, i.e., compost should possess carbon: nitrogen (C/N) ratio in between 20:1 to 11:1. The C/N ratio above 20:1 is nitrogen starved and below 11:1 is likely to have a possibility of nitrogen loss (as ammonia) due to volatilization.

Biological, chemical and respirometry properties are essential to assess during the composting process to provide the brief idea on the degradation process of organic wastes. The biological process includes determination of biological oxygen demand, chemical oxygen demand and bacterial counts such as the most probable number. The determination of volatile solids, total organic carbon, pH, electrical conductivity and nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, sodium comes under the chemical properties. The oxygen uptake rate and carbon dioxide evolution rate are some respirometry parameters evaluate the compost maturity and stability. The discussed parameters are essential to know the compost quality and degradation rates. However, its feasibility of application cannot be explained without understanding its physics or physical parameters. Composting physics plays an essential role during every stage of compost production, handling, and its utilization.

It includes measurements of parameters such as bulk density, porosity, moisture content, free airspace, void ratio, and particle density within the compost matrix during the process. These parameters are interrelated and affect degradation rate and also on heat and mass transfer during the composting process (such as air supply, water evaporation, and heat balance) (Huet et al., 2012). According to Agnew and Leonard (2003) the physical properties influence the compost production and its utilization as a soil conditioner. Another critical aspect of *H. verticillata* is its higher moisture content (88-92%) as reported in the earlier studies (Meier et al., 2014). To support the metabolic processes of microbes, water plays an important role, which is produced and required for microbial activity (Baeta-Hall et al., 2005). Water is the medium for the transports nutrients, chemical reactions and allows the microbes to move about (Rynk, 1992). However, the higher moisture content is likely to affect the composting process by reducing its air voids thus affecting the degradation process. The research studies have identified that the addition of carbon-rich agents can improve the composting of such organic waste. Numerous carbon-rich agents including wood chips, sawdust, grass clippings, dry leaves, rice husks, wood shavings, cotton waste or peanut shells were utilized for the moisture adjustment and to maintain carbon: nitrogen ratio in the composting mixtures (Adhikari et al., 2009; López- Cano et al., 2016; Liu et al., 2017).

A study carried out by Zhang and Sun (2014) states that carbon-rich agents also improve the structural, functional and physical properties during the composting process. It also enhances microbial activity by providing efficient aeration. Hence, improving composting physical properties and conditions that can substantially improve the overall development and properties of mature compost and thus benefits during the application in various soils. Compost obtained from multiple organic wastes was applied previously to the various soils that have shown significant positive impact on overall soil health (Vandecasteele et al., 2014; D'Hose et al., 2014; Goswami et al., 2017). Compost application has also benefitted the soil by avoiding the nutrient leaching in the groundwater (Li et al., 1997; Grey and Henry, 1999). Thus it reduces financial issues (purchasing of chemical fertilizers) and probably decreases the environmental impact associated with fertilizer production and utilization. Several successful studies are available on compost application prepared using various composting technologies. However, no scientific research has been reported on the efficacy of rotary drum composting of *H. verticillata*, insight on physical properties during composting process.

The influence of carbon-rich agents during composting, and application of the compost prepared from *H. verticillata* were also not studied. Therefore, the thesis aimed to investigate the fundamental composting properties during composting of *H. verticillata*, a study on composting physics, the role of carbon-rich agents during rotary drum composting of *H. verticillata* and finally its application in two different sandy soils. The study is divided into four phases, i.e., Phase 1: efficacy of rotary drum composter for management of *H. verticillata*; Phase 2: study on composting physics; Phase 3: role of carbon-rich agents during composting and Phase 4: study on compost application and its effects on sandy soils.

1.3 OBJECTIVES OF THE STUDY

The broad objective of the study was to find out the efficacy of rotary drum composting for *H. verticillata* and to optimize best combination of waste materials for producing stabilized compost within shorter duration. The purpose was also to find the best strategy for improved treatment efficiency by utilizing different carbon-rich agents during composting and application of the compost in the soil. The scope of the present study is limited to:

1. To study efficacy of rotary drum composter for the management of *H. verticillata*.
2. Insight of composting physics and its comparative study during composting of various organic wastes viz. *H. verticillata,* water hyacinth, vegetable wastes, sewage sludge and paper mill sludge.
3. To study the role of carbon-rich agents such as dry leaves, grass clippings, wood chips and biochar during rotary drum composting of *H. verticillata.*
4. To study the effect of compost application prepared from *H. verticillata* on alluvial and laterite soil properties.

1.4 NEED OF THE STUDY

Overgrowth of aquatic weed is the major problem in many developing countries due to illegal waste disposal, and their control by adopting various biological agents and chemical application is creating nuisance in the aquatic bodies. People residing near by aquatic bodies mainly depend on various resources available in the water bodies for their livelihood. But the poor quality of water affects aquatic life as well as other living beings.

H. verticillata is the invasive aquatic weed found in enormous quantities in the wetlands of Northeast India. Deepor Beel (beel = lake) is one of the important wetland of Assam, India that is enriched with various useful resources. However, dense mats of *H. verticillata* have greatly affected the structural and functional properties of lake. Composting is a proven, safe and sustainable method to manage such huge biomass of *H. verticillata.* Because agriculture is the mainstay of many developing countries, and people mainly depend on agriculture for their sustenance and livelihood. The quality fertilizer that consists of beneficial nutrients, required for the growth of plants and good outcome from agriculture is an essential commodity. In developing countries, farmers mostly do not have access to chemical fertilizers and pesticides. Use of natural fertilizers should be preferred over chemical fertilizers for the prevention of side effects of the crop as well as soil. Therefore, quality organic compost is the primary requirement for efficient and beneficial agricultural system not only for India but also for the whole world.

The process of composting will need more than 60% moisture and essential nutrients (nitrogen, phosphorus and potassium) that can be easily contributed by *H. verticillata.* For composting, shredding might not be necessary as whole plants can be easily decomposed, still for better and faster results shredding can be adopted. An area of compost utilization of *H. verticillata* should be explored so as to use the plant and to convert the waste into best. The knowledge of composting of *H. verticillata* and changes in physico-chemical parameters and micro and macro nutrients is required to understand, and there is a dire need to check if decomposition of *H. verticillata* can be a quality compost with respect to the nutrient content requirement of plants and eco-friendly material.

1.5 SCOPE OF THE THESIS

The scope of the thesis is confined to the efficacy of the rotary drum composting of *H. verticillata* and its application in the soil by understanding its physical properties. The rotary drum composting was carried in five trials with different proportions of cow dung and sawdust. The compost application was carried out in different percentages in the 2 soils (viz. alluvial and laterite soil). The major portion of the work was on the collection of *H. verticillata* with the help of local boatmen; its transportation to the Indian institute of technology Guwahati, Guwahati, Assam for further experimental purposes.

Collection of other wastes such as dry leaves, cow dung, saw dust, grass clippings, wood chips from different places; cutting/shredding of the wastes in the desired size. Preparation of the different composting feedstocks and feeding in the rotary drum composter; observation/monitoring of the temperature during rotary drum composting and analysis of biological, chemical, physical and respirometry properties during the composting process and handling and analysis of the data. Similarly, the preparation of different combinations of compost and soil, and feeding in the pots; observation/monitoring of the moisture during pot study and analysis of soil properties and handling and analysis of the data

1.6 THESIS ORGANIZATION

The thesis is organized as follows

- Chapter 1 is about problems associated with aquatic weeds, the option for composting of *H. verticillata* weed, the objectives and need of the study; and the scope of the thesis.
- Chapter 2 gives the detailed literature review of the aquatic weed problems, the problem of *H. verticillata,* the different techniques of composting, quality of compost, importance of physical properties, role of carbon-rich agents during composting process, and the compost application in the laterite and alluvial soil.
- Chapter 3 deals with the experimental flow of various phases of this study; collection of the wastes; other feedstock materials; composting methods adopted in the study; pot study experiments and; detailed procedures for physical, chemical, biological analyses.
- Chapter 4 is about results and discussion regarding of all the phases including temperature profiles, variation in chemical, biological and physical properties, comparative studies on composting physics, role of carbon-rich agents for composting of *H. verticillata*, and effect of compost application on physical, chemical and nutritional properties of laterite and alluvial soil.
- Chapter 5 lists the conclusion and the recommendations from this study.

Chapter 2

LITERATURE REVIEW

This chapter deals with the available relevant literature concerning the general problems associated with aquatic weeds, occurrence of *H. verticillata* globally and its growth rate, chemical composition, problems associated, control methods, utilization of weed and peculiarities as a compost feedstock. The composting technologies, factors affecting composting process, various composting properties and its importance, composting physics and its importance, carbon-rich agents and its effect on during composting of organic wastes and lastly the application of compost and their later effects on soil properties are also discussed.

2.1 AQUATIC WEEDS AND PROBLEMS ASSOCIATED

Aquatic plants play a major role in maintaining the structural and functional properties of the aquatic ecosystem (Jeppesen and Sondergaard, 1998). They act as a shelter for few insects, which is, then become the food for many aquatic fauna. But anthropogenic activities have created negative impact on the aquatic ecosystem. Various anthropogenic activities generate large amount of wastes that is get disposed in nearby aquatic bodies leading to eutrophication. This condition cause increase in the growth of aquatic plants. Outgrowth of these plants is defined as the aquatic weeds that take form of noxious vegetation by outcompeting other species present in the aquatic ecosystem (Varshney et al., 2007). Weeds are unwanted and undesirable plants that interfere with the use water resources. Maximum aquatic bodies in the globe are threatened by the overgrowth of the weeds (Ray and Hill, 2013). Basically the aquatic weeds are classified as i) Floating, ii) Submerged and iii) Emergent weeds. Various types of weeds are also illustrated in Fig. 2.1. Floating weeds are mostly seen in the surface of large, deep and shallow depths of aquatic bodies, the roots of whose are hanging in the water. *Eichhornia Crassipes* is one of the examples of the floating weeds. According to Jayan and Sathyanathan (2012) these weeds make loss of water through evapotranspiration. The weeds those roots are anchored to the hydrosoil and grow below the water surface are known as submerged weeds. These weeds are said to be more dangerous as they are not visible to the surface hence their removal is more difficult. *H. verticillata* (L.f.) Royle is one of the submerged weeds (Fig. 2.2).

a) Emergent Weeds

b) Floating Weeds

c) Submerged weeds

Fig. 2.1. Type of aquatic weeds (*Source*: WP Law Incorporated)

The aquatic weeds rooted extending above the water surface are called emergent weeds (e.g. *Typha* spp.) (Jayan and Sathyanathan, 2012). They usually grow in the shallow depth water bodies. It is observed in many countries that some of the deadly species grow in natural freshwater storages such as lakes. These noxious weeds tend to alter the environmental conditions as well as physical or chemical properties of water and sediments (Zehnsdorf et al., 2015). These plants (noxious weeds) possess various mechanisms of vegetative reproductions that enable it to spread rapidly.

The United States Congress declared Arundo donax (giant reed), *Eichhornia crassipes* (water hyacinth), *H. verticillata* (L.f.) Royle (water thyme), *Pistia stratiotes* (Family: Araceae), etc. as the most troublesome, invasive plant species in the United States and they are listed as federal noxious weeds (Coetzee et al., 2011; USDA, 2012). In India, over more than 140 different aquatic weeds are of primary concern some of which includes *Eichhornia crassipes, Ipomoea aquatica, Hydrilla verticillata, Nitelia* sp, *Vallisneria spiralis, Typha angustata, Salvinia molesta, Chara* sp, *Ceratophyllum demersum (*Varshney *et al.*, 2008). The dense growth of such weeds causes many problems to the aquatic bodies.

Fig. 2.2 *Hydrilla verticillata*

It suppresses the growth of native plants and poses negative impact on microbes. It also affects growth of phytoplankton's thus affecting fisheries and biodiversity (Gichuki et al., 2012). The large mats of these weeds also prevent oxygen transfer below the water surface (Villamagna and Murphy, 2010). A lower dissolved oxygen level is dangerous for the fishes. Moreover, lower DO levels catalyse the release of phosphorus from the sediment in the water bodies. It accelerates eutrophication that further leads to a subsequent increase in the growth of the weeds (Bicudo et al., 2007). They often clog the waterways thus hampering fishering recreations, navigation channels, hydropower, and irrigation channels (Ndimele et al., 2011). Therefore, it is essential to keep such weeds under control for better utilization of the water bodies.

2.2 *HYDRILLA VERTICILLATA*

2.2.1 Invasion and main cause of invasion

Species invasions are mainly affected by both ecological and chronological factors (Brown, 1995; Gaston, 2003). Climatic surroundings are supposed to be the critical environmental control for the species invasion on a large scale, and ecological conditions constraint the distributional potential of species (Peterson, 2003). Owing to increase in pollution the detrimental effects has been observed in the environment leading to climate change that shows warming of a few degrees, but it involves reorganization of many aspects of climate, such as rainfall (Houghton et al., 2001). The *H. verticillata* can adept any environmental conditions thus can quickly cultivate in warmer regions and was the primary cause of its invasion (Sousa et al., 2009). *H. verticillata* is a member of the family of *Hydrocharitaceae* that is native to the warmer regions (Asia) and is a submerged, perennial and vascular aquatic plant found in freshwater habitats (Langeland, 1996; Sousa et al., 2009). The 20th century experienced the most terrible warming pattern of the last era with average temperatures uprising by about 0.6°C (Jones et al., 2001). The invasion potential of *H. verticillata* has been predicted by using ecological niche models by three earlier researchers (Peterson, 2003; Barnes et al., 2014; Zhu et al., 2017). Numerous successful invasions were correlated with the existence of manifold introductions, combining genotypes from distinct source populations (Dlugosch and Parker, 2008; Bock et al., 2015).

A detailed literature survey provides a brief idea about its worldwide growth. It is a cosmopolitan species that occurs in Europe, Asia, Australia, New Zealand, the Pacific Islands, Africa, Europe, South America and North America as represented in Fig. 2.3. In the 1950s, it was imported into Florida as an aquarium plant under the name Indian star-vine (Michel et al., 2004). The weed was found to be unsatisfactory and disposed of into a canal near Tampa Bay where they survived and thrived (McCann et al., 1996). Slowly it was found growing in North America in 1951 or 1952 in the Tampa Bay area (Schmitz et al., 1991) followed by the Southeast as far north as the Potomac River and State of Maryland (Langeland, 1996). By 1955, aquarium plant from these Tampa aquatic regions was transported to Miami for cultivation and trade sale. The plant spread aggressively in Miami, Florida, followed by Texas and California, which might be owing to subsequent accidental/careless releases no doubt followed (Yeo and McHenry, 1977). The monoecious northern form and dioecious southern form of *H. verticillata* appeared in South Korea and the Indian subcontinent, respectively (Schmitz et al., 1991).

Dense mats of *H. verticillata* were found in many parts of India. Jana and Choudhuri (1980) and Taheruzzaman and Kushari (1989) reported its occurrence in the ditches of Burdwan University Campus, West Bengal, India. The whole weeds were collected from ponds, irrigation canals and paddy fields in and around Calicut and Sasthamkotta Lake, the largest freshwater lake in Kerala, India (Abbasi et al., 1990). In the southern part of India, it is found in the state of Tamilnadu in water sources of Asaripallam, Nagercoil and Kanyakumari district andwas authenticated by the Taxonomist of Botanical Survey of India, Coimbatore (Kensa and Neelamegam, 2014).

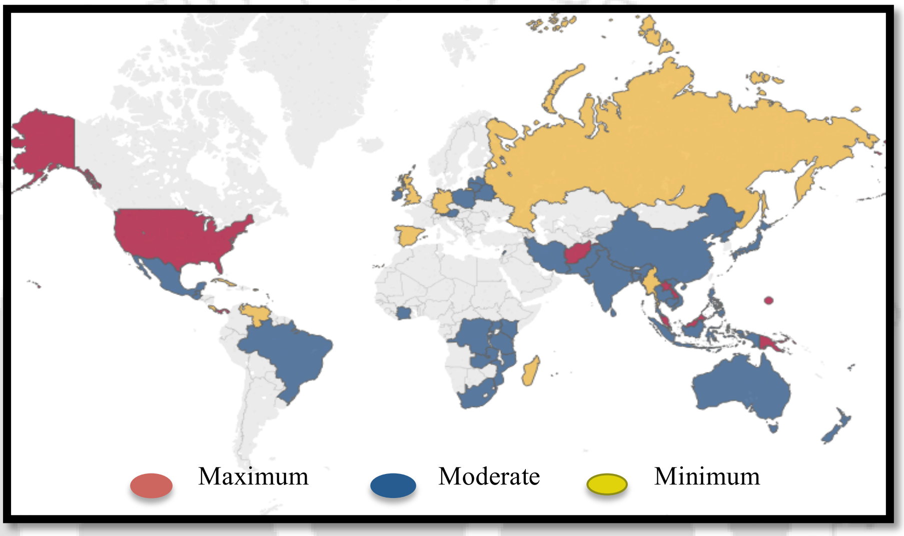


Fig. 2.3. World Occurrence of *H. verticillata*

Jha et al. (2015) observed the growth of *H. verticillata* in Jamtara district lying Chhotanagpur Plateau, Eastern India, Jharkhand. Singh et al. (2012) studied about the growth of *H. verticillata* from the pond of Rohilkhand University, Bareilly, Uttar Pradesh, India. The northeast part of India equally contributes regarding the increase of *H. verticillata*. It is found in Deepor Beel, Guwahati, Assam, India, which is a freshwater lake. Considering its rapid growth, it is known as aquatic attacker and is the invasive aquatic weed because of its ability to adapt and aggressively compete in its environment (Langeland, 1996). There are other numerous characteristics that support the *H. verticillata* to out-compete the native vegetation and establish it efficiently. These features include its rapid methods of development and coverage. Small fragments of the weed, as long as they possess a single node can cultivate roots and develop into an entirely new plant (Langeland, 1996). The four methods of reproduction are fragmentation, tubers, turions and seeds (Schardt, 1997).

The subterranean turions can endure several days out of water bodies if removed, approximately 4 years in undisturbed sediment, and the ingestion by waterfowl (Williams et al., 2007). *H. verticillata* is capable of absorbing carbon more proficiently than any other invasive species. The weed can survive in a wide variety of aquatic conditions. It can withstand water with lower to higher acidity/alkalinity (Cook and Lüönd, 1982). It can also face in the water, which is heavily polluted by sewage. It can grow in organic sediments, but it can also endure in sandy or rocky substrates. It has been observed from these attributes that once established; *H. verticillata* is very difficult to eradicate.

2.2.2 Growth

H. verticillata looks identical to other submersed aquatic weeds, but its vegetative propagative structures and a well-developed root system for carbohydrate storage make it different from others. It is either monoecious or dioecious with both male and female flowers that can grow under almost all ranges of water chemistry conditions (Cook and Lüönd, 1982). It is a perennial plant, and its permanent structures allow rapid growth after treatments or environmental stresses (Netherland, 1997; Owens and Madsen, 1998). It is commonly found in oligotrophic (low nutrients) to eutrophic (high nutrients) lakes (Cook and Lü.nd, 1982). Langeland (1996) reported *H. verticillata* photosynthesizes earlier in the morning and can migrate rapidly in deep water even with the low light requirement (1% of full sunlight or less). The optimum growth temperature for *H. verticillata* is 20-27°C and the maximum temperature it can withstand is 30°C. It can grow in water having up to about 7% of salinity or higher (Haller et al., 1974; Steward and Van, 1987) and can tolerate a broad range of pH, but tends to grow better at pH=7 (Steward, 1991). The growth of *H. verticillata* has been found to be very speedy i.e. 2.5 cm day^{-1}. It also can regenerate itself from any bud along its entire shoot (Charudattan, 1972) and stems can grow longer than 10.6 m when the plant grows in deep water (Schardt, 1997). It can be found in shallow and deep waters, anywhere from 0.5 to 15 m deep, as long as the deepwater environs have very clear water. Research studies also spectacles that one tuber of *H. verticillata* can lead to the development of nearly 5000 per square meter of new tubers.

2.2.3 Nutrient uptakes and chemical composition

The growth of a plant is an integral process, which consists of the flow of minerals and organic substances from the place of the formation to sites of utilization. Some studies state that the roots, as well as leaves of *H. verticillata*, have an excellent capacity to take in all kind of minerals, nutrients, and chemicals. It can also incorporate significant levels of heavy metals (such as arsenic, chromium, and copper) in its tissues (Barko et al., 1988; Dixit and Dhote, 2010; Srivastava et al., 2010; Xue et al., 2010) along with radioactive substances (such as uranium). The uptake of metallic elements such as phosphorus, iron, and manganese increases with the increase in light intensity and temperature (Basiouny and Garrard, 1984). Das et al. (2015) investigated arsenic uptake and metabolism in *H. verticillata* and concluded that the accumulation of arsenic by the plant is dependent on both concentration of the metalloid in water and the duration of exposure. It contains various essential nutrients and chemicals that include beta–carotene, abundant trans minerals polysaccharides, amino acids, micro, and macronutrients, antioxidants (Best and Boyd, 1996). The chemical compositions of *H. verticillata* according to various sources are summarized in Table 2.1.

2.2.4. Interferences

- ***Interferences with aquatic flora and fauna***

The introduction of *H. verticillata* in water bodies adversely affects the ecologically important submersed species such as (*Potamogeton spp.*), tape grass (*Vallisneria Americana*) and coontail (*Ceratophyllum demersum*) (Colle and Shireman, 1980; Van, 1985). Haller (2002) reported problems for fishing due to the infestation of *H. verticillata*. The author further reported that in the upper Parana River in Brazil, many fishers faced inconvenience because they had their fishing gear dragged by large quantities of loose *H. verticillata*.

- ***Interferences with navigation and irrigation***

H. verticillata interferes with both recreational and commercial shipping (Haller, 1978; Colle and Shireman, 1980; Langeland, 1996). The growth of such weed may cause choking of canals drainage that can lead to clogging of intake pumps in irrigation canals and may cause flooding (Gallagher, 2007). Many swimmers have been entangled and have drowned because of aquatic plants. Getsinger et al. (2014) reported many drowning incidents in *H. verticillata* infested waters of California, Florida, Minnesota, and Texas.

- ***Interferences with terrestrial living beings***

The *H. verticillata* mats can serve as a cause of breeding for different vector organisms. It may release disease-causing organisms that adversely affect human health. In such conditions, if the growth rate is increased, it may lead to poor health conditions of people. According to the study given by Williams et al. (2007), a disease recently discovered Avian Vacuolar Myelinopathy is causing death bald eagles (Haliaeetus leucocephalus) and waterfowl in the southeastern United States. AVM is associated with cyanobacteria, which lives on *H. verticillata*. Birds ingest neurotoxin produced by cyanobacteria epiphytic, which is the primary cause of fatal.

Table 2.1. Physical and chemical composition of *H. verticillata*

Parameters	Varshney and Rzóska (1976)	Abbasi et al. (1990)	Spencer et al. (1997)	Shah et al. (2010)	Das B et al. (2015)	Lu et al. (2015)	
						FHV[a]	DHV[b]
Dry matter (%)	8	-	6.12	8		-	
Organic matter (%)	6.5	-	80.44	-		-	
Crude protein (%)	-	-	17.10	19.94		-	
Ether extract (%)	-	-	2.79	3.5		-	
Crude fibre (%)	-	-	13.34	-		-	
Nitrogen free extract (%)	-	-	43.92	-		-	
Ash (%)	-	-	19.45	27.1	13.93	-	
C/N ratio	14.2	-	-	-		-	
Cellulose (%)	-	-	-	32.1		30.98	30.17
Hemicellulose (%)	-	-	-	-		24.46	24.19
Lignin (%)	-	-	-	-		12.54	15.36
Phosphorus (%)	-	0.28	-	0.28			
Carbon (%)	-	-	-	-	40.16	44.27	42.73
Nitrogen (%)	-	-	-	-	3.03	2.35	2.49
Magnesium (%)	-	0.72	-	0.9		-	
Calcium (%)	-	13.91	1.29	4.5	-	-	
Potassium(%)	-	2.33	-	2.9	-	-	

[a]FHV – Fresh Hydrilla; [b]DHV – Dried Hydrilla

- ***Ecological and other problems***
    - *Positive impacts*

  Mostly aquatic macrophytes play a significant role in maintaining the structural and functional properties of marine bodies (Wetzel, 2001). *H. verticillata* is comprised of the wide variety of nutrients that may aid in supplying food to other aquatic fauna. The dense mats of such species are beneficial to provide shelter, and refuge for a diversity of organisms such as fishes, invertebrates, and waterfowl (Pelicice et al., 2005; Rybicki and Landwehr, 2007). *H. verticillata* is also capable of accumulating heavy metals such arsenic, cadmium, copper, and chromium. The *H. verticillata* was observed to be beneficial in accumulating CO_2 in the tissues mainly during the night (Holaday and Bowes, 1980). The vast biomass growth also decreases water flow thus promoting the sedimentation of suspended and improving turbidity of water (Dixit and Dhote, 2010).

    - *Negative impacts*

  Despite the ecological importance of *H. verticillata*, the dense mats may infestations can alter water chemistry and oxygen levels (Pesacreta, 1988). Itmay reduce the dissolved oxygen available in the infested body of water and hence aquatic lives could not survive for a long time (Madsen, 1997). One of the most significant problems of *H. verticillata* is related to hydroelectric power generation reported in Brazil. Hydroelectric power generation was profoundly impacted by high biomass production by submerged macrophytes (Sousa, 2011). *H. verticillata* is aggressive and has frequently dominated the native phytoplanktons (Rybicki and Landwehr, 2007). Studies have indicated that biomass of *H. verticillata* can exert a substantial impact on colonies of invertebrates (Sousa, 2011).

2.2.5 Control methods

Various types of control measures on the growth of *H. verticillata* are reported in the literature. The control measures can be mechanical harvesting, chemical treatment or biological treatments as presented in Table 2.2. Biological control can be an efficient mechanism to control this invasive species. The specific controlled agents usually reduce the biomass development of the targeted species but do not eliminate it completely (Sousa, 2011). However, the introduction of biological treatment can cause consequences that can be more disastrous to the ecosystem, such as the propagation of new pests (Madsen, 1997; Mullin et al., 2000).

Chemical herbicides are mostly used for management of overgrowth of such weeds, but there is no surety given about its long-term sustainability. Diquat chemical herbicide affects the shoot portions of the plant but not to roots, rhizomes or tubers, requiring subsequent applications (Netherland, 1991). An aquatic herbicide named Fluridone requires very long exposure times but is effective at very low concentrations. The response of different plant species to different herbicides depends on properties of both the plant and the herbicide. The applicator also needs to match an herbicide with an appropriate concentration and exposure time relationship for the targeted species (Netherland, 1991). But it's hard to control or destroy the weeds.

Easley and Shirley (1974) suggested that the aquatic plants should be removed mechanically from water rather than destroying them by herbicides as it may deteriorate the weed quality and the quality of water as well. Hence, for restricting the rapid growth of such aquatic plants in drinking water bodies, mechanical removal is preferred (Langeland, 1996). The various mechanical methods used so far which include hand cutting/hand pulling, grinding, shredding, driver operated suction harvester and rotovating. Haller (2002) reported that mechanical harvesting provides immediate resolution of *H. verticillata* growth within 3-5 months. Hence using the automatic control on large lakes without the use of herbicides or other control methods is found to be costly with other constraints such as short-term effects, logistical constraints, etc. Harvesting may manage small initial populations, but the complete removal of the plant parts from the water and a proper disposal may face some limitations as the plant fragments can quickly start a new infestation.

A study by Doyle and Smart (2001) indicate that despite a yearlong drawdown, there was no significant decrease in the density of *H. verticillata*; means that lowering of water level will not work on its growth control. Evans and Wilkie (2010) reported the use of life cycle assessment approach to quantify significant energy, material and monetary flows associated with the mechanical harvest of *H. verticillata* and the subsequent use of harvested biomass for bioenergy and organic fertilizer production.

2.2.6 Possible utilization of *H. verticillata*

According to Edwards (1980), *H. verticillata* can be utilized for various purposes depending on the availability and requirement. The study on the process of drying has been applied on aquatic weeds (*Eichhornia crassipes*) and the factors such as combustibility, heat content, combustion efficiency and effect of moisture content has been studied on dried weed makes it suitable for fuel production (Tag El-Din, 1992).

However, this process requires a high investment in machinery, equipment and a large area for drying. Sun drying or direct burning found to be useful on a small scale in certain parts of the world. However, when it comes to the massive production of weed, incineration can be preferred. A compressed block of any combustible biomass material such as charcoal, sawdust, wood chips, peat, or paper used for fuel that helps to start a fire can also be called as a briquette. Briquetting would be an option for the treatment of the phytoremediation aquatic plants such as *H. verticillata*. It can be made from biomass of agriculture and marine waste and can act as the replacement for fossil fuels. It is widely used for cooking in many developing countries. Thomas and Eden (1990) reported briquette as a possible treatment for *E. crassipes*. The material resulting after briquette of *E. crassipes* has an energy density as 8.3 GJ m^{-3}, which is almost equal to that of the charcoal i.e. 9.6 GJ m^{-3}.

Hu et al. (2015) investigated the pyrolysis characteristics and kinetics of *H. verticillata* using non-isothermal thermo-gravimetric analysis. The activation energies ranged from 92.3 to 506.1 and 190.4 to 222.4 kJ mol^{-1} was observed. Abdalla and Hafeez (1969) suggested the use of *E. crassipes* ash as plant fertilizer. However, burning significantly reduces nitrogen and organic matter, which in turn reduces fertilization capacity of the plant. The biomass growth for *H. verticillata* is too robust. This property makes its application for the production of green manure, provided regular cleaning of water bodies is made prerequisite (Edwards, 1980; Lamsal et al., 2014). Few researchers (Burkill, 1935; Suwatabandhu, 1950; Varshney and Rzoska, 1976) suggested *H. verticillata* as the best source to convert into green manure. To reduce the shortage of animal feed, *H. verticillata* can be an option as a natural food. Burkill (1935), Varshney and Rzoska (1976) and Edwards (1980) reported a study in which *H. verticillata* can be used as cattle and pig fodder. A study carried out by (Hentges et al., 1972) on Bermuda grass, *Eichhornia crassipes* and *H. verticillata* reveals that *H. verticillata* can be fed to cattle as pelleted diets. Frank (1976) reported that *H. verticillata* is more palatable than *Eichhornia crassipes*. The high arsenic content of *H. verticillata* aquatic plants may be used for the making of charcoal, and the by-product gas can be utilized as a fuel (Srivastava et al., 2010).

Table 2.2. Biological and chemical control methods adopted by different sources

Sr. No.	Name of Agent	Place of study	References
Biological treatment			
1.	*Bagous hydrillae O'Brien*	Australia	Balciunas (1985)
2.	*Parapoynx diminutalis* Snellen	Florida Biological Control Laboratory	Buckingham and Bennett (1996)
3.	Biocar 405 and *Mycoleptodiscus terrestris (Gerd.) Ostazeski*	-	Shearer (1998)
4.	*Hydrellia pakistanae*	Quarantine laboratory, Florida	Buckingham et al. (1989)
5.	*Ctenopharyngodon idella Valenciennes*	Santee Cooper reservoirs, South Carolina	Kirk and Henderson (2006)
6.	*Cricotopus lebetis*	Florida's Crystal River watershed	Stratman et al. (2013)
Chemical treatment			
1.	Allelopathic Chemicals	Fort Lauderdale, Florida	Sutton (1983)
2.	Bensulfron methyl	Gainesville, Florida	Rattray et al. (1993)
3.	Fluridone	Withlacoochee River, Florida	Fox et al. (1994)
4.	Endothall, triclopyr and dichlobenil	New Zealand	Hofstra and Clayton (2001)
5.	Combination of Copper, diquat, or the mono salt of endothall dipotassium salt of endothall	Greenhouse aquariums Lewisville Aquatic Ecosystem Research Facility (LAERF), Lewisville, TX, USA	Pennington et al. (2001)
6.	Fluoridone	New Zealand	Hofstra and Clayton (2001)
7.	Fluridone and dipotassium salt of endothall	Lake Seminole, Georgia, Florida.	Maceina et al. (2004)
8.	Chitosan	Beijing China	Xu et al. (2007)
9.	Aquathol K (endothall)	Pinellas County, Florida	Beall and Swift (2008)

The *H. verticillata* also possess medicinal values along with other reported above potential values as green manure or fodder. The study by Pal and Nimse (2006) reported little-known uses of *H. verticillata* as a nutrient powerhouse that contains hundreds of enzymes. *H. verticillata* is considered to be the most valuable for vegetarian's individuals. It possesses Vitamin B12 and iron that are mostly supplied by animal foods (e.g., milk, cheese, meats). Pizzorno Jr and Murray (1990) reported more calcium in *H. verticillata* compare to any other whole food source on earth. It also contains beta-carotene, which aids in delivering more antioxidants, free radical scavenging, anti-aging and anti-pollution properties. The two biologically important novel natural products, i.e., outlines A and B, obtained from this weed exhibits potent antitumor properties (Araki et al., 2003). The consumption of processed dried *H. verticillata* revealed the strengthening in the immune system of the human body thus aid in maintaining blood sugar level (Pal and Nimse, 2006).

2.3 COMPOSTING

Composting is the biological decomposition and stabilization of organic substrates. It occurs under the condition that allows development of thermophilic temperatures (between 40 to 70°C) as result of biologically produced heat, to produce an end product that is bio stable, free from pathogens and plant seeds, and can be applied on land (Haug, 1993). Composting strongly depends on temperature. This exothermic process produces a large quantity of energy out of which 40-50% can be utilized by microorganisms to synthesize ATP and remaining energy lost as heat in mass. This heat causes an increase in temperature in mass. Another important parameter during composting is moisture content. Kalamdhad and Kazmi (2009) and Varma and Kalamdhad (2014) reported 50-65% moisture content as optimum whereas therein is controversy about range; as the moisture content of end product is solely depending on the type of substrate. For the survival of essential microorganism, aeration is must during composting to maintain the aerobic condition that can be achieved in many ways, which in turn depend on technology to be used. Composting involves following chemical reaction (Tchobanoglous et al., 1993):

$$\text{Organic waste} + O_2 + \text{nutrients} \rightarrow \text{New cells} + \text{Energy} + CO_2 + H_2O + \text{compost} + NH_3$$

From the chemical reaction, it is clear to provide aeration system to remove excess carbon dioxide, excess moisture and to inhibit heat accumulation. Degradation process involves changing in properties of organic materials, which in turn changes, as therein is fluctuation in other properties. Also, decomposition process causes to change in volume as well as the weight of material that lowers bulk density and thus limits microbial activity.

Composting not only influences physico-chemical or biological properties during the decomposition process, furthermore, it also reduces the concentration of heavy metals. Leaching of heavy metals is of more concern during composting of aquatic wastes as heavy metal assimilates in the weed through the contaminated water (Singh and Kalamdhad, 2012). Overviews of the various heavy metal (Zn, Cu, Ni, Cr, Cd, Pb, Fe, Mn) reduction techniques from the composting of different wastes have also been reported in studies (Singh and Kalamdhad, 2013; Singh et al., 2013). Several composting studies have been carried out on various substrates such as water hyacinth, vegetable wastes, cattle manure, poultry manure. These studies explained the stability of end product about biological parameters such as oxygen uptake rate (OUR) and carbon dioxide (CO_2) evolution rate and quality about physico-chemical properties such as moisture content, volatile solids, C/N ratio and heavy metals (Kalamdhad and Kazmi, 2009; Prasad et al., 2013; Singh et al., 2013; Nayak and Kalamdhad, 2014). The researchers have performed the composting studies using different composting technologies such as windrow composting, aerated pile composting, static pile composting, in-vessel composting, decentralized composting, vermicomposting (Mohee and Mudhoo, 2005, Khalil et al., 2008; Kalamdhad et al., 2009; Iqbal et al., 2010; Varma and Kalamdhad, 2014; Zhang and Sun, 2016). The studies revealed successful transformation of organic wastes into stable and quality end product. However, due to ever increasing wastes generation the time is the main constraint to manage such wastes. The conventional composting process (windrow composting, aerated pile composting, static pile composting) requires 90-270 days to produce stable and good quality compost, according to (Khalil et al., 2008). But the rotary drum composter, which is one kind of in-vessel composting process provides possible conditions to produce stabilized compost in just 20 days (Varma and Kalamdhad, 2014; Singh et al., 2016; Hazarika et al., 2017). It provides mixing and aeration of the waste organic matter, to produce a consistent and uniform compost of water hyacinth (Kalamdhad and Kazmi, 2009).

2.3.1 Types of composting

According to Haug (1993) the composting process can be achieved by the different methods as represented in Fig. 2.4

- ***Open process***
    - *Windrow process*

Piling of the biodegradable wastes in long rows refers as windrow composting. This method is most suited for large volumes of wastes. Using specific turners to improve aeration and porosity or to remove excess moisture content usually turns the windrows. The temperature of the windrows must be measured and logged constantly to determine the optimum time to turn them for quicker compost production. Typically, the shapes of the windrows are trapezoidal and size varies from 90 to 360 cm in height, and width from 300 to 600 cm. The time required to achieve good quality compost depends on type of wastes but usually it takes 90-270 days to complete the process. It is commonly used farm scale composting methods.

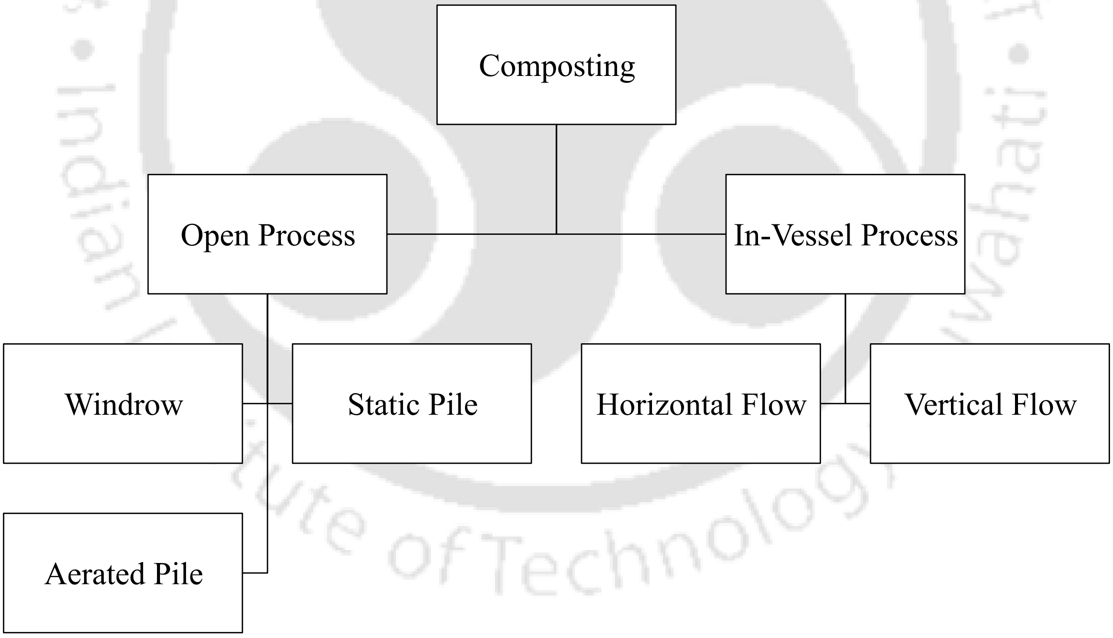


Fig. 2.4. Composting methods

- *Passive aerated pile*

Air is contributed to the composting feedstocks via perforated pipes inserted under each pile, thus eliminating the need for turning. The pipe ends are open.

The principal behind passive aerated pile that air flows into the perforated pipes and through the pile because of the chimney effect built as the hot gases rise upward out of the pile. The pile should be 90-120 cm high. The FAO (2003) reported the holes drilled in the pipes should be about 1.27 cm diameter. When the composting period is completed, the pipes are removed, and the base material is mixed with the compost. This method has been studied and used in Canada for composting seafood wastes with peat moss, manure slurries with peat moss, and solid manure with straw or wood shavings. The time required to achieve good quality compost depends on type of wastes but usually it takes 45-90 days to complete the process.

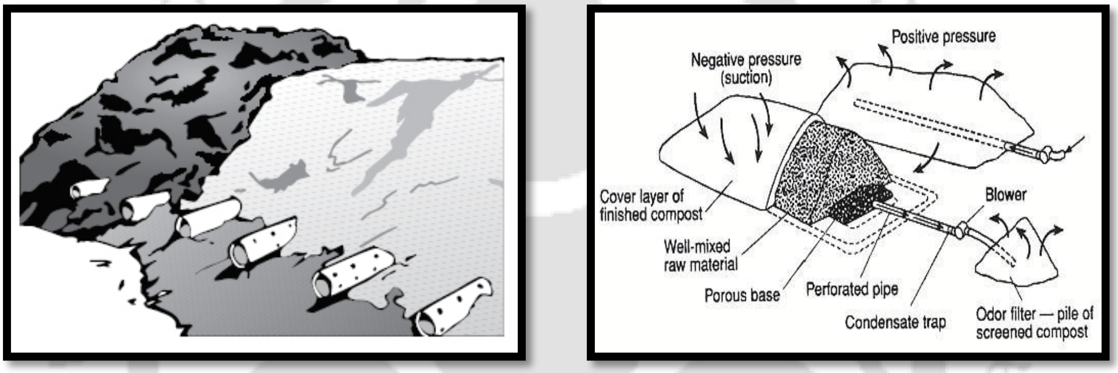
Fig. 2.5 Windrow Process

- *Active aerated pile*

In this type of composting method, the blended feedstock's is placed on the perforated piping's, and for air circulation pipes are connected to the blower. In large scale composting systems, force aeration is performed by the computerized monitoring system. Depending on the substrates porosity, environmental conditions the height of the aerated pile systems should be maintain between 150-245 cm whereas the width varies about 300-490 cm generally triangular in shape.

- ***In-vessel process***

In-vessel process refers to a group of methods that confine the composting materials within a container or vessel (NRAES, 1992). In-vessel methods rely on a different techniques to expedite the composting process. Wide variety of in-vessel methods either individual or with different combinations of vessels, aeration devices, and turning mechanisms utilized by many researchers in past. Most of the techniques were used to manage municipal solid waste, including final treatment of sewage biosolids, to a safe stable state for reclamation as a soil amendment. In general, in-vessel process are usually decentralized systems where small scale composting can be performed in batch or continuous modes.



a) Passive aerated pile b) Active aerated pile

Fig. 2.6. Pile composting (Rynk, 1992)

Horizontal and vertical reactors are commonly referred in-vessel systems. Vertical composting reactors (Fig. 2.7) are generally over 4 meters (yards) high, and can be housed in silos or other large structures. Waste is typically fed into the reactor from the top through a distribution mechanism, and it flows by gravity at the bottom. The height of these reactors makes process control difficult due to the high rates of airflow required per unit of distribution surface area. Neither temperature nor oxygen can be maintained at optimal levels throughout the reactors, leading to zones of non-optimal activity. Horizontal reactors avoid the high temperature, oxygen, and moisture gradients of vertical reactors by maintaining a short airflow pathway (Fig 2.7). Agitated systems usually use the turning process to move material through the system in a continuous mode, while static systems require a loading and unloading mechanism.

Materials handling equipment may also shred to a certain degree, exposing new surfaces for decomposition, but excessive shredding may also reduce porosity. Aeration systems are usually set in the floor of the reactor, and may use temperature and/or oxygen as control variables. Systems with agitation and bed depths less than two to three meters (yards) appear effective in dealing with the heterogeneity of MSW.

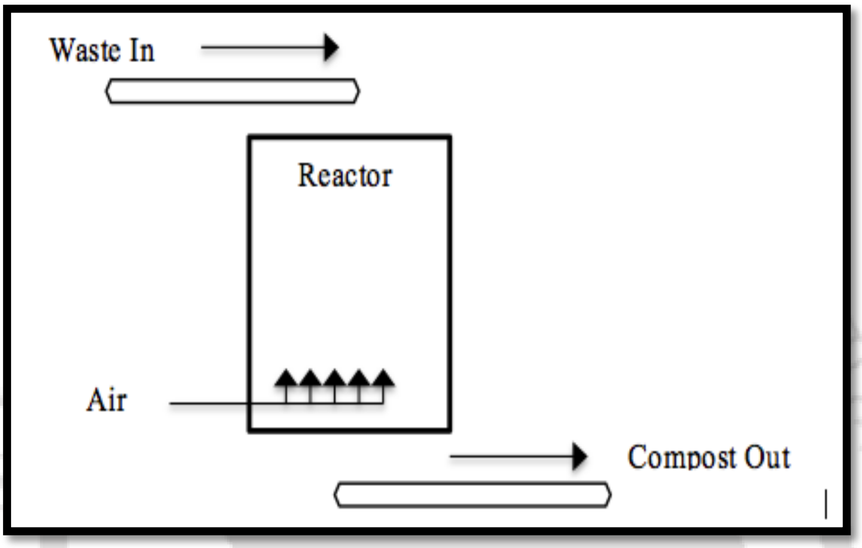


Fig. 2.7 Vertical Reactors

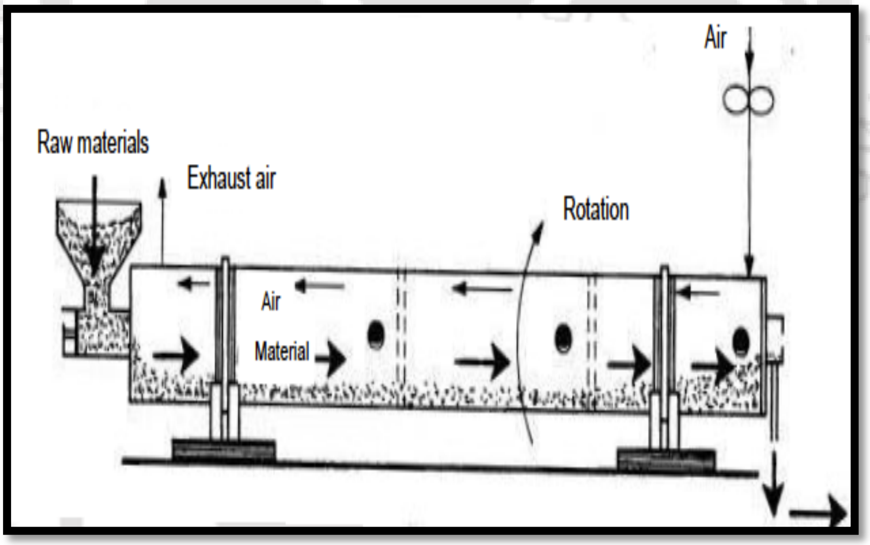


Fig.2.8 Rotary drum composter (Rynk, 1992)

An efficient and promising technique of decentralized composting is the rotary drum composter. Rotary drum provides agitation, aeration and mixing of the compost, to produce a consistent and uniform end product. The composting time is drastically reduced to 2–3 week. Rotary drum of medium sizes can also be placed at waste generation sites. Different types of waste (cow dung, swine manure, municipal bio-solids, brewery sludge, chicken litter, animal mortalities and food residuals) can be decomposed effectively in rotary drum.

Rotary drum (horizontal flow reactor) employs a bin of varying geometry and method of agitation. There are critical types of rotary drum, which differ in geometry, and method of agitation (Haug, 1993). The most extensively used type of rotary drum is Dano Drum. Dano Ltd. in Denmark developed it in 1933 for composting refuse. It dealt with high rate composting of municipal solid waste. However, information on operational aspects and compost dynamics for the mixed organic wastes in a rotary drum composter is rather limited.

2.3.2 Factors affecting composting

- ***Temperature***

In the consideration of temperature as an environmental factor, the interest is in the effect of temperature on the well-being and activities of the microbial population, rather than in the effect of microbial well-being and activity on temperature level. In short, environmentally oriented interest is on the effect of temperature on microbial well-being and activity; whereas operationally oriented interest is on the effect of microbes on temperature.

A straight-line relationship exists in terms of increase in process efficiency and speed and rise in temperature because of the overlapping of optimum temperatures at levels lower than 30°C.The slope of a curve showing efficiency or speed of the process as a function of temperature would flatten somewhat between 35 and 55°C, perhaps with some decline between 50 and 55°C.The existence of an activity plateau at the transition from the mesophilic range to the thermophilic range is due not only to the involvement of many types of organisms but also to adaptation of organisms or enrichment for organisms adapted to a given range. As the temperature rises above 55°C, efficiency and speed drop and are negligible at temperatures above 70°C. At temperatures higher than 65°C, spore formers rapidly enter the spore stage and, as such, are dormant. Most nonspore formers die off.

- ***Moisture content***

Theoretically, the optimum moisture content of the wastes is one that approaches saturation, provided that the material can be sufficiently aerated to meet the oxygen demand. Although meeting the demand is technologically feasible, it also is economically unfeasible. Hence, the term permissible maximum is introduced. It is the moisture content above, which oxygen availability becomes inadequate and anaerobiosis ensues. The maximum permissible moisture content usually is also the optimum content.

Because the air entrapped in interstices between particles is the primary source of oxygen for the microbial population, interstitial ("pore") volume is a decisive factor (i.e., the more numerous the pores the greater the interstitial volume). Hence, porosity is a key consideration. The relation to moisture stems from the fact that the greater the fraction of the pore volume occupied by water, the less is the volume available for air and hence for oxygen

- ***Carbon: nitrogen ratio***

The available carbon to available nitrogen ratio (C/N) is the most important of the nutritional factors, in as much as experience shows that most organic wastes contain the other nutrients in the required amounts and ratios for composting. The ideal ratio is about 20 to 25 parts of available carbon to 1 of available nitrogen. A C/N higher than 20/1 or 30/1 can slow the compost process. A C/N that is too low (less than 15/1 to 20/1) leads to loss of nitrogen as ammonium N. The addition of a nitrogenous waste can lower an unfavorably high C/N, whereas the addition of a carbonaceous waste can raise an undesirably low C/N. Examples of nitrogenous wastes are grass clippings, green vegetation, food wastes, sewage sludge, and commercial chemical fertilizers.

- ***Aeration rate***

Oxygen availability is a prime environmental factor in composting, inasmuch as composting is an aerobic process. Oxygen is a key element in the respiratory and metabolic activities of microbes. Interruption in the availability leads to a shunt metabolism, the products of which are reduced intermediates, which characteristically are malodorous. The microbes involved in the composting process obtain their oxygen from the air with which they come in contact (i.e., the air that impinges upon them). Consequently, the oxygen content of this air must be continually replenished or the air itself must be continually replaced. The interstitial oxygen content in a windrow can be estimated by use of an oxygen probe inserted into the windrow. The oxygen content of the airstream into and out of a static windrow (forced aeration) and in-vessel systems can be directly measured. For convenience, the amount of oxygen required by the microbes is termed "oxygen demand."

- ***pH***

The optimum pH range for most bacteria is between 6.0 and 7.5, whereas the optimum for fungi is 5.5 to 8.0. Precipitation of essential nutrients out of solution rather than inhibition due to pH per se establishes the upper pH limit for many fungi. In practice, little should be done to adjust the pH level of the composting mass. Owing to the activity of acid-forming bacteria, the pH level generally begins to drop during the initial stages of the compost process. These bacteria break down complex carbonaceous materials (polysaccharides and cellulose) to organic acid intermediates. Some acid formation may also occur in localized anaerobic zones. Some may be due to the accumulation of intermediates formed by shunt metabolisms. Shunt metabolism may be triggered by an abundance of carbonaceous substrate and/or perhaps by interfering environmental conditions.Whatever the cause, the early pH drop in composting MSW may be to 4.5 or 5.0. The drop could well be lower with other wastes.

- ***Particle sizes***

Theoretically, the smaller the particle size, the more rapid the rate of microbial attack. In practical composting, however, there is a minimum size below which it is exceedingly difficult to maintain an adequate porosity in a composting mass. This size is the “minimum particle size” of the waste material. In composting, the practical “optimum” is a function of the physical nature of the waste material. With a rigid or not readily compacted material such as fibrous waste, twigs, prunings, and corn stover, the suitable size is from 1⁄2 in (13 mm) to about 2 in (50 mm).The particle size of the greater part of a fresh green plant mass such as vegetable wastes, fruits, and lawn clippings should be no less than 2 in (50 mm). On the other hand, depending upon their overall decomposability, their maximum particle size can be as large as 6 in (0.15 m) or even larger.

2.3.3 Pecularities of *H. verticillata* as a compost feedstock

Use of aquatic macrophytes as compost substrates are found to be the most promising method since very less drying is required and is easier to transport as the compost plant can be installed at shores of water bodies. Composting can be defined as the biological decomposition and stabilization of organic substrates. It is carried out under the controlled environment that allows the development of thermophilic temperatures as a result of the biologically produced heat.

The final stable product that is free from pathogens and plant seeds and is beneficial when applied to land (Haug, 1993). It does not require chemicals or mechanical devices and can be a suitable option for developing countries where commercial fertilizers are too expensive (Ruskin and Shipley, 1976). Wile et al., 1978 reported the study on the use of Eurasian watermilfoil as a substrate for composting. Mitra and Banerjee (1976) conducted the lab-scale study on aquatic weeds such as water hyacinth, *Spirodela polyrrhiza*. Another study by Singh and Kalamdhad (2013) reported the water hyacinth as the substrate for rotary drum composting. They used phumdi biomass and Salvinia natans as a substrate for composting, which was collected from Lok Tak Lake in Manipur, India, respectively. Dalzell et al. (1981) and Elserafy et al. (1980) reported the optimal moisture content of about 60% is required for the composting process. Studies have been reported on compost of *Eichhornia crassipes* (Singh et al., 2012) and it has been found that use of *Eichhornia crassipes* as compost substrate has many advantages. It has positive effects on crop growth, and the huge population of aquatic weed can be managed and utilized positively. Aquatic weeds are usually characterized by a comparatively low carbon to nitrogen (C/N) ratio. Additionally, such aquatic weeds biomass typically has higher moisture content and, for aquatic weeds grown in marine or brackish environments, high salinity (Mendo et al., 2006). Aquatic weeds can also have higher metals content and mostly associated possess harmful toxins. The physical and chemical characteristics of *H. verticillata* to be stabilized by composting are summarized in Table 2.1. These aspects and the role they play in the composting process as discussed below.

- ***Carbon to nitrogen (C/N) ratio***

The C/N ratio of the organic substrate to be composted is essential as it impacts the microbial activity, quality and nutritional value of end product. According to Abbasi et al. (1990), the C/N ratio of *H. verticillata* was 10-14. The substrate with a low initial C/N ratio decomposes rapidly but consequently can cause nitrogen loss via ammonia NH_3 volatilization, which leads to wastage of essential nutrients and the causes unwanted odors generation (Haug, 1993). It is suggested that compost feedstock have an initial C/N ratio of at least 30 (Haug, 1993; An et al., 2012), which is the case for the seaweed *Posidonia oceanica*, (C/N of 36 (leaves) and 81 (fibres) (Cocozza et al., 2011). The C/N ratio declines with progression in the aerobic decomposition of organic matter and a final C/N ratio around 15 is recommended for the end product (compost).

- ***Moisture content***

The moisture content in organic substrates to be composted is a crucial parameter. It affects biological activity as well as the physical structure and thus has a central effect on the biodegradation of organic substrates (Ahn et al., 2008). It has been narrated that microbial activity is suppressed when moisture content decreases below 25%, and the aeration can be limited when the moisture content is more than 70% (Rodriguez et al., 1995). Most organic substrates are best when composted in moisture content from 50 to 70%, while some other materials can be composted efficiently outside this range (about 25–80% on a wet basis) (Richard et al., 2002; Cronjé et al., 2004). Typical values of the moisture content of *H. verticillata* are 92%, 87.03% and 85–95% that are given by (Boyd, 1969; Abbasi and Chari, 2008; Meier et al., 2014).

- ***Nutrient availability***

As shown in Table 2.1 the species *H. verticillata* is composed of essential nutrients in enormous quantity. The composts prepared from *H. verticillata* can be beneficial if applied as a soil conditioner. Colle and Shireman (1980) determined the crude protein of water hyacinth and *H. verticillata* from a wide variety of environmental conditions. The study by Shah et al. (2010) reported 13.3 and 17.1% of crude fiber and protein, respectively. It was found that the maximum nitrogen and phosphorus content of *H. verticillata* is 3.3% and 0.7%, respectively of the dry weight of plant materials (Spencer et al., 1997). *H. verticillata* can store phosphorus for the longer duration when the phosphorus resources are limited. Other essential macronutrients that were found in H. verticillata were magnesium, calcium, and potassium and observed to be 0.9, 4.5 and 2.9%. This nutrients availability aid in improving growth and cultivation of plants when utilized as organic fertilizer.

2.4 COMPOSTING PHYSICS OR PHYSICAL PROPERTIES

To design a material processing or handling system, it is important to have information on the nature of the materials involved and how the characteristics of the materials affect the process and the components of the system. In the case of compost production, this information demands an understanding of the process as well as the physical means of facilitating the process. A useful description of how physical and biological parameters are brought together in the design of composting systems is provided by Keener et al. (1993) in their description of design optimization.

Composting physics or physical properties play a major role in every stage of compost production as well as the managing and application of the end product. Properties such as bulk density; porosity, air-filled porosity, and moisture content principle the requirements for the optimal composting environment. To keep microorganism active, it is important to monitor and to provide optimum air and water during the process (Agnew and Leonard, 2003). Author further states that sufficient amount of moisture is required for microbial transport and nutrition. To support the metabolic processes of microbes, water plays an important role that is produced by and required for microbial activity (Baeta-Hall et al., 2005). Water is the medium for the transports nutrients, chemical reactions and allows the microbes to move about (Rynk, 1992). A range of moisture content reported by Jeris and Regan (1973) is 40–65% with a preferred range of 50–60% at the start of composting. The continuity of voids is also an important factor since this influences how easily air and water will flow through the material (Rynk, 1992). The heat and mass transport processes and therefore microbial kinetics in an organic compost matrix were influenced by free air space (Jeris and Regan, 1973; Miller, 1991; Haug, 1993). Bulk density was proving to be precious physical property as it determines power requirements for turning or mixing of wastes. According to Iqbal et al. (2010), a physical parameter holds a healthy relationship between each other, i.e., a small variation in one parameter may cause adverse effects on an additional parameter and thus degradation process would be compromised.

2.4.1 Important physical parameters

- ***Moisture content***

Decomposition of substrates can be evaluated by the loss of moisture content, as a result of heat generation during the composting process (Kalamdhad et al., 2009). Excess moisture content inhibits the aeration process by clogging pores, whereas insufficient moisture content arrests biological process, thus producing unstable compost (de Bertoldi et al., 1983). Moisture content is an essential parameter that influences the changes in physical, chemical, and biological properties of waste materials during the advancement of decomposition of organic matter. The moisture is required to supply a suitable environment for the microbial population growth. The optimum moisture content needed for composting process must be between 40-60% (Haug, 1993; Nelson et al., 2006). However, it depends on the physical structure of substrate (Venglovsky et al., 2005; Kim, 2016).

- ***Bulk density***

Bulk density is the critical parameter that optimizes composting process, as it determines optimal conditions for microbial development, microbial activity, and organic matter degradation. Bulk density depends on texture, densities, organic matter and the packing arrangement of material. Evaluation of bulk density roughly provides degradation process of organic matter that can be seen from the volume of the mass under composting and its reduction during the process (Breitenbeck and Schellinger, 2004; Larney et al., 2000). Bulk density during composting is generally affected by moisture content, ash content, particle size distribution, and decomposition. The particle size plays a significant role in the increase in the bulk density. The study performed on different particle size fractions of municipal solid waste compost revealed that if the particle size of wastes decreases the bulk density of the composting mixture increases during the process (Zhao et al., 2011).

- ***Free air space***

Free air space (FAS) is defined, as the ratio of the volume of air to the total volume of compost and it is a physical parameter that plays an important role maintaining favorable aerobic conditions. It helps to determine the path of air inside the compost, the quantity of air, carbon dioxide, moisture, and heat removal etc. from the process. It is a key factor in determining the magnitude and movement of air through the composting mix. The literature reported the FAS values are as high as 85–90% without significant adverse effect to compost mix. It should be present more than 30% for proper aeration during composting process.

- ***Porosity***

Geometry, size, and distribution of pores and the composition of composting material significantly affect the transport of mass and heat in compost matrix (van Ginkel et al., 1999). Hence, information on spatial distribution of porosity is very much of importance. Porosity provides the information on requirements for the optimum composting environment (Agnew and Leonard, 2003). Evolution of microorganism depends on the availability of oxygen, which is present between the spaces among particle. Spaces between these particles in compost mix are referred as porosity. Composting process turns out to be slower when the material becomes saturated with water, resulting in the decrease of air between spaces.

- ***Particle density***

Particle density is defined as the average density of all the minerals that compost consists. Particle density depends on the nature and density of materials, which make the individual soil particles and plays a significant role to determine the physical properties such as bulk density and porosity.

2.4.2 Relationship between different physical parameters

The parameters such as porosity, bulk density, free air space and moisture content are interrelated and influence biological decomposition and also on heat and mass transfer during the composting process (such as air supply, water evaporation, and heat balance) (Huet et al., 2012). According to Iqbal et al. (2010), a physical parameter holds a healthy relationship between each other, i.e., a small variation in one parameter may cause adverse effects on an additional parameter and thus degradation process would be compromised. Some of the keys physical parameters that contribute to the composting process are bulk density, porosity, moisture content, and free air space. Bulk density is defined as the ratio of the total weight (mass) of compost to its volume and expressed as kilograms per cubic meter (kg m^{-3}). For the ease of storage and transport of compost, bulk density is considered as an important parameter. It can be mathematically expressed as

$$\text{Wet Bulk Density} = \gamma_{wet} = \frac{W_{wet}}{V_{wet}} \tag{2.1}$$

$$\text{Dry Bulk Density} = \gamma_{d} = \frac{\gamma_{wet}}{1+\omega_{wet}} \tag{2.2}$$

where, W_{wet} = weight of wet compost; V_{wet} = Volume of wet compost; ω_{wet} = wet moisture content of compost to be analyzed.

Distribution of air within the compost mix is a major factor that can be maintained by porosity. Porosity and free air space can be expressed in terms of bulk density and moisture content, and mathematically expressed as

$$\text{Porosity} = \eta = 1 - \frac{\gamma_{wet}}{g \times \gamma_{w}(1+\omega_{wet})} \tag{2.3}$$

$$\text{Free Air Space} = 1 - \frac{\gamma_{wet}}{g \times \gamma_{w}(1+\omega_{wet})}(1 + g \times \omega_{wet}) \tag{2.4}$$

where g = specific gravity; γ_{w} = bulk density of water

2.4.3 Past studies on determination of physical parameters

Agnew and Leonard (2003) have provided the detailed literature review on physical properties of compost. According to the authors the compost production, handling and its utilization requires complete understanding of the process, involvement of raw materials and their physical properties. The study indicated that these properties influences the process and the product in various ways from aeration effectiveness to compost-soil interactions. The study concluded that there is lack of specific standards for describing and measuring compost physical properties.

Mohee and Mudhoo (2005) have determined the physical properties during composting of vegetable wastes mixed with chicken manure and wood chips. The study was conducted using 200-L capacity in-vessel containers. The authors have studied various physical properties that include temperature, moisture content, porosity, bulk density and particle density. The study has reported increase in the bulk density from 255 to 628 kg m^{-3} whereas the decrease was observed in the free air space and porosity with composting period. The study concluded that free air space varied linearly with dry (R^2 = 0.89) and wet bulk densities (R^2 = 0.95). Therefore, the study indicated strong relationship between the physical properties.

Iqbal et al. (2010) have studied the physical properties of various bulking agents (bagass, paper, peanut shell and sawdust) to be added for composting of municipal solid wastes (MSW). The main objective of the study was to quantify MSW generation in study area in summer and winter season and to assess the effect of different percentage of bulking agents on moisture reduction and free air space in composting matrix. Moreover, the dry bulk density of the bulking agents was determined by using four different levels of compression forces. The study concluded indicating 40% addition of sawdust was the best to optimize 60% moisture content in composting process. The studies results also concluded that bulk density, and free air space are simple and useful tools to determine composting period and its cost.

Huerta-Pujol et al. (2010) has demonstrated the study on relationship between the bulk density and the composting process development. The moisture content, total organic matter, wet and dry bulk densities were determined during the composting process. Total of 114 samples were determined for the above-mentioned properties. The study results showed the increase in the dry bulk density with the decreased total organic matter as a result of biological activity. The study has concluded that bulk density is simple and important tool to determine composting process.

Chowdhury et al. (2014a) studied prediction of changes in physical properties such as moisture content, bulk density, particle density and air-filled porosity during composting of separated animal slurry fractions. The study was performed in lab-scale reactors for 30-days under forced aeration. The sampling was performed after every 10 days interval during composting. The study results showed development of thermophilic phase (40- 70°C) within 7 days. Maximum reduction of 37% was observed in moisture content after 30 days of composting process. Particle density was estimated using loss of ignition data estimated as particle density of 1441 kg m^{-3} for volatile solids and 2625 kg m^{-3} for fixed solids. The authors concluded the existence of linear relationship between wet bulk density and air-filled porosity.

Zhang and Sun (2016) have performed two-stage composting of green wastes in cement containers. The green wastes (i.e.. grass, fallen leaves and branch cuttings) were mixed different bulking agents (i.e., wood chips and composted green wastes). The study was performed for total period of 30 days and physical, chemical and microbiological properties were evaluated. The study results showed best quality compost after the addition of combined wood chips and composted green wastes compared to individual addition of materials. The combined addition of bulking agents not only improved nutritional properties of end product but also improved aeration, water retention and cation exchange capacities.

From the past studies it is observed that very few studies have explained the insight of physical properties during the composting process. There are no specific standards for the physical properties. The studies that have investigated about variation in physical properties such as bulk density, free air space, porosity, particle density, moisture content, temperature, during *H.verticillata* composting, and other wastes viz. water hyacinth, vegetable wastes, sewage and solid pulp and paper mill sludge using rotary drum composter is still unclear. Moreover, none of the studies evaluated physical parameters using rotary drum composter.

2.5 ROLE OF CARBON-RICH AMENDMENTS DURING COMPOSTING

2.5.1 Locally available agents

Carbon-rich agents are utilized primarily to absorb an excess moisture content produced during the composting process. Addition of carbon-rich agents maintains carbon: nitrogen ratios in the feedstock. It enhances microbial activity and improves water penetration. Addition of carbon-rich agents also adjusts the porosity of the material to be composted and thus improves overall aeration as well as water penetration (Shao et al., 2014). Several research studies have been carried out on the effect of bulking agents during composting of various types of sludges (sewage and industrial sludge) using different composting methods (Dias et al.,2010, Uçaroğlu et al., 2016). A study was also performed to evaluate effects of carbon-rich agents on municipal wastes and animal manures composting (Adhikari et al., 2010). The earlier research studies demonstrated effects of carbon-rich agents on either biological or chemical properties or gaseous emissions. Few studies have utilized dry leaves, grass clippings, and wood chips as locally available carbon-rich agents during composting of various organic wastes.

The study conducted on composting of cattle manure added with wood chips has reported a more significant reduction in moisture content and reduced nutrient losses (Kato and Miura, 2008). The studies also demonstrate better compost quality after the utilization of woody residues (Vandecasteele et al., 2013; Koivula et al., 2004). Similarly, the studies by Varma et al. (2014) and Kalamdhad et al. (2009) indicated overall improvement in nutritional parameters during composting of raw vegetable wastes that possess higher (88-92%) moisture content. The researchers further stated that the addition of dry leaves aid to reduce the moisture content and was observed within the range of 50-60% in the final product. According to Haug (1993), the recommended range of moisture content must be between 40-65%.

Grass clippings are considered as the solid waste in the environment. The number of such residues has increased rapidly due to the development of urban green spaces in many countries (Zhang and Sun, 2014). Grass clippings possess a moderate amount of moisture content and lower bulk density (López et al., 2010). The composting process is a suitable technique to recycle grass clippings by adding it with the other organic wastes that possess higher moisture content. A very recent study by Oviedo-Ocaña et al. (2017) reported utilization of grass clippings during composting of unprocessed and processed food wastes. The authors further stated grass clippings aid in maintaining thermophilic temperatures for more extended periods, which is essential for standard sanitization of the materials (Haug, 1993). These various carbon-rich agents has been utilized for other organic wastes; however, its effect on composting of *H. verticillata* is still unclear. Performance of these locally available carbon-rich agents on physical properties are still unclear.

2.5.2 Past studies on amendment of locally available carbon-rich agents

Eftoda and McCartney (2004) have composted municipal bio-solids amended with wood chips as a carbon-rich agent. Municipal bio-solids are known for very less free air space within the solids thus affecting degradation processes. Therefore, authors have conducted the study on requirement of wood chips to achieve better air space within the solids for better decomposition.

The study was performed in four volumetric ratios of wood chips and municipal bio-solids ranging from 1:1 to 4:1. In this study only physical parameters (total air space and free air space) were evaluated during composting process in the windrow pile. The authors have also investigated maturity, fecal coliforms density, salmonella availability and presence of total heavy metals at the end of the run. The results suggested to achieve optimum FAS > 20% and a minimum pore space oxygen content >5%, the ratios were estimated as 2.5:1 and 2.8:1 (woodchips: biosolids, vol:vol). However, the study indicated no evolvement of thermophilic temperatures during composting of municipal bio-solids but better improvement in free air space and pore space.

Adhikari et al. (2008) have conducted the study on composing of food wastes mixed with various locally available bulking agents viz. chopped hay, chopped wheat straw, pine wood shavings, and cardboards. The authors studied various physico-chemical properties that include pH, total Kjeldahl nitrogen, moisture content, C/N ratio etc. The main objective of the study was to quantify the amount of food wastes produced by Montreal households and the restaurants. The study concluded that the chopped wheat straw and hay were the best bulking agents to be added for composting of food wastes as it increases water absorption capacity of over 500%, a neutral pH and the balanced carbon: nitrogen ratio.

Dhal et al. (2012) composted water hyacinth (a dominant aquatic weed) mixed with cow dung and two different types of locally available carbon-rich agents (saw dust and rice straw). Overall six different trials (three trial for each type of carbon-rich agents) were prepared and composted using pile composting method. The physico-chemical analyses were investigated in this study. The results of the study indicated better higher temperatures with higher amount of water hyacinth amended with both carbon-rich agents. The lower pH values were also observed for higher amount of water hyacinth amended with both carbon-rich agents. But the data suggested the better results for composting of water hyacinth with rice straw due to higher nutrients concentration. However, the moisture reduction was prominent for the composting of water hyacinth with saw dust compared to rice straw.

Varma et al. (2014) have performed the study on composting of vegetable wastes added with cattle manure and saw dust. But still due to higher amount of moisture content additional bulking agent, i.e., dry leaves were added in five different trials in 550 L rotary drum composter. The authors reported that addition of dry leaves provided better aeration and decomposition.

Leachate production was not observed in the trials, which was amended with dry leaves. Additionally amendment of dry leaves also aid in achieving higher temperatures for longer duration that benefitted in reduction of harmful pathogens. The quality of end product was observed to be superior with higher TKN (3%), and total phosphorus (3.2%). The study concluded that the addition of bulking agents is essential to maintain carbon: nitrogen ratio as well as to achieve better reduction in moisture content along with higher nutrients concentration.

Zhang and Sun (2016) have performed two-stage composting of green wastes in cement containers. The green wastes (i.e.. grass, fallen leaves and branch cuttings) were mixed different bulking agents (i.e., wood chips and composted green wastes). The study was performed for total period of 30 days and physical, chemical and microbiological properties were evaluated. The study results showed best quality compost after the addition of combined wood chips and composted green wastes compared to individual addition of materials. The combined addition of bulking agents not only improved nutritional properties of end product but also improved aeration, water retention and cation exchange capacities.

A very recent study by **Oviedo-Ocaña et al. (2017)** on composting of processed food and unprocessed food wastes added with grass clippings were conducted in three different treatments. The study has monitored the process itself and the end quality of the product. The data suggested the combination of processed and unprocessed food wastes in the ratio 3:2 with grass clippings were observed to be the best. This particular ratio has reached thermophilic temperatures within shorter period of time and improved compost quality was observed compared to other treatments. The study indicated lower EC values and ash content. Further, authors have reported fertiliity index of compost between 4.8-5.0 that suggests the compost is suitable for agricultural use.

It is found from the vast literature studies that not a single study is available on utilization of locally carbon-rich agents during composting of *H. verticillata.* Moreover, the literatures are also deficit with the study on effect of locally carbon-rich agents on the physical parameters during rotary drum composting of *H. verticillata*.

2.5.3 Role of biochar

Biochar is a carbonaceous material that is obtained after the pyrolysis of woody biomass in temperature ranges of 400-900°C under depleting oxygen conditions (Ahmad et al., 2014; Weidner et al., 2015;). The Biochar has got the wider attention due to its positive impacts to alleviate the numerous environmental problems such as degraded soil quality, discharge of greenhouse gases, accumulation of carbon-di-oxide in the environment, and disposal of organic wastes (Hussain et al., 2016; Godlewska et al., 2017; Xiao et al., 2017;).

One of Biochar advantages, especially in the context of current research, is its capacity to absorb excess moisture content, mitigation of nitrogen loss, improved organic matter degradation, improved porosity, free air space and heavy metals reduction during the composting of organic wastes. Due to properties such as higher content of organic carbon with larger specific surface area, diverse functional groups and greater affinity to adsorb inorganic as well as organic contaminants (Sánchez-García et al., 2015; Stefaniuk et al., 2016; Awasthi et al., 2016; Liu et al., 2017).

Till date numerous research have been performed on application of biochar during composting of various organic wastes and found to be very promising. Liu et al. (2017) evaluated the amendment of biochar for composting of sewage sludge and indicated mitigation of N-losses along with lead and arsenic reduction within 31 days. The composting of sewage sludge amended with 12% biochar exhibited reduction in green house gas emission such as methane and other gases, i.e., ammonia and N_2O (Awasthi et al., 2016). The research on composting of chicken manure amended with biochar exhibited good performance for waste degradation with improved organic matter degradation rate and microbial reproduction (Liu et al., 2017). The researcher also carried out composting of poultry manure amended with bamboo biochar that exhibited increase in the porosity, air permeability and reduction in methane emission (Liu et al., 2017). Another study on composting of poultry manure with barley straw indicated rapid organic matter degradation rate and favored nitrogen mineralization due to addition of 3% biochar (Sánchez-García et al., 2015). It was observed that most of the studies were carried out on composting of different manures, sewage sludge or agricultural wastes. But, there are no such studies on application of biochar during composting of nitrogen-rich aquatic weed that is present considerably in the ecology.

2.5.4 Past studies on amendment of biochar as a carbon-rich agents

Chowdhury et al. (2014b) has performed composting of solids separated from anaerobically digested animal manure amended with different bulking agents including biochar. The study was conducted in small-scale laboratory composter for 28 days. Biochar was mixed with digested sludge in the ratio 1:3 and 1:6. The study reported maximum emission of methane gas during the thermophilic phase with little effect on N_2O emissions. Biochar was also found to be favorable for the reduction of cumulative NH_3-N losses. The study has concluded the addition of biochar during composting of digested sludge aid in reducing total green house gases.

Sánchez-García et al. (2015) conducted composting study on poultry manure with barley straw. The authors have prepared two mixtures (i) control comprising of 78% poultry manure and 22% barley straw (dry weight) and (ii) same mixture were added with (3%) biochar dry weight. The study was carried out using windrow method for 19 weeks and the results were compared between the two treatments for physico-chemical parameters, gaseous emissions (CO_2, CH_4, N_2O, and H_2S) and agronomic properties. The results of this study suggests that the biochar addition improved overall physical properties and prevented clumps formation.

It also favored microbial activities without negative effect on N losses and gaseous emissions. The study concluded that 3% biochar addition for composting of poultry manure has reduced the time required for the process by 20%.

López-Cano et al. (2016) has reported the beneficial effects of biochar during composting of low nitrogen wastes (such as olive mill wastes). Composting was carried was out using pile method. Two treatments were prepared (i) a control comprised of olive mill waste 46% + sheep manure 54% (dry weight) and in the other the same mixture was treated with addition of biochar (4%). The duration of composting process was 31 weeks. The results of the study indicated the increase in the concentration of NO_3^- in the final product with reduction in nitrogen loss by 3.2 kg of nitrogen per ton of treated wastes with biochar compared to control. Moreover, biochar did not increase the amount of N_2O, methane and carbon-di-oxide. Biochar addition not also affected the nutrients and heavy metals concentration.

Janczak et al. (2017) have composted mixture of poultry manure (nitrogen-rich waste) & wheat straw in the ratio 1:0.4 on wet weight basis. The same mixture was treated with different amounts of biochar (5 and 10%). The impact of biochar was studied on total ammonia emissions (gaseous and liquid emissions). Total 42 days composting study was conducted in 165 L composting reactors. The study has concluded positive effect of biochar addition during composting of mixture of poultry manure & wheat straw as compared to that without addition. The authors have reported that due to the better sorption capacity of biochar the ammonification process became slower thereby reducing nitrogen loss during the process. The authors also have correlated differences in gas ammonia emissions with the dose of biochar which indicated that the addition of biochar did not affected the NH_4-N concentration in condensate or leachate.

Liu et al. (2017) has studied the impact of biochar on nitrogen transformation and heavy metals in sludge composting. The different percentages of biochar were added (0, 1, 3, 5 and 7%) to the mixture of sludge, straw and microbial agents, respectively. The study was performed for 31 days using pile method. Seven different total heavy metals (Pb, Ni, Cu, Zn, As, Cr and Cd) were considered for this study along with study in variation of total nitrogen, nitrate and ammonia emission and temperature and pH. The study reported that the addition of biochar resulted in the increase in the thermophilic temperature (70°C) and also resulted in pH between 6.5-7 in most of the treatment except for 0 and 1% biochar addition. The biochar addition also resulted in reduction of N losses during composting.

It also aid in reducing the availability of heavy metals in the end product particularly lead and arsenic. Overall considering all the parameters biochar with 5% addition was found to be best in sludge composting.

It is found from the past studies that most of the biochar addition studies were conducted on composting of different manures and sewage sludge. During these studies the physico-chemical, gaseous emissions, and total heavy metals were analyzed. However, rarely aquatic weeds (nitrogen-rich wastes) were treated using biochar. Moreover, the literatures are deficit with the study on role of biochar as a carbon-rich agent on the physical parameters during rotary drum composting of *H.verticillata*.

2.6 LACK OF SOIL FERTILITY AND COMPOST APPLICATION

The two soil deposits (alluvial and laterite) are mostly found in the Northeastern region of India (Singnar and Sil, 2018). The alluvial soil is generally characterized as the coarse-size textured soil due to the more significant amount of sand and little amounts of fine particles of silt and clay (Das et al., 2018). These soils are replenished continuously from the origin due to recurrent floods and become weak and immature (Yadav et al., 2000). It is rich in minerals such as potash and other chemical compounds such as phosphoric acid as well as alkalies. But the nitrogen content of the alluvial soil is very low (Amossé et al., 2015). In addition to the above, due to the presence of a more considerable amount of sandy particles the water holding capacity and cation-exchange capacity of the alluvial soil is very low which is not beneficial for agriculture purposes. On the other hand, the laterite soil, which is red due to the presence of iron oxide, is typically characterized as the sandy soil (Dwevedi et al., 2017). The soil nature of soil generally indicates higher cation-exchange capacity and water holding capacity (Ko, 2014). According to Dwevedi et al. (2017), the laterite soil possesses a lower content of nitrogen, phosphorus, potassium, lime, and magnesia due to which it lacks fertility (Byju et al., 2015). But the presence of 90–100% of iron, aluminum, titanium, and manganese oxides the laterite soil makes it valuable source as a building material (Anifowose, 2000). Soil fertility and soil quality can be explained by the availability of the major nutrients viz. nitrogen (N), phosphorus (P) and potassium (K). Chemical fertilizer has provided these nutrients to the soil but the long-term application has also shown negative impacts on physical and nutritional properties of soil (Rasool et al., 2008; Nayak et al., 2012) and has shown an increase in the concentration of heavy metals in soil (Rascio and Navari-Izzo, 2011).

Therefore, there is a dire need to change existing practice of using chemical fertilizer to improve the overall soil health. Previous studies suggest that amendment of organic manure or compost is the best option to improve soil physical, nutritional and sorption characteristics (Aggelides and Londra, 2000; Głąb et al., 2018).

Compost application nourishes soil by increasing its nutrients levels and soil organic matter. It also benefits the soil by improving physical properties such as bulk density, porosity, water holding capacity, cation-exchange capacity and other chemicals as well as biological properties (Weber et al., 2007; Curtis and Claassen, 2009; Tits et al., 2014). Compost application also reduces financial issues (purchasing of chemical fertilizers) and can decrease the environmental impact associated with fertilizer production and utilization. Compost prepared from various organic wastes has been applied to the soil that has shown significant positive effects on overall soil health (Vandecasteele et al., 2014; D'Hose et al., 2014; Goswami et al., 2017; Ren et al., 2018). For instance, Willekens et al. (2014) indicated an increase in the available potassium contents in the soil after the application of the compost. Compost application has also benefitted the soil by avoiding the nutrient leaching in the groundwater (Li et al., 1997; Grey and Henry, 1999).

2.7 INFERENCE FROM LITERATURE REVIEW

Hydrilla Verticillata is troublesome aquatic weed that causes the deterioration of aquatic bodies. Various control methods (viz. biological agents, chemical treatment, mechanical methods) have been adopted to control the growth of the *H. verticillata*. But none of them were successful to control its complete growth. The inherent properties of *H. verticillata* shown its potentiality for the sustainable agricultural production. Composting can be an effective technology for the sustainable waste utilization as it produces agricultural product and reduces the cost of disposal. Rarely studies are available on composting of *H. verticillata.* Rotary drum composting is the best method to manage wastes in the less duration. Moreover, no data are available on efficacy of rotary drum composter for the management of *H. verticillata.* Till date various studies on composting showed improvement in biological, chemical, total heavy metal reduction and gaseous emissions. But very limited studies are available on determination of physical properties during composting of various wastes in rotary drum composter. The limitation with the composting of *H. verticillata* is its high moisture content and low carbon content.

There is need to manage such issues which is only possible by the utilization of carbon-rich agents. So far such studies are rarely available for composting of *H. verticillata.* Similarly no studies are available on role of biochar during composting of *H. verticillata.* Last but not the least, the compost production is worth after its successful land application. Such studies of compost application on various soils are available in the past studies. However, no scientific studies are available on compost application prepared from *H. verticillata* + biochar in alluvial or laterite. Therefore, the aim of the thesis was to find the efficacy of rotary drum composting for management of *H. verticillata,* insight of physical properties during compost production, role of carbon-rich agents and its effect on physical properties, and the application of the compost in the sandy soils.

Chapter 3

MATERIALS AND METHODS

Different experimental approaches were used to accomplish the stipulated objectives. The research work was carried out in different phases using various waste material combinations. The detailed methodology is given in this chapter.

3.1 EXPERIMENTAL DESIGN

In order to accomplish the objectives, the study was proposed to carry out in different phases as summarized below. Fig. 3.1 shows experimental design of the thesis work. In phase 1, the experiments were conducted on initial characterization of *H. verticillata* and efficacy of rotary drum composter during composting of *H. verticillata* with cow dung and saw dust were studied. In phase 2, composting physics or physical properties were evaluated on different wastes viz. *H. verticillata, E. Crassipes*, vegetable wastes, sewage sludge and paper mill sludge. Their optimized ratios were selected from the earlier conducted studies and comparison was made. In phase 3, the role of carbon-rich agents was studied on the best ratio obtained in phase 1. In phase 4, the best compost that is achieved in phase 3 was applied on two soils and their effect on soil properties were studied.

3.2 COMPOSTING MATERIALS AND FEEDSTOCK COMBINATIONS

3.2.1 PHASE 1: Efficacy of rotary drum composter for *H. verticillata*

Five different composting ratios of *H. verticillata*, cow dung and sawdust were placed in a different rotary drum composter (Fig. 3.2) comprising of the total weight of 100 kg (w/w) (Table 3.2). *H. verticillata* (Fig. 3.3a) was collected from Deepor Beel, which is 12 km away from Indian Institute of Technology Guwahati (IITG), Guwahati, Assam, India. Cow dung and sawdust were obtained from dairy farm and sawmill, respectively, which is located nearby in Amingaon, Guwahati (Fig. 3.3b and 3.3c). The selected ranges of physicochemical properties of the innovative materials are presented in Table 3.1. The initial moisture content of *H. verticillata* was recorded in the range 92-95% (Table 3.1), and sawdust was added as a bulking agent to adjust the moisture content. The cow dung was added as an inoculum to enhance the rate of degradation. *H. verticillata* was shredded to 2-3 cm sizes for the homogenized blending of the cow dung, and sawdust.

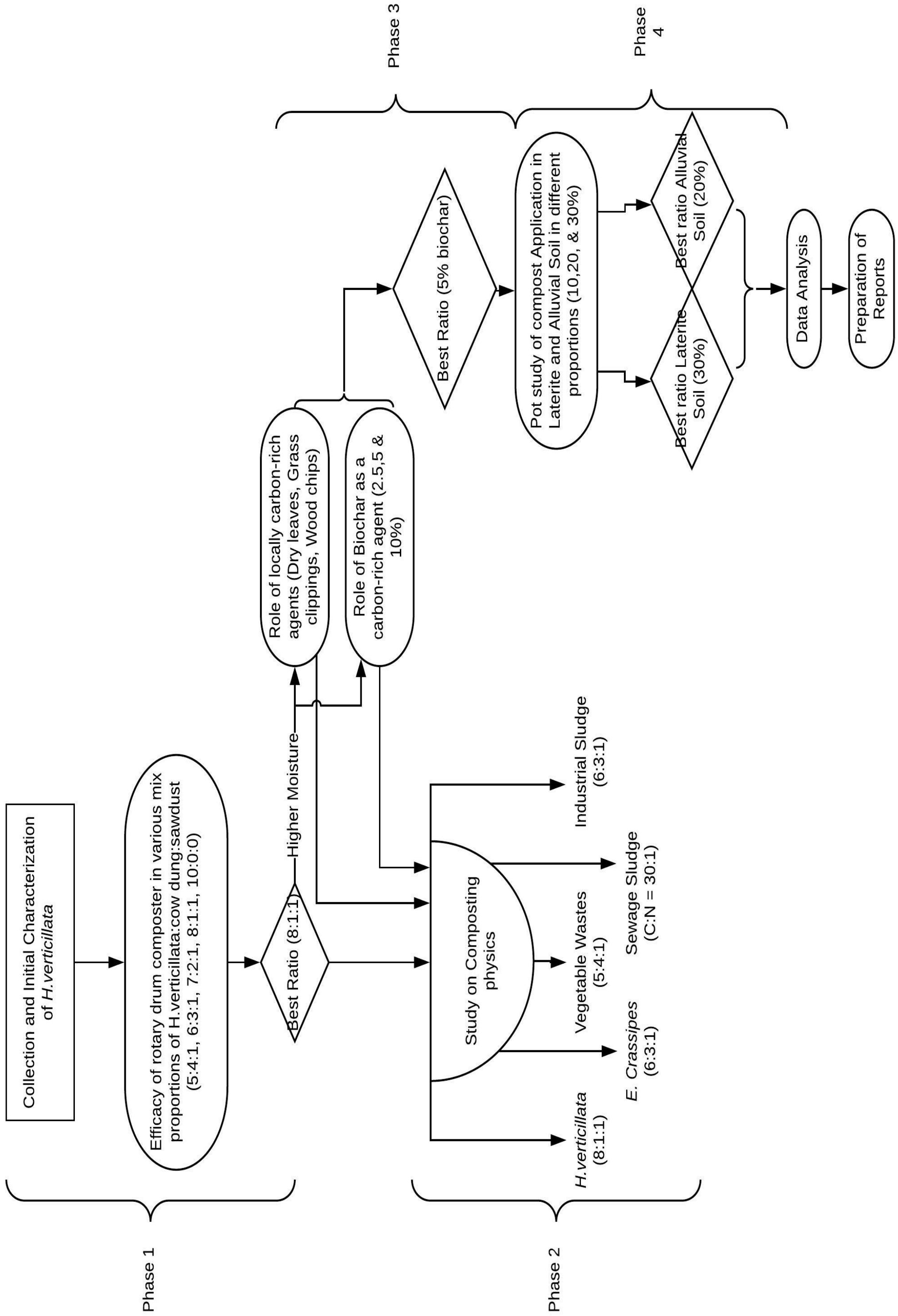


Fig. 3.1. Experimental flow chart

Varma and Kalamdhad (2014) and Singh et al. (2016) reported that, the rate of degradation and stabilization of waste material is higher in the rotary drum composting than any other composting methods, thus the detention period of 20 days is chosen for the experiment. Manual turning was done to maintain aerobic conditions inside the drum at every 24 h by one complete rotation of the drum.

3.2.2 Sampling

Triplicate samples (1 kg each) were collected from each drum at three different locations (20 cm from the base of the surface) at 0, 2, 4… and so on till 20 days respectively. The samples were divided into two parts, each one with 0.5 kg. One part was stored at 4°C immediately for biological analysis, and the other one was air-dried, ground to pass through a 212 μ sieve and kept in a desiccator for further physicochemical studies.

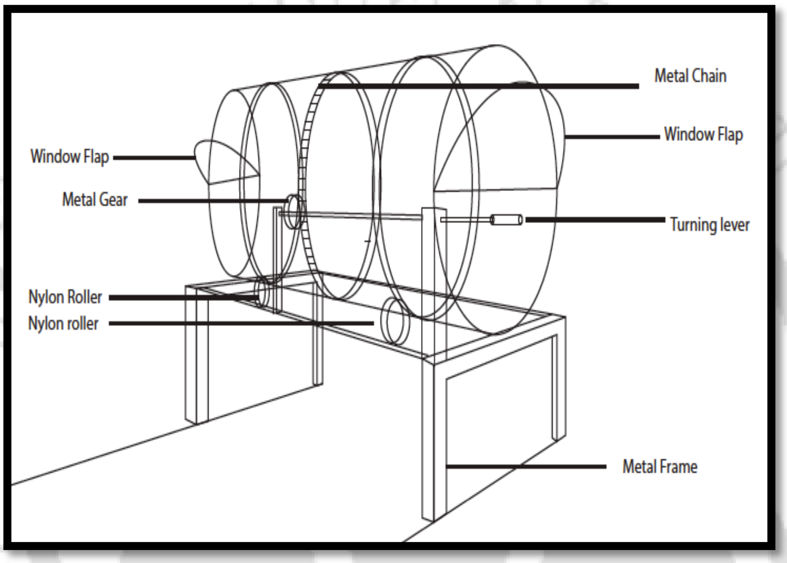
Table 3.1. Initial selected physico-chemical characteristics

Parameters	*Hydrilla Verticillata*	Cow Dung	Sawdust
Moisture content (%)	93.5±0.7	82±3.3	15±0.2
Volatile solids (%)	70±3.3	90±4.5	22±2.3
Ash content (%)	32±1.7	11±2	78±0.7
Ph	7.5±0.2	6.9±0.1	6.5±0.2
Electrical conductivity (ds/m)	8.2±0.3	3.7±0.2	0.4±0.2
Total kjeldahl nitrogen (%)	3.4±0.2	1.3±0.1	0.3±0.1
Total phosphorus (g/kg)	4.8±0.5	5.1±0.3	2.4±0.3
Available phosphorus (g/kg)	2.3±0.3	3.2±0.1	1.1±0.2
Sodium (g/kg)	1.1±0.2	2.3±0.4	1.2±0.2
Potassium (g/kg)	25.1±1.5	1.0±0.1	0.7±0.1
Calcium (g/kg)	6.3±0.3	9.7±0.2	2.2±0.1
C/N ratio	11.5±0.8	27±1.5	325±17.6

All values are means ± stdeva of triplicates (dry weight basis)

Table 3.2. Mix proportions of different trials

Trial Name	Mix Proportions	*H. verticillata* (kg)	Cow dung (kg)	Sawdust (kg)	Total (kg)
T1	5:4:1	50	40	10	100
T2	6:3:1	60	30	10	100
T3	7:2:1	70	20	10	100
T4	8:1:1	80	10	10	100
T5	10:0:0	100	-	-	100



a) 3-D view

b) Pictorial View

Fig. 3.2. Rotary drum composter

a) *Hydrilla Verticillata*

b) Cow dung c) Sawdust

Fig. 3.3. Raw materials in phase-1

Fig. 3.4 Preparation of feedstocks and feeding in the rotary drum composter

3.2.3 PHASE 2: Composting physics and comparative study

This research study on composting of various organic wastes was performed in solid waste laboratory at the IITG campus. The vegetable wastes (VW) (MC = 92.1%, VS = 69.1%, C/N = 18:1) were collected from the institute hostels. An aquatic waste, i.e., water thyme (WT) also known as Indiana star vine (or *H.verticillata)* (MC = 93.9%, VS = 74.3%, C/N = 11:1) and water hyacinth (MC = 93.3%, VS = 85.2%, C/N = 14:1) was gathered from the eutrophic wetland (Deepor beel) situated around 20 km from the institute. The industrial sludge (IS) (MC = 58.3%, VS = 44.2%, C/N = 19:1) of pulp and paper mill was collected from the unit of Hindustan Paper Corporation (Nagaon Paper Mill) situated around 20 km from the institute. The sewage sludge (SS) (MC = 85.1%, VS = 38.6%, C/N = 11:1) was collected from institute sewage treatment plant. Bulking agent (dry leaves) was gathered from the institute and saw dust and cow dung were gathered from nearby wood cutting mill and dairy farm, respectively. The selected ranges of physical properties of the various experimental materials are shown in Table 3.3

The optimized five mixtures (of various organic wastes) were prepared considering their mix proportions as mentioned in the previous studies on rotary drum composter (Varma et al., 2014; Nayak and Kalamdhad, 2014; Singh et al., 2016; Hazarika et al., 2017).

The composition of various organic wastes initial feedstocks as follows:

Drum A: WT (80 kg) + CD (10 kg) + SD (10 kg)
Drum B: WH (60 kg) + CD (30 kg) + SD (10 kg)
Drum C: VW (60 kg) + CD (30 kg) + SD (10 kg) + DL (10 kg)
Drum D: SS (87 kg) + CD (45 kg) + SD (18 kg)
Drum E: IS (60 kg) + CD (30 kg) + SD (10 kg)

The mixtures were fed in different rotary drum composters. The drum was horizontally aligned cylindrical vessel made of mild steel (3-D view as shown in Fig. 3.2). The volumetric capacity of the drum was 550 L. The composter was kept partially opened from both sides to achieve aerobic conditions. The composter was rotated daily once to homogenize the mixtures.

a) *Hydrilla Verticillata*

b) Water Hyacinth

c) Vegetable Wastes

d) Sewage sludge

e) Paper mill sludge

Fig.3.5. Raw materials in phase 2

3.2.4 Sampling

Triplicate samples (1 kg each) were collected from each drum at three different locations (20 cm from the base of the surface) at 0, 2, 4, 6, 10, 14, 18 and 20 days respectively. The samples was air-dried, ground to pass through a 212µ sieve and kept in a desiccator for further physicochemical studies.

3.2.5 PHASE 3: Role of carbon-rich agents during composting

- ***Locally available carbon-rich agents***

In this study, aquatic green waste *H. verticillata* was composted after addition of various locally available CA (dry leaves, grass clippings, and wood chips). All experimentations were performed in IITG campus. A primary substrate, i.e., *H. verticillata*, was acquired from the eradicated wetland. Inoculum, i.e., (cow dung) was acquired from a proximate dairy farm. Dry leaves and grass clippings were collected from IITG campus whereas wood chips were collected from the nearby wood cutting mill. Sawdust was utilized to prepare the uniform mixture with cow dung (to prevent lumps formation) and it was acquired from the proximate sawmill of IITG campus. The initial physical characteristics of the different experimental substrate and CA are shown in Table 3.4. The *H. verticillata* was brought to the laboratory, IITG campus. The whole weed was shredded to a smaller size of 2-3 cm; whereas wood chips were gathered from the wood cutting mill that yielded size of 3-4 cm.

Table 3.3. Initial characteristics of various experimental feedstock materials

Parameters	Moisture content (%)	Volatile solids (%)	pH	Bulk density (kg/m^3)	Total Kjeldahl N (%)	C/N
Water thyme	94.0±1.3	74.3±2.2	7.0±0.1	122±3.6	3.1±0.2	15±2
Water hyacinth	93.3±1.1	85.2±0.6	7.4±0.1	257±3.1	2.1±0.1	14±0.5
Vegetable waste	92.1±0.5	69.1±1.4	5.6±0.2	327±7	1.7±0.1	18±0.5
Sewage sludge	85.1±0.8	38.6±0.8	7.3±0.1	510±10	1.4±0.3	19±0.3
Industrial sludge	58.3±0.1	44.2±2.1	7.2±0.1	400±4.5	0.4±0.1	11±0.6
Cow dung	83.5±0.5	84.0±4.2	7.0±0.1	532±3.8	1.3±0.2	28±2.1
Sawdust	33.0±0.8	68.0±0.7	6.0±0.2	182±2.1	0.4±0.1	90±5.3
Dry leaves	12.0±0.4	88.0±0.5	8.0±0.2	175±0.1	0.2±0.1	130±7.2

A smaller particle size is important to achieve higher and appropriate degradation. Total weight of 110 kg was deliberated for the feeding of prepared feedstock's having *H.verticillata* as a substrate. Inoculum and sawdust were mixed (10 kg each) homogenously in the proportion of 1:1 and it is then homogeneously mixed with 80 kg of shredded *H.verticillata.*

Furthermore, 10% CA, i.e., dry leaves, grass clippings and wood chips of total weight (10 kg) each was added to a different prepared (100 kg) compost feedstock mixture and named as Run A, B and C, respectively. Following are the four distinctive composting feedstock's prepared for this study (wet weight basis):

- Run A: *H. verticillata* (80 kg) + SD (10 kg) + CD (10 kg) + DL (10 kg).
- Run B: *H. verticillata* (80 kg) + SD (10 kg) + CD (10 kg) + GC (10 kg).
- Run C: *H. verticillata* (80 kg) + SD (10 kg) + CD (10 kg) + WC (10 kg).
- Control: *H. verticillata* (80 kg) + CD (10 kg) + SD (10 kg)

a) *Hydrilla Verticillata*

b) Cow dung

c) Sawdust

d) Dry Leaves

e) Grass clippings

f) Wood chips

Fig. 3.6. Raw materials in phase 3 (Part 1)

- ***Biochar as a carbon-rich agent***
    - *Biochar preparation*

The biochar was prepared from woody biomass of *Prosopis juliflora* by slow pyrolysis at 400-500°C, in a low oxygen environment. A representative sample of biochar was air dried and the particle size distribution determined by weighing the fractions penetrating a series of standard sieves. The uniformity of coefficient was observed to be 3.21 and value of coefficient of curvature, i.e., 1.03 indicated that biochar used was well-graded. The particles were classified into five size groups, ranging from <1 mm to >0.15 mm. The biochar is having calorific value of 7800-7900 Kcal kg^{-1} and C: N ratio of 382-446. It was produced by Greenfield Eco Solutions Pvt. Ltd., Jodhpur, India (www.greenfieldeco.com) and the initial characteristics of the biochar are summarized in Table 3.5. The pictorial view of biochar used is shown in Fig. 3.7.

Table 3.4. Initial characteristics of various experimental raw materials in phase 3 (part 1)

Parameters	*Hydrilla Verticillata*	Cow Dung	Saw Dust	Wood Chips	Dry Leaves	Grass clippings
Moisture content (%)	92.07±1.3	85±0.5	16.3±0	48±2.1	24.9±4	56.8±0.9
Volatile solids (%)	70±2.7	89±4.1	64±1.9	87.3±0.6	72±1.5	85.3±1.2
pH	7.2±0.01	6.5±0.0	6.1±0.0	6.7±0.0	6.95±0.	6.1±0.0
Electrical cond. (ds/m)	6.8±0.0	3.4±0.0	0.6±0.0	0.9±0.05	0.6±0.0	0.73±0.0
Bulk density (kg/m^3)	435±9.8	104±3	375±13	265±9.5	73±4.4	157.3±6
Tkn (%)	3.3±0.2	1.5±0.1	0.35±0	0.2±0.0	0.4±0.0	2.1±0.3
C/N ratio	14±0.5	25.8±2	160±16	85.5±1.0	45.2±2	12.5±0.9

Table 3.5. Initial characteristics of various experimental raw materials in phase 3 (part 2)

Parameters	Moisture Content (%)	Volatile Solids (%)	pH	EC (dS/m)	Total Kjeldhal N (%)	Total P (g/kg)	C/N
H. verticillata	94±1.3	72±2.2	7±0.3	6.5±0.4	3.4±0.2	4.5±0.3	15±2
Cow dung	87±0.5	84±4.2	7±0.5	3.2±0.7	1.5±0.2	4.9±0.7	28±3
Sawdust	18±0.8	68±0.7	6±0.2	0.8±0.3	0.4±0.1	2.3±0.3	160±30
Biochar	1.8±0.4	88±0.5	8±0.2	1.4±0.1	0.2±0.1	1.9±0.2	400±30

a) *Hydrilla Verticillata* b) Cow dung

c) Sawdust d) Biochar

Fig. 3.7. Raw materials in phase 3 (Part 2)

Inoculum, i.e., fresh cow dung (CD) was gathered from a nearby dairy farm. Sawdust (SD) used to prepare the homogeneous mixture (to avoid lumps formation) with cow dung, collected from the nearby sawmill, located in Amingaon, Guwahati, Assam, INDIA. The selected physical properties of the various experimental materials are shown in Table 3.5.

Four different composting mixtures were prepared with the following compositions (wet weight basis):

- Trial A: HV (80 kg) + CD (10 kg) + SD (10 kg) + 2.5% (w/w) biochar.
- Trial B: HV (80 kg) + CD (10 kg) + SD (10 kg) + 5.0% (w/w) biochar.
- Trial C: HV (80 kg) + CD (10 kg) + SD (10 kg) + 10% (w/w) biochar.
- Control: HV (80 kg) + CD (10 kg) + SD (10 kg).

3.2.6 Sampling

Triplicate samples (1 kg each) were collected from each drum at three different locations (20 cm from the base of the surface) at 0, 2, 4… and so on till 20 days respectively. The samples were divided into two parts, each one with 0.5 kg. One part was stored at 4°C immediately for biological analysis, and the other one was air-dried, ground to pass through a 212μ sieve and kept in a desiccator for further physicochemical studies.

3.2.7 PHASE 4: Compost application in alluvial and laterite soil

The composting feedstocks were prepared by mixing fresh *H.verticillata* (collected from Deepor Beel) with different organic wastes, i.e., saw dust and cow dung in ratio 8:1:1. Biochar (5% w/w) were used as an additive to achieve appropriate moisture level of the end product as recommended for soil application. The sawdust and cow dung were collected from wood cutting mill and dairy farm nearby to the IITG campus, respectively. The efficient utilization of these wastes attributes towards sustainable waste management. The proportion of various wastes used to prepare compost is as follows:

- *H. verticillata* (80 kg) + Cow dung (10kg) + Sawdust (10kg) + Biochar (5 kg)

Full detailed information about raw materials and the composting process is discussed in section 3.2.1. The compost were prepared using rotary drum composter having working volume of 550 L. The composter was operated in batch mode. The composter was rotated daily to achieve aerobic conditions. The detention period of the composter was 20 days. The detailed description of the composter is given in discussed in section 3.2.1. The total 105 kg of wastes that is comprised of *H. verticillata,* cow dung, sawdust and biochar were fed into the composter. Temperature, moisture content, and volatile solids were considered as controlling parameters of the composting process. The characteristics of the compost produced are tabulated in Table 3.7, which indicates the good quality of compost.

A Quadrimester (120 days) research study was conducted during the period January-April, 2018 in IITG campus. The alluvial soil was used for this research study, which was collected from the bank of Brahmaputra River in the area of Amingaon, in the neighborhood (26°10’57. 3” N, 91°41’48. 3” E) of IITG campus and laterite soil was collected from the IITG campus (26° 11' 4.5" N, 91° 41' 35.7" E). The alluvial soil is a typical fluvial soil having average particle size of 18 μm whereas laterite soil is having average particle size of 5 μm. The initial characterization of the soil is presented in Table

3.7. Both soil were characterized with a very low amount of nitrogen and available phosphorus.

Table 3.6. Mix proportions of different trials

Treatments name	Weight of soil (kgs)	% Compost application (kgs)	Total weight (kgs)
LS_0	4	0% (0)	4
LS_{10}	4	10% (0.4)	4.4
LS_{20}	4	20% (0.8)	4.8
LS_{30}	4	30% (1.2)	5.2
AS_0	4	0% (0)	4
AS_{10}	4	10% (0.4)	4.4
AS_{20}	4	20% (0.8)	4.8
AS_{30}	4	30% (1.2)	5.2

The pot study was conducted in a reactor of working volume 0.012 m^3 that was made from hard plastic. At the bottom of pot plastic sheet was placed to avoid any water loss. The bottom layer (10-20 cm) was placed with gravels having sizes between 4-16 mm. Next layer (30-40 cm) was placed the homogenized mixture of soil (4 kg) and prepared compost. The study was designed for varying proportion (0, 10, 20, 30%) of compost in the both soil, referred as treatments as shown in table. Each varying proportion of the mixtures was placed in triplicates.

3.2.8 Sampling

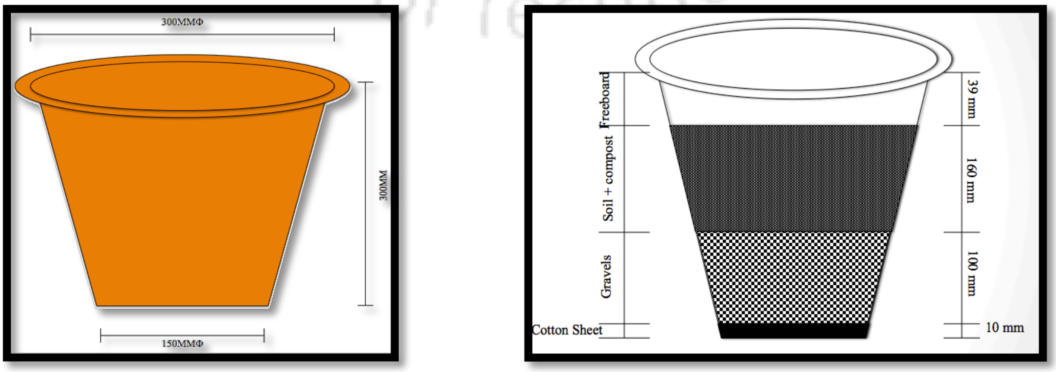
For each reactor, soils were sampled immediately after placing the reactor (referred as day 0 sample) and then after on day 15, 30, 45, 60, 90, and 120. One homogenized sample was obtained from each reactor that was taken randomly at 10 cm depth with the help of soil auger (Karak et al., 2015). The collected soil samples were subjected to dry in hot air oven at 105°C for 24 h and ground to pass through 200μ IS sieve.

a) *Hydrilla Verticillata* b) Cow dung

c) Sawdust d) Biochar

e) Alluvial Soil f) Laterite Soil

Fig. 3.8. Raw Materials in Phase 4



a) Pot b) Soil

Fig. 3.9. Pot dimensions

Fig. 3.10. Pictorial representation of feeding of pots

Table 3.7. Chemical, nutritional and physical properties of tested composts prepared from *H.verticillata*, cow dung, sawdust and biochar (mean±std.)

Parameters	Compost
Dry matter (%)	41±0.7
Volatile solids (%)	55±3.3
Ph	7.6±0.1
Electrical conductivity (ds/m)	3.7±0.2
Total organic carbon (%)	30±3.1
Total kjeldhal nitrogen (%)	5.2±0.1
Available phosphorus (g/kg)	3.4±0.5
Potassium (g/kg)	38.1±0.3
Calcium (g/kg)	48.6±0.2
Sodium (g/kg)	1.4±1.5
Bulk density (g/cm^3)	0.76±0.12

Table 3.8. Initial characteristics of soils used in the experiments

Parameters	Laterite Soil (LS)	Alluvial Soil (AS)
Moisture content (%)	24±1.2	34±1.7
Soil organic matter (%)	1.2±0.3	4.5±0.1
Ph	5.96±0.01	6.93±0.02
Soil organic carbon (%)	0.7±0.2	2.3±0.5
Total kjeldahl nitrogen (%)	0.1±0.0	0.31±0.0
Available phosphorus (g/kg)	0.13±0.04	0.9±0.07
Cation exchange capacity (cmol/kg)	5±0.4	12±0.8
Water holding capacity (%)	12±0.3	18±1.0
Bulk density (g/cm^3)	1.36±0.1	1.67±0.1
Porosity (%)	55±2.1	45±3.0
Sand (%)	32±0.5	15±0.5
Silt (%)	56±0.7	65±0.3
Clay (%)	12±0.4	20±0.3

3.3 MONITORING AND ANALYSES

3.3.1 Temperature measurements

Temperatures in the top, middle, and bottom portion of the composting mixtures were monitored using a digital thermometer consisting of a temperature sensor attached to it. Temperature data were collected daily after every 4 h during the entire composting process, and three reading were averaged per composting mix. Ambient temperature was also recorded using the same temperature sensor.

3.3.2 Biological and respirometry analyses

The other part of the sample which was stored at 4°C was used for biological analyses. The soluble biochemical oxygen demand (sBOD) is determined by dilution method, soluble chemical oxygen demand (sCOD) by dichromate method and bacterial population including total coliforms and fecal coliform (1:10 w/v waste: water extract) by inoculation of culture tube media using most probable number (MPN) method (APHA, 2012). Stability of compost samples, based on Carbon-di-oxide (CO_2) evolution was measured using static measurement method (Knoepp and Vose, 2002; Kalamdhad et al., 2008; Varma and Kalamdhad, 2014).

The oxygen uptake rate (OUR) was calculated by following the method described in APHA (1995). Kalamdhad et al. (2008); Varma and Kalamdhad (2014) described the details of CO_2 evolution and OUR determination.

3.3.3 Chemical analyses

The muffle furnace was used to determine the volatile solids (VS) content (weight loss on ignition at 550°C) (Page et al., 1982; Tiquia and Tam, 1998; Kalamdhad et al., 2008; Varma and Kalamdhad, 2014). The mechanical shaking of samples were performed for 2 h with distilled water with waste to water extract ratio of 1:10 (w/v) to get pH and EC values. Ammonium nitrogen (NH_4-N) was determined using KCl extraction (Tiquia and Tam, 2000; Varma and Kalamdhad, 2014). The Kjeldahl method and the Stannous chloride method (acid digestion) was used to find the total nitrogen (TKN) and available and total phosphorus, respectively (APHA, 2012). Sodium (Na), Potassium (K) and Calcium (Ca) are determined by a flame photometer and magnesium (Mg) by atomic absorption spectroscopy (AAS) by digesting 0.2 g air-dried 212µ sieved sample with 10 ml H_2SO_4 and $HClO_4$ (5:1) at 300°C for 2 h.

3.3.4 Physical analyses

The moisture content was determined by drying samples at 105°C using hot air oven for 24 h and expressed as given in Eq. 1 (Tiquia and Tam, 1998). As the wet bulk density (BD) of compost matrix affects the size of composting facilities and maturation centers, this was evaluated immediately after collection by weighing the quantity required filling a 2 L mild steel container (Adhikari et al., 2008) and expressed as given in Eq. 2. The air-filled porosity was calculated from the bulk density and particle density of the compost mixture using Eq. 3. Particle density (PD), taken as the ratio of the total mass of solid particles to the total volume of solid particles (i.e. excluding water mass and pore or air space) of mix was measured using the 50 mL density bottle with hexane (0.78 kg/L) as reference liquid (Mohee and Mudhoo, 2005; Adhikari et al., 2008). The analyses were performed in triplicate.

$$\text{Moisture content (\%)} = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial weight}} \times 100 \tag{3.1}$$

$$\text{Bulk density, BD} \left(\frac{\text{kg}}{m^3}\right) = \frac{\text{Mass}}{\text{Volume}} \tag{3.2}$$

$$\text{Free Air Space, FAS (\%)} = 100 \times \left(1 - \frac{\text{BD}}{\text{PD}}\right) \tag{3.3}$$

3.3.5 Soil analyses

The pH for soil sample were measured as per the described method in (Rayment and Higginson, 1992). Cation-exchange capacity was determined by 1 M ammonium acetate extraction method buffered at pH 7 for 30 min using atomic absorption analyzer. Soil organic carbon was measured by the Walkey and Black method (Nelson and Sommers, 1982). Determinations were made of total kjeldahl nitrogen using Kjeldahl nitrogen distillation method whereas available phosphorus as per given in (Olsen, 1995). The physical properties such as bulk density and total porosity was determined as per the described method (Xin et al., 2016). The water holding capacity of the soil is determined on volume basis using method described in (Goswami et al., 2017)

3.3.6 Statistical analysis

In order to determine significant differences among trials at the same composting time, the data were subjected to ANOVA. Physical analyses data were subjected to correlation analysis. For the statistical analyses, SPSS v20.0 was used with 95% confidence level. As noted earlier, the samples gathered from individual composting reactors were treated as triplicates for each sampling time and their mean with standard deviation is reported, which is calculated using StatPlus: Mac, 2010. All correlation equations, coefficients and other statistical data were obtained using StatPlus: Mac, 2010.

3.4 INSTRUMENTS USED

Following table 3.8 shows the various instruments used for performing the analyses during this research work

Table 3.9. Different instruments used in experimentation

Parameters	Instrument	Company (Make/Model)
Temperature	Digital thermometer	Mextech St-9823
Volatile solids	Muffle furnace	Int. commercial traders
Moisture content	Class-ii high accuracy hot air oven	Satwik scale industries
pH	pH system 361	Systronics

Electrical conductivity	Conductivity meter (vsi- 04 deluxe)	VSI electronics pvt. Ltd.
Total kjeldahl N	TKN distillation apparatus	Pelican instruments
Total P	Visible spectrophotmeter	Thermo fisher
Available P	Visible Spectrophotmeter	Thermo fisher
Macronutrients (Na, Ca, K)	M controller based flame photometer with compressor	Systronics
Micronutrients	Atomic Absorption Spectroscopy	Thermo fisher Scientific
Co_2 evolution rate	Bod incubator	Int. Commercial traders
Oxygen uptake rate	Do meter	HACH
sBOD	Bod incubator	Int. Commercial traders
sCOD	Cod digestor	HACH
Serial dilution	Vortex	Spinix
MPN	Laminar flow chamber	Clean air
Sterlization	Autoclave	Equitron
Stirring	150 RPM rotary shaker	---
Centrifuge	---	Remi

Chapter 4

RESULTS AND DISCUSSION

4.1 PHASE 1 - EFFICACY OF ROTARY DRUM COMPOSTER FOR MANAGEMENT OF *H. verticillata*

This chapter deals with the performance of rotary drum composter (Phase 1) for the degradation of *H. verticillata* in combination with cow dung and sawdust in five different proportions as discussed in section 3.2. This phase also accomplishes the first objective of this study.

The primary interest of this study is to determine the efficacy of specially designed rotary drum composter for composting of *H. verticillata* and to explore the possible conditions for the composting of *H. verticillata* with the inoculum (cow dung) and bulking agent (sawdust). Biological nutrient transformation and other associated physicochemical parameters were monitored during the composting process and compared to the different mix proportion of substrate, inoculum and bulking agent. The utilization of *H. verticillata* as a primary substrate for composting is a novel approach in the present study, which is rarely reported, in past studies.

4.1.1 Physico-chemical analyses

- ***Temperature and moisture content***

Temperature monitoring is essential to interpret the biological degradation during the composting process. It indicates an evolution rate as well as the mortality rate of the microorganisms. Thermophilic phase (> 45°C) for a longer time is a crucial phase of the composting process as it attributes towards the killing of pathogens and reduces readily biodegradable carbon (Haug, 1993). Temperature plots obtained for five trials (T1, T2, T3, T4 and control, i.e., T5) of different mix proportions are shown in Fig. 4.1 (a). The study depicted all the temperature phases (mesophilic, thermophilic, second mesophilic and cooling) during the composting process. The thermophilic phase was observed within 24 h of feed. Temperature observations of T1, T2, T3, and T5 were 46.9, 47.2, 48.5 and 45.9°C respectively, whereas T4 showed 53.7°C, which is higher in comparison with the other trials. The thermophilic phase in T4 lasts longer for 2 days. Significant variations in temperature are observed between days ($p<0.0001$) whereas it is not noted between mixed proportions ($p=0.22$). The further decrease in temperature was seen in all trials with cooling phase till the 15th day and maturation prolonged up to the 20th day.

The higher temperature peak was recorded for T4 that indicates a comparatively higher rate of decomposition in T4 than the other trials, and it is supported by OUR data, represented in Fig. 4.5 (a). The presence of moisture in an active phase was observed while turning the rotary drum. The daily rotation of the drum is also the one reason for declining temperature.

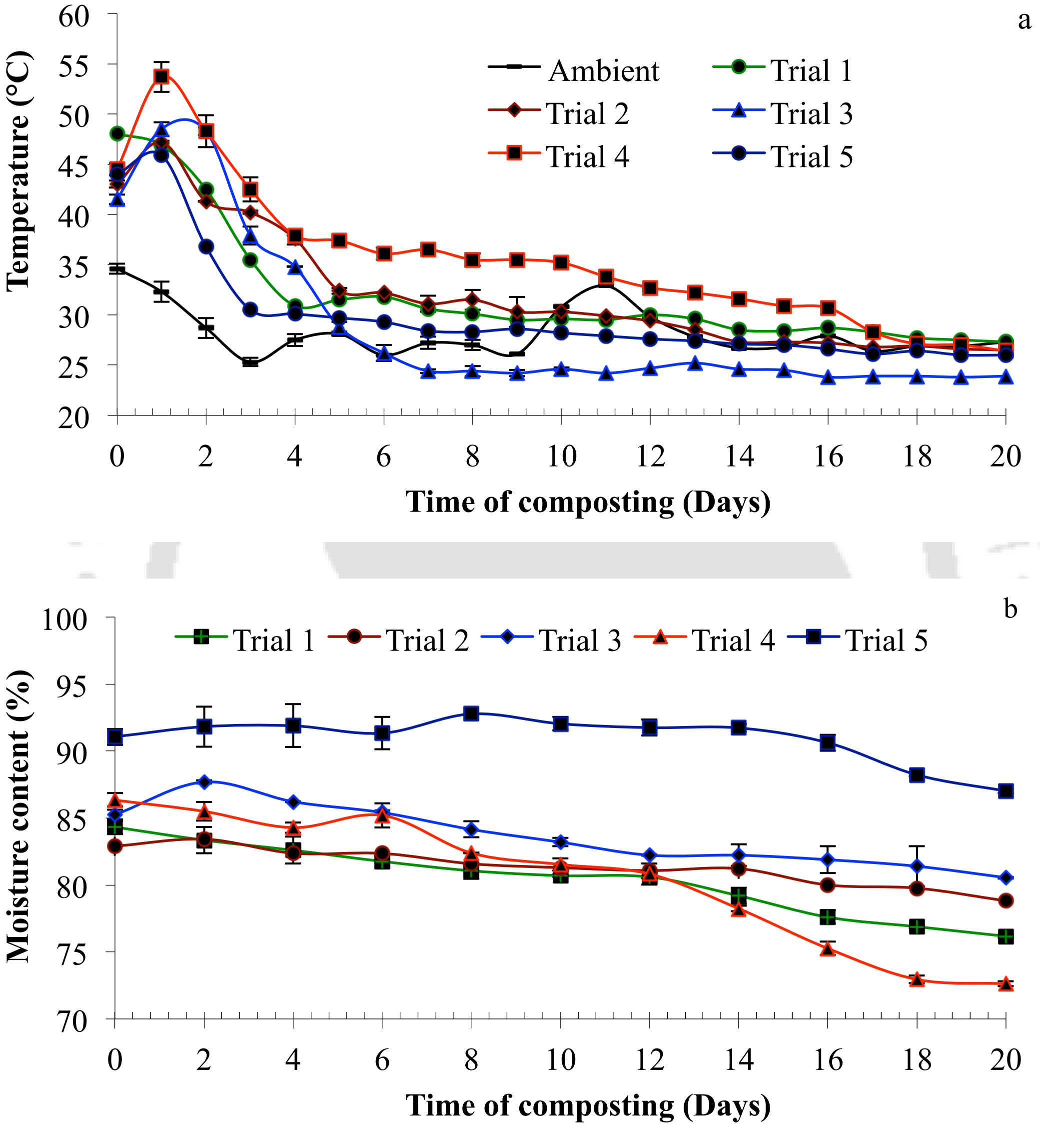


Fig. 4.1. Variation in a) Temperature and b) Moisture content during composting process

It is expected to maintain the uniform moisture content during the composting, to achieve the microbial activity of the microorganisms, involved in the circulation of gasses and liquids through their cells (Madejon et al., 2002). The variations in the moisture content were observed in all trials during composting. The extent of moisture generation depends on the substrate, initial moisture content, mix proportions and rate of aeration.

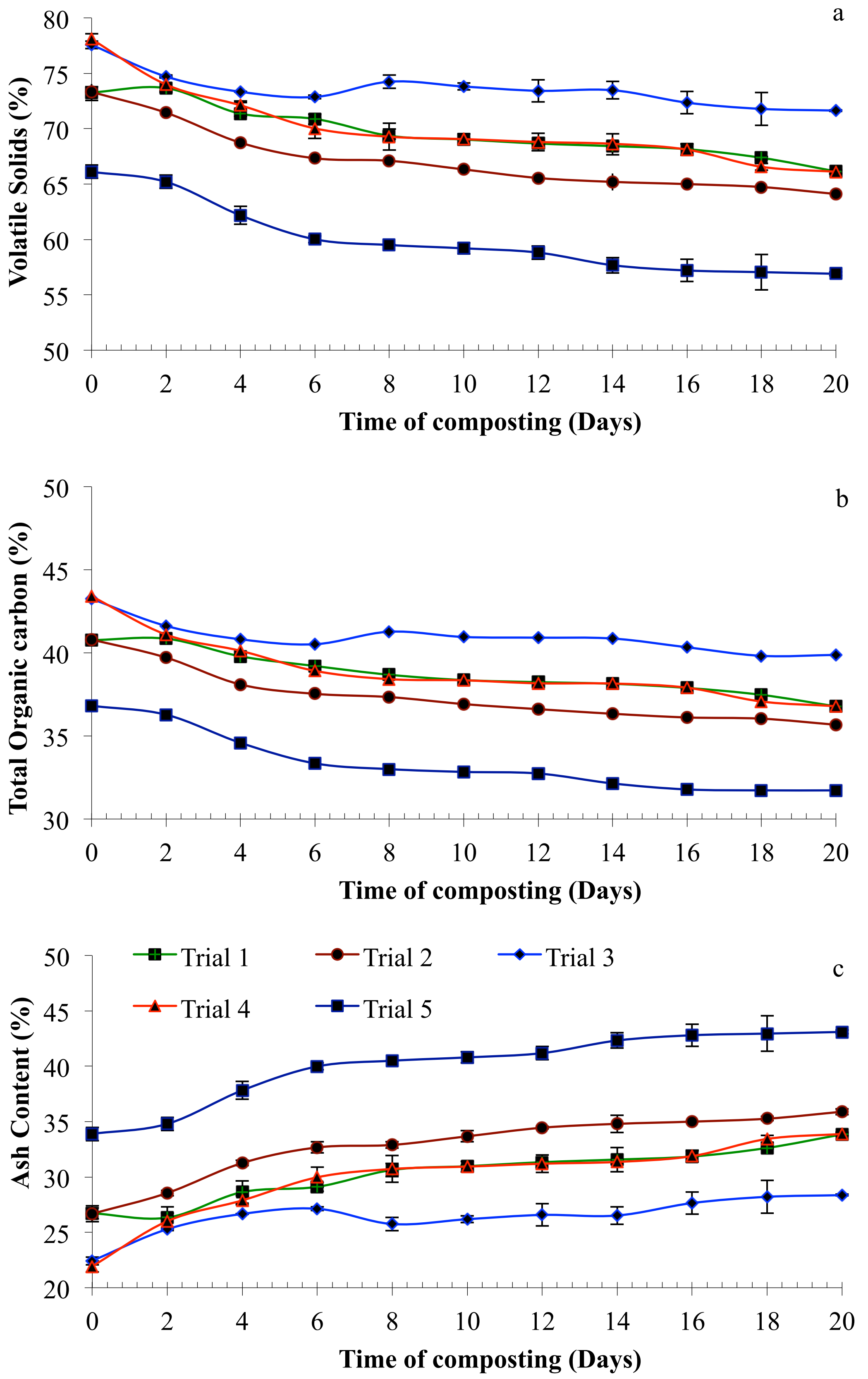


Fig. 4.2. Variation in a) Volatile solids, b) Total organic carbon and c) Ash content during composting process

A plot of the mean of all trials with a standard deviation of moisture content versus time of composting is represented in Fig. 4.1 (b). A fall in a gradient of moisture content was recorded with a maximum loss of 15% in T4 whereas loss occurred as 9.7, 4.9, 5.5 and 4.4% respectively, in T1, T2, T3, and T5. Data were analyzed by ANOVA shows the moisture content varied significantly between days and different mix proportions ($p<0.0001$). The maximum reduction is achieved in T4 and is supported by the temperature data presented in Fig. 4.1 (a). Due to increase in the temperature, the heat was generated and released in the form of vapors inside the drum, out of which a part of vapor was evaporated in the atmosphere, and the leftover was condensed in a drum to provide the moisture content for the microbial activity.

- ***Volatile solids (VS), total organic carbon (TOC) and ash content (AC)***

A volatile solid represents the amount of organic matter in the wastes. The higher the concentration of volatile solids more is the organic matter. It is beneficial in assessing the biologically inert organic matter, such as lignin. The content of volatile solids decreased by about 15% in T4, over the period of the composting. The possible reason for the reduction is the loss of organic matter because of microbial degradation. The trials T1, T2, T3 and T5 showed the reduction of 9, 12, 7 and 13% respectively (Fig. 4.2 (a)). Data were analyzed by ANOVA that shows the volatile solids varied significantly between days and different mix proportions ($p<0.0001$). The increase in ash content was recorded that might be because of the decrease in volatile solids. The maximum reduction in volatile solids was observed within the first week of composting when the process was in thermophilic phase. In this phase, rapid decomposition of organic matter takes place by thermophilic bacteria's.

Early degradable compounds, such as proteins, cellulose, and hemicellulose cause the mineralization of organic matter after composting. A 60-70% of total carbon is converted into carbon dioxide by microorganisms, and the remaining amount is utilized as their body cell components (Barrington et al., 2002). As shown in Fig. 4.2 (d), contents of total organic carbon (TOC) decline significantly in T4, from 43% to 36%, as a reduction in volatile solids. With the increasing rate of decomposition, the organic carbon decreases. Initially, the percentage of total organic carbon was around 40, 41, 43, 44 and 37%, which was then reduced to 37, 35, 40, 37 and 32%, in T1, T2, T3, T4, and T5 respectively. Data were analyzed by ANOVA that shows the total organic carbon varied significantly between days and different mix proportions ($P<0.0001$). Around 15% of the TOC is utilized by the microorganism, as a source of energy in T4 as compared to 9, 12, 7 and 13% in T1, T2, T3, and T5 respectively.

The ash content was recorded as 21, 25, 21, 35 and 21% for T1, T2, T3, T4, and T5, respectively in the end product. The ash content was observed to be increasing over the period of composting, due to the reduction in organic matter by microbial degradation. A set of plots of the mean of all trials with a standard deviation of ash content versus time of composting is represented in Fig. 4.2 (c). Data were analyzed by ANOVA that shows the ash content varied significantly between days and different mix proportions ($p<0.0001$). The decrease in the organic matter is synchronized with an increase in the mass ash of all trials. The presented result shows the maximum amount of loss of organic matter in trial T4 compared to other trials.

- ***pH and electrical conductivity (EC)***

pH and EC might be considered as good indicators for compost stability (Wu et al., 2000). The pH value 7.2, 7.07, 7.19, 7.2, and 7.18 was observed for mix proportions T1, T2, T3, T4, and T5, respectively, and gradually increased from the first day after feeding. The final values recorded as 8.43, 8.42, 8.28, 8.19 and 8.4, for T1, T2, T3, T4, and T5 respectively. Data were analyzed by ANOVA that shows the pH varied significantly between days ($p<0.0001$) and different mix proportions ($p=0.0001$). The rise in pH (Fig. 4.3a) is induced due to the production of ammonia, during ammonification and mineralization of organic nitrogen, as a result of microbial activities (Bishop and Godfrey, 1983). These results indicated that the pH was in the range of 7 to 8.4, during the composting of different mix proportions.

The EC values reflect the degree of salinity, illustrating its possible phytotoxic/phyto-inhibitory effects on the plant growth when applied to soil. As shown in Fig. 4.3b, the electrical conductivity was declined significantly, which could be due to the presence of mineral salts such as phosphates and ammonium ions (Wong et al., 1995; Kalamdhad et al., 2008; Varma and Kalamdhad, 2014). The initial EC values of 7.3, 6.98, 8.53, 8.47 and 8.21 dS/m, respectively, in T1, T2, T3, T4, and T5 was decreased to 5.79, 5.93, 7.32, 5.19 and 6.70 dS/m over the period of composting. The volatilization of ammonia and the precipitation of mineral salts may be the reasons for the decrease in EC values. Data were analyzed by ANOVA that shows the electrical conductivity varied significantly between days and different mix proportions ($p<0.0001$).

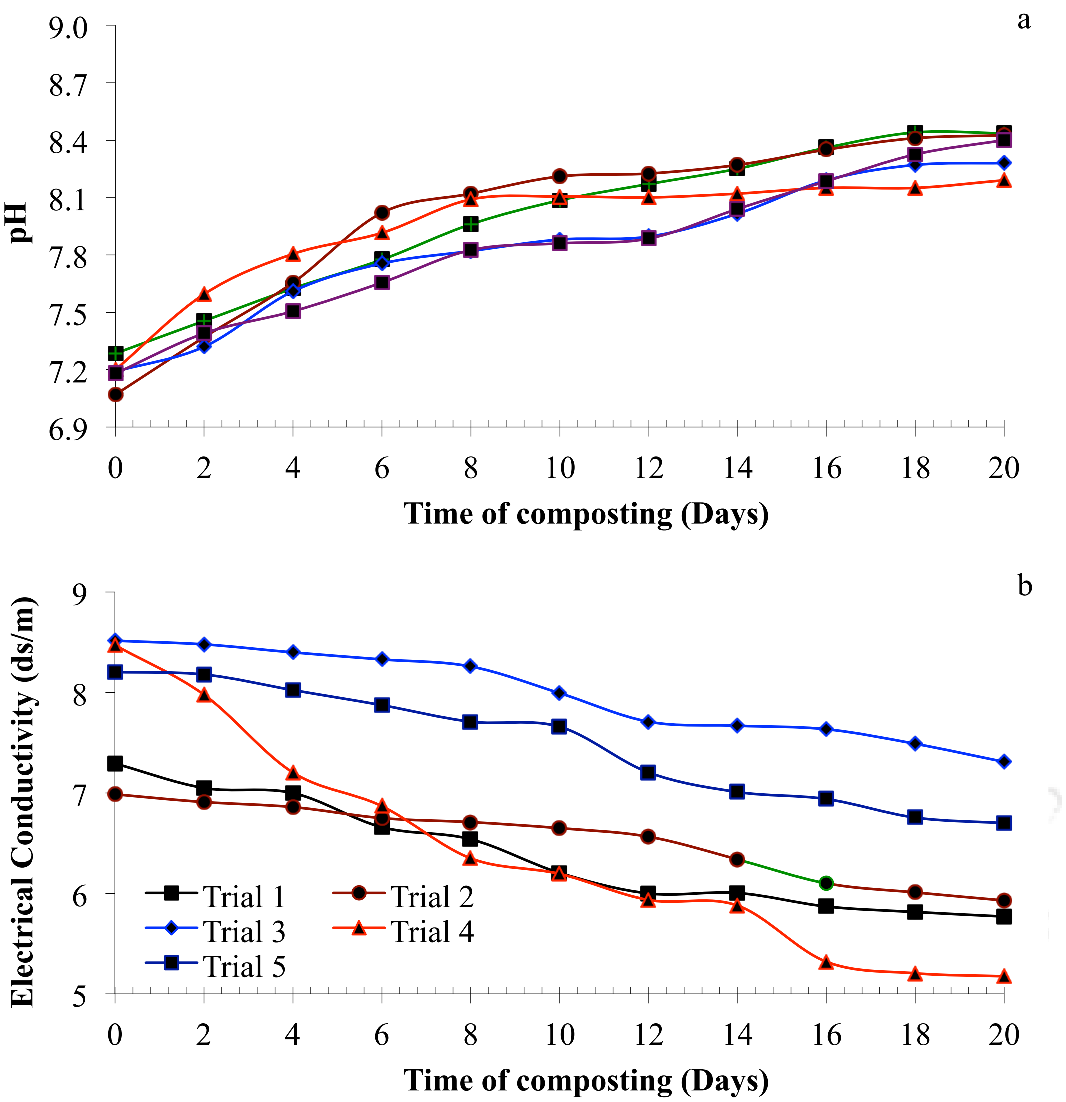


Fig. 4.3. Variation in a) pH and b) Electrical conductivity during composting process

- ***Nitrogen dynamics***

Fig. 4.4 (a) and (b) show the time progression of total Kjeldahl nitrogen (TKN) and ammonium nitrogen (NH_4-N). Nitrogen is affected by the action of the proteolytic bacteria in the first step of composting (Kapetanios et al., 1993; Zorpas et al., 2000). In general, the loss of nitrogen to the atmosphere occurs at a high temperature of the composting process. Percentage change in TKN was recorded as 25, 20, 15, 24 and 7% in T1, T2, T3, T4, and T5, respectively, after 20 days of the composting process with respect to initial values. The reduction observed is may be due to the decrease in the percentage of carbon, as a result of the loss of carbon dioxide and azotobacter bacteria that fixes nitrogen from the atmosphere.

Data were analyzed by ANOVA that shows the total Kjeldahl nitrogen varied significantly between days and different mix proportions ($P<0.0001$). The concentration of NH_4-N increased immediately after the feeding of the reactors. During the thermophilic phase of the composting process, NH_4-N concentration decreased (26%) in T4.

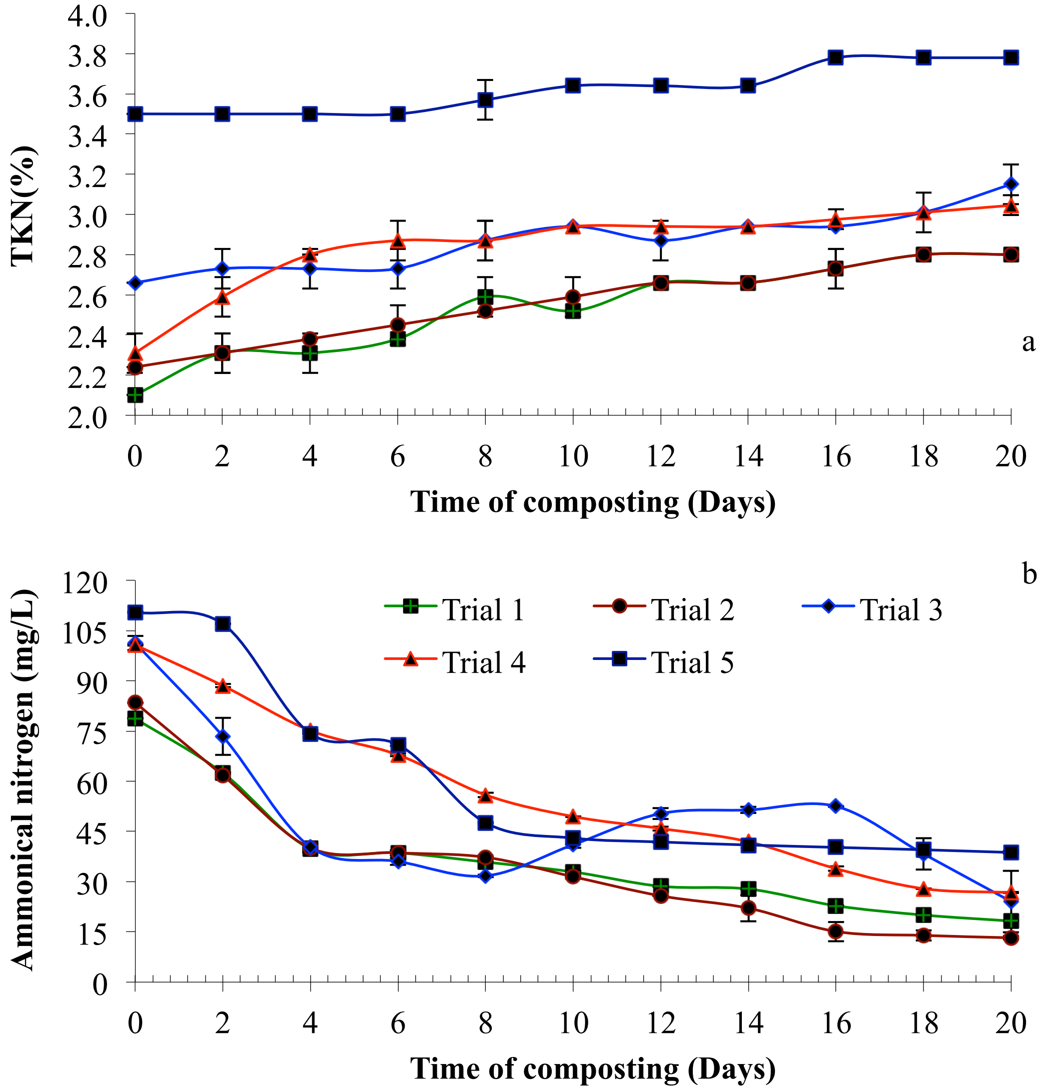


Fig. 4.4. Variation in a) Total Kjeldahl N, b) Ammoniacal N during composting process

Percentage change from initial NH_4-N was recorded as 77, 84, 76, 73, and 65% in T1, T2, T3, T4, and T5 respectively. A result indicates that there is a significant decrease in NH_4-N concentration in all trials. However, T4 that contains a higher percentage of NH_4-N shown more maturity as compared to other trials. Data were analyzed by ANOVA that shows the NH_4-N varied significantly between days and different mix proportions ($p<0.0001$). The decrease in NH_4-N is the indicator of good-quality compost (Varma and

Kalamdhad, 2014). However, the presence of nitrate is not detected during the 20 days composting process of *H. verticillata* in all trials.

- ***Total and available phosphorus***

Another essential nutrient that is consumed by the plant is phosphorus (P). Data were analyzed by ANOVA that shows the total phosphorus varied significantly between days and different mix proportions ($p<0.0001$). The concentration of available and total P was increased due to the decomposition of organic matter and the loss of mass during rotary drum composting. The change in the percentage of total phosphorus was 60%, which was higher in T2, followed by 57, 52, 51 and 29% in T1, T4, T3, and T5, respectively. It indicates the higher microbial activities in T2 and T1, which is due to the addition of a higher amount of inoculum.

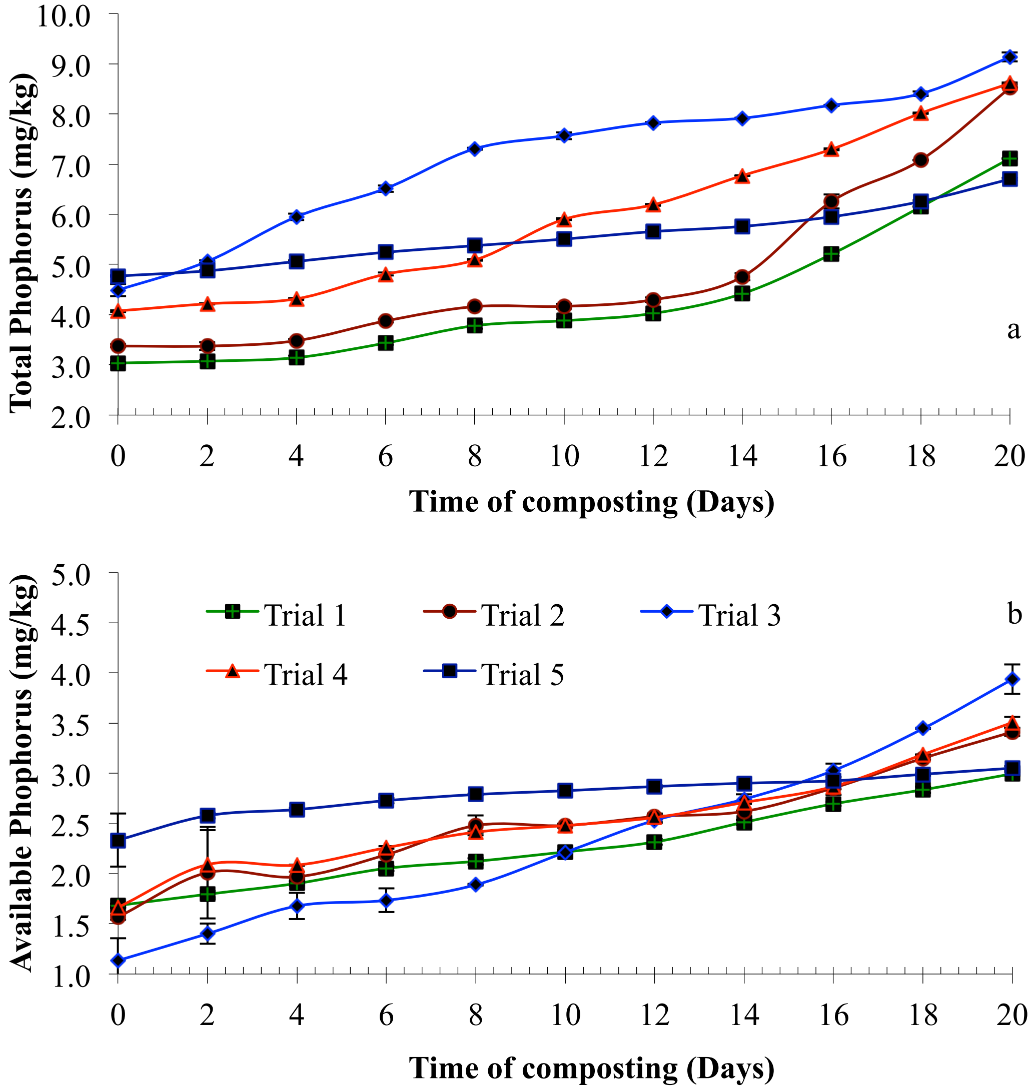


Fig. 4.5 Variation in a) Total P and b) Available P during composting process

The change in the percentage of available phosphorus was 71%, which was higher in T3, followed by 54, 52, 43 and 23% in T2, T4, T1, and T5, respectively. Data were analyzed by ANOVA that shows the available phosphorus varied significantly between days ($p<0.0001$) and different mix proportions ($p=0.0004$). A set of plots of the mean of all trials with a standard deviation of total and available phosphorus versus time of composting is shown in Fig. 4.5 (a and b). Final moisture content was observed as 76.1, 78.8, 80.5, 72.6 and 87.5% for T1, T2, T3, T4, and T5, respectively during the present study, however, no leachate was observed throughout the composting process.

- ***Macronutrients***

Potassium is the mineral required for plant productivity after nitrogen and phosphorus. Fig.4.6 (a, b, and c) show the time course of sodium (Na), potassium (K), and calcium (Ca). These elements followed the increasing trend for all trials during 20 days of composting. The change in the percentage of sodium, potassium, and calcium was observed as 53, 27, 25 and 24% respectively for T1, 21, 17, and 22 respectively for T2, 25, 22, and 25 respectively for T3, 23, 31, and 23 respectively for T4 and 27, 29, and 11 respectively for T5. Data were analyzed by ANOVA that shows the all macronutrients varied significantly between days and different mix proportions ($p<0.0001$).

- ***C/N ratio***

The C/N ratio of the final product should be less than equal to 20 (CPHEEO, 2000). The C/N ratio decreased to 14, 14, 13, 12 and 9 from 19, 18, 15, 18 and 11 for T1, T2, T3, T4, and T5 respectively after 20 days of the composting process. Data were analyzed by ANOVA that shows the C/N ratio varied significantly between days and different mix proportions ($p<0.0001$). During the experimental work, it was found that the C/N ratio was decreased, which is tabulated in Table 4.1.

Table 4.1. Initial and Final C/N (ratio)

Trials	Proportion	Intial	Final
T1	5:4:1	19	13
T2	6:3:1	18	14
T3	7:2:1	16	12
T4	8:1:1	19	12
T5	10:0:0	11	9

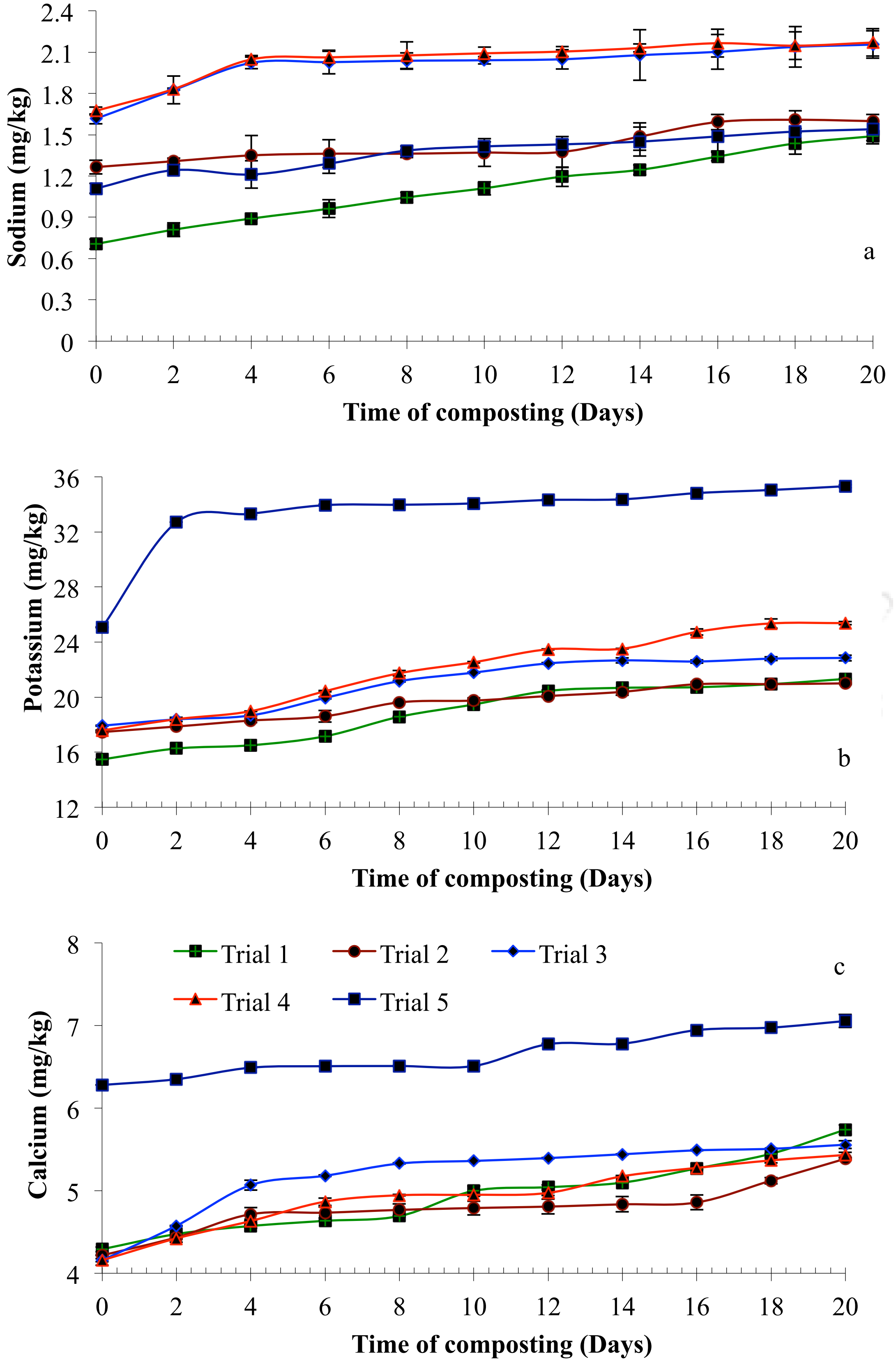


Fig. 4.6. Variation in a) Potassium, b) Sodium, and c) Calcium during composting process

4.1.2 Biological analyses

- ***sBOD and sCOD***

The respiration process of biodegradable organic matter in compost involves aerobic conditions. The percentage of BOD and COD depends upon the biological organic content. The decline in biological content reduces the BOD and COD, ultimately reducing the carbon dioxide emission. sBOD and sCOD values dropped from 141 to 59 and 589 to 341 mgL^{-1} in T1 and 129 to 49 and 577 to 330 mgL^{-1} in T2, while in T3, T4 and T5 125 to 47 and 544 to 280 mgL^{-1}, 118 to 37 and 523 to 200 mgL^{-1} and 72 to 39 and 320 to 197 mgL^{-1} , respectively, within 20 days of composting period. The maximum reduction in sBOD and sCOD was observed in T4 as 69 and 62%. However, it was 62, 62, 58 and 45%, and 48, 43, 42 and 38%, respectively, in T3, T2, T1, and T5 during 20 days of composting. Data were analyzed by ANOVA that shows sBOD, and sCOD varied significantly between days and different mix proportions ($p<0.0001$).

Results indicate the worst decomposition of organic matter in trial 5 and trial 1 as compared to other trials because of the high moisture content. According to Mangkoedihardjo (2006), the BOD/COD ratio tends to zero, when the rate of decrease of COD is less than that of BOD. The lesser BOD/COD ratio indicates more non-biodegradable and stable compost.

- ***Respirometry analyses (OUR and CO_2)***

Fig. 4.7 (a) shows a change in oxygen uptake rate during 20 days composting processes. The oxygen uptake rate (OUR) of T1, T2, T3, T4 and T5 decreased from 13.1, 9.3, 12.4, 13.8 and 8.5 mg g^{-1} volatile solids (VS) d^{-1} to 2.0, 2.0, 2.3, 1.9 and 1.3 mg g^{-1} volatile solids (VS) d^{-1} respectively, whereas CO_2 evolution rates decreased from 6.0, 4.7, 5.1, 5.1 and 4.0 mg g^{-1} (VS) d^{-1} to 2.6, 2.1, 2.6, 2.0 and 2.6 mg g^{-1} (VS) d^{-1}. Data were analyzed by ANOVA that shows the OUR varied significantly between days ($P<0.0001$) and different mix proportions ($p=0.0017$). The change in percentage in OUR values from initial value is found to be 84, 78, 81, 86 and 84% in T1, T2, T3, T4, and T5 respectively after 20 days composting process. A decrease in CO_2 evolution rate of respiration was observed in all trials, except for trial T4. Final results show the percentage decrease of 57, 56, 49, 61 and 33% in the rate of respiration achieved in T1, T2, T3, T4, and T5, respectively (Fig.4.7 (b)). Data were analyzed by ANOVA that shows CO_2 evolution rate varied significantly between days ($P<0.0001$) and different mix proportions ($P=0.0004$).

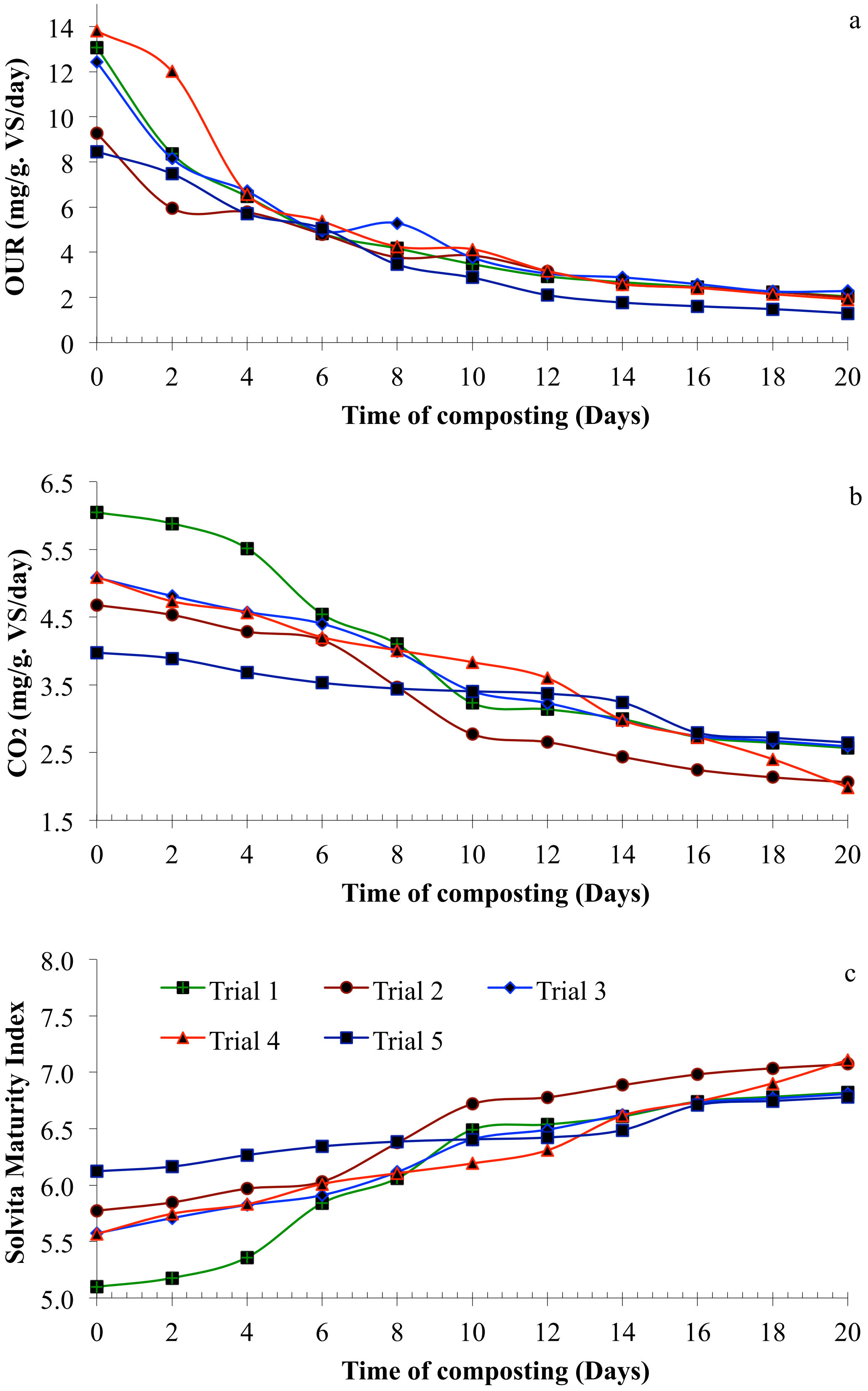


Fig. 4.7. Variation in a) Oxygen uptake rate, b) CO_2 evolution rate and c) Solvita maturity index

Based on CO_2 evolution, Solvita maturity index was calculated (Brinton, 2001; Kalamdhad et al. 2008). The stability trend varies inversely with the respirometry process, which depends upon the Solvita maturity index. The Solvita maturity index indicates the maturity of C/N ratio after 20 days of composting. In the present study, the Solvita maturity index (Fig. 4.7 (c)) is increased from 5.1, 5.8, 5.5, 5.7 and 6.1 to 6.8, 7.1, 6.8, 7.2 and 6.7 for trails T1, T2, T3, T4, and T5 respectively which is based on CO_2 evolution. From these observations, it can be said that the rotary drum used in this particular study is efficient for composting of *H. verticillata*.

- ***Coliforms***

The sanitary quality of compost is expressed by the presence of coliform bacteria. The Fecal density value for compost hygienization is 5×10^2 MPNg^{-1} dry weight (Vuorinen and Saharinen, 1997). Table 4.2 indicates the decrease in total coliforms levels at the initial stage of composting. The reduction observed was due to the high temperature and unfavorable conditions during the thermophilic phase (Hassen et al., 2001).

Table 4.2. Values of Total and Fecal Coliforms for 20 days rotary drum composting of *H. verticillata*

		Total Coliforms			Fecal Coliforms		
Trials	Proportion	0-day	10-day	20-day	0-day	10-day	20-day
T1	5:4:1	2.3×10^6	9.3×10^3	2.3×10^2	4.3×10^5	2.3×10^3	1.50×10^2
T2	6:3:1	2.3×10^5	1.5×10^4	2.3×10^3	2.3×10^4	9.3×10^2	7.5×10^1
T3	7:2:1	4.30×10^4	7.5×10^3	9.3×10^2	2.3×10^4	2.3×10^2	4.3×10^1
T4	8:1:1	1.5×10^6	1.5×10^3	1.5×10^1	4.3×10^5	2.1×10^2	2.1×10^0
T5	10:0:0	7.50×10^5	9.3×10^4	7.5×10^3	2.3×10^5	2.3×10^4	4.6×10^3

The decrease in total coliforms is found higher in T4 as compared to other trials, due to the high temperature (53°C). The average number of fecal coliforms decreased considerably, from 4.3×10^5 to 2.1×10^1 MPN g^{-1} dry weight in T4, while for T1, T2, T3, and T5 decreased, from 4.3×10^5 to 1.5×10^2, 2.3×10^4 to 7.5×10^1, 2.3×10^4 to 4.3×10^1 and 2.3×10^5 to 4.6×10^3 MPN g^{-1} dry weight, respectively during 20 days of composting. The observations are may be due to the formation of thermophilic phase during initial days of composting.

4.1.3 Concluding Remarks

During the 20 day process of composting, the trial 4 showed the maximum temperature of 53°C that indicates the development of thermophilic phase (>45°C). Daily turning of rotary drum (one rotation) helps to provide proper aeration that in turn triggered 15% decrease of moisture content in Trial 4 i.e. 8:1:1, which is highest amongst all trials. *H. verticillata* is nitrogen rich, and during the process of degradation, the increase is an amount of nitrogen is observed that agrees on the range of 3.3-3.5%. Increase in total and available phosphorus, sodium, potassium, calcium, and magnesium is also recorded. Trial 4 shows the highest reduction in sBOD, sCOD, CO_2 evolution rate and OUR values during the 20 days composting process. The solvita index is in the range of 7.0-7.2, which is an indicator of stable compost.

4.2 PHASE 2 - COMPOSTING PHYSICS DURING COMPOSTING OF VARIOUS ORGANIC WASTES: A COMPARATIVE STUDY

In this Phase 2 as mentioned in chapter 3 (3.1 Experimental design section), The physical properties were determined during composting of various organic wastes and a comparative study was made.

The study was conducted to provide better insight on composting physics for various organic waste materials using batch mode rotary drum composter. The multivariate statistical analyses such as scatter plot matrix and principal component analysis (PCA) were used to understand the variability between the parameters. Another important aim of this study is to assess the feasibility of end product (compost) application in the soil for agricultural or engineering fields. Hence, the composting study was carried out on different organic wastes, i.e., municipal waste (vegetable wastes), aquatic biomass (*H. verticillata* and water hyacinth) and solid sludge (sewage and paper mill). The results and discussion of entire study is divided into following sections: (1) Insight on organic matter degradation and first-order kinetics; (2) insight on composting physics; (3) statistical correlation between physical parameters using scatterplot matrix and principal component analysis (PCA); (4) feasibility of end product for application in either agricultural or civil engineering fields.

4.2.1 Organic matter degradation and its kinetics

The degradation of organic matter occurs due to the biological activity of microorganisms during the composting process. In the initial thermophilic phase of the composting process, the mineralization process initiates, which in turn causes rapid loss of organic matter. But as the process enters secondary mesophilic phase, the slower reduction in organic matter occurs indicating stabilization of the compost. The initial volatile solids content recorded for the present study were 78, 82, 74, 53, and 47% for Runs (A-E), respectively. The lesser the volatile solids content in Drums (D and E) indicated the lower organic matter availability. As the Drums (A-E) achieved the thermophilic temperatures, the maximum organic matter degradation rapidly occurred. The volatile solid content reduction followed the same pattern as that of moisture content reduction, i.e., maximum reduction occurred in Drum D that was comprised of sewage sludge. The reduction pattern that has observed for volatile solids was Run D > Run B > Run A > Run C > Run E. The volatile solids content recorded for the final day were 66, 62, 65, 32 and 41%, respectively.

- ***Composting kinetics***

The organic matter decomposition during composting over the period of time follows first-order kinetics and expressed as:

$$\frac{d(OM)}{dt} = -k(OM) \quad (4.1)$$

where: OM is the quantity of decomposable organic matter at any time of the composting process in kilograms, t is time in days, k is the first-order reaction rate constant (days^{-1}).

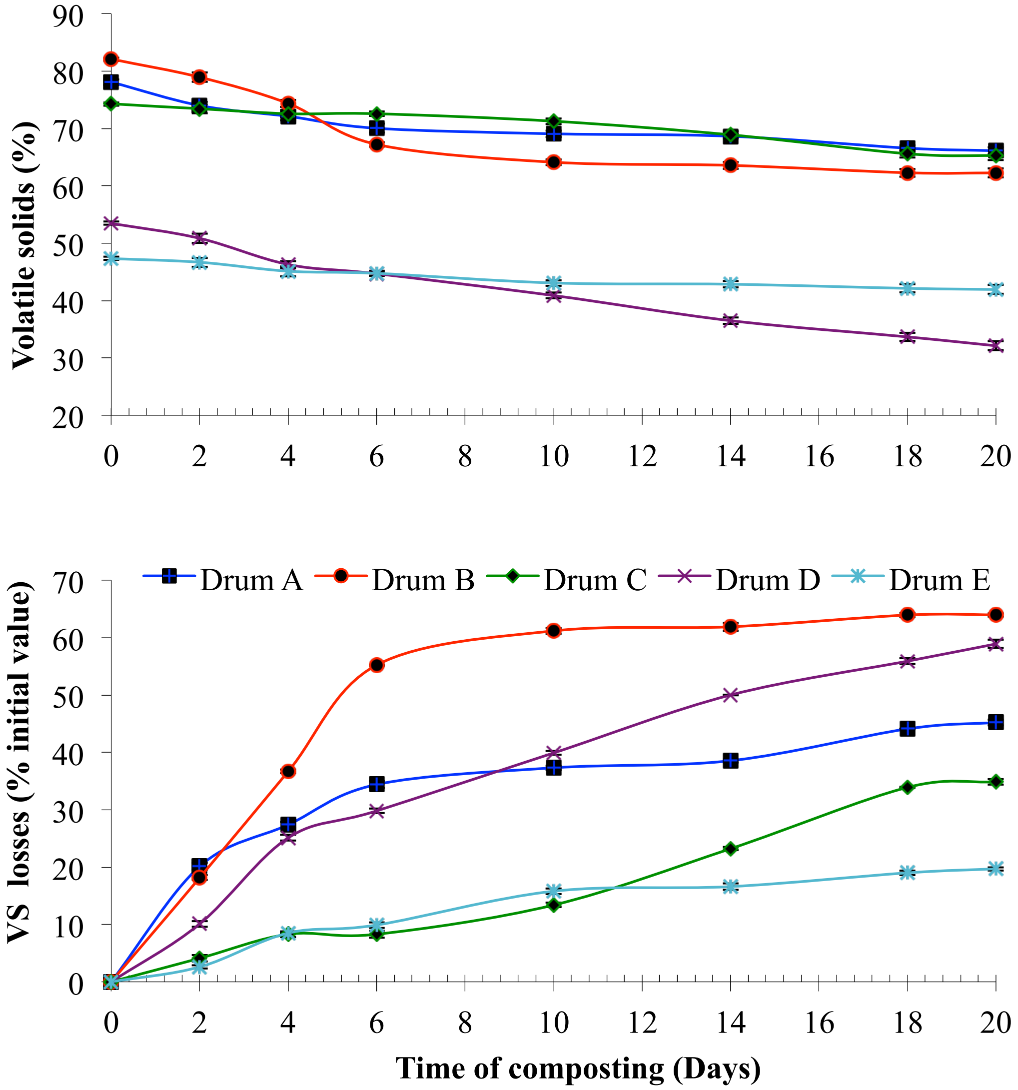


Fig. 4.8. Volatile solids and VS losses during composting process

The kinetic study aid in assessing the loss of organic matter during composting process over the period. The kinetic study is carried out using experimental data obtained in this study for various organic wastes

Integrating Eq. 5 by letting OM = OM_0 at t = 0, the concentration of organic matter at any time in the compost mixtures can be expressed as follows:

$$Ln\left(\frac{OM}{OM0}\right) = -kt \tag{4.2}$$

Simplifying eq.6 we get,

$$\text{OM loss} = OM_0(1 - e^{-kt}) \tag{4.3}$$

The curve fitting values from the experimental composting data for the drums (A-E) is tabulated in Table 4.3. All equations were noteworthy at $P < 0.05$, although the degradation kinetics of drum B and D fitted this equation better compare to other drums, as shown by the higher F and lower RMSE value of the drums. The organic matter degradation rate was abysmal for the composting of paper mill sludge (Drum E), as confirmed by the lower value of k. However, the rotary drum composter was observed to be efficient for composting of water hyacinth (drum B) > *H. Verticillata* (drum A) > vegetable waste (drum C) > sewage sludge (drum D) > paper mill sludge (drum E). This lower decomposition rate may have been owing to the least organic matter in drum E, which caused unfavorable conditions for microbial activity. The plot between OM losses and time is shown in Fig. 4.8b.

4.2.2 Composting physics

- ***Temperature study***

The biological activity and the composting process dynamics can be understood by monitoring temperature profile (Awasthi et al., 2016). As represented in Fig. 4.9, all the Runs (A-E) exhibited typical pattern of temperature phases i.e. initial thermophilic phase immediately followed by cooling phase. But the conventional composting technologies exhibit four temperature phases (mesophilic, thermophilic, second mesophilic and cooling phase). This temperature pattern in rotary drum composter showed rapid reduction in the time required for the stability of the compost. During the start of the composting process, the mean maximum temperature in the two drums A and D were recorded between 40-45°C whereas the remaining drums B, C and E depicts a range of 30-35°C. The reason behind such less initial temperature in drums (B, C and E) is might be due to its lignocellulose property, which kept the temperature much lower compared to other drums (A-C). The ambient temperature was also monitored each day during the composting process. The range of ambient temperature was recorded from 22±0.7 and 26±0.5°C.

The temperature rise was observed immediately after attaining the feasible composting conditions in all the drums (A-E). This fact is due to the biological activity or microbial decomposition that caused release of heat. Moreover, the addition of cow dung and sawdust in all the runs attributed to increase of temperature.

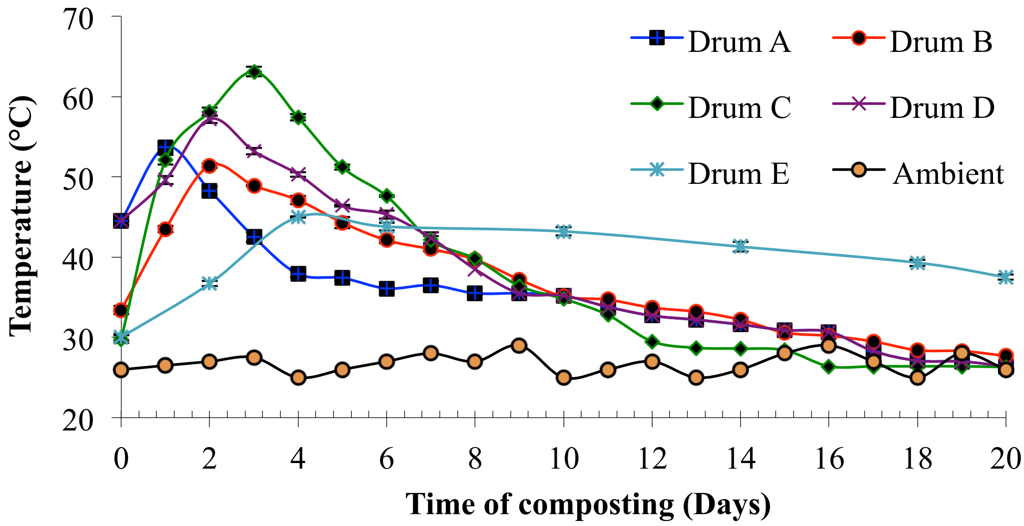


Fig. 4.9. Temperatures during composting of different organic wastes

The maximum temperature was recorded for the drum C (64.2°C on day 3) followed by drum D (57.4°C on day 2), drum E (53.1°C on day 1), drum B (51.3°C on day 3) and drum A (45°C on day 2). As anticipated, the rotation of the composter resulted in loss of heat, which in turn caused decrease in the temperature. The temperature for all the drums (A-E) started attaining the temperature nearer to ambient i.e. 27°C from day 18. According to Haug (1993) for the self-destroying of the harmful pathogens as well as weed seeds the thermophilic phase (>45°C) for more than three days is essential. All the runs except for the drum E followed this pattern of temperature. However, the research studies on composting of various organic wastes by Sadaka and El-Taweel (2003); Margesin et al. (2006) Zhang et al. (2013); Liu et al. (2017) indicated that the composting process should retain the temperature range of 55-60°C for more than 3 days, for complete reduction in pathogens as well as to achieve standard sterilization. In this study, only drum C achieved the requirement of temperatures (55-60°C).

- ***Moisture study***

Each waste has its unique moisture holding capacity that also affects the composting process. Thus, each of mixtures were mixed with sawdust to provide feasible composting conditions.

The biological activity during decomposition that occurs during the process also contributes moisture content to the process. At the start of the process the moisture content of the composting mixtures were recorded for all drums (A-E) as 86.3±0.3, 84.7±0.6, 67.9±0.7, 60± 0.5, and 47.2±0.4%, respectively. As anticipated the drum A and B exhibited highest amount of moisture as aquatic weeds are considered to be the moisture's substrate. The recommended range of the moisture content for the compost mixture should be between 60-70%. However, research studies revealed that several organic wastes have been composted in the range (about 60–80% on a wet basis) (Willson, 1989; Haug, 1993; Richard et al., 2002; Cronje et al., 2004; Singh and Kalamdhad, 2013). The end product moisture content of the composting mixtures for drums (A-E) are shown in Table 4.4. The moisture content also plays a significant role during the composting process as it affects the composting physics. The more the moisture content the less is the air movement.

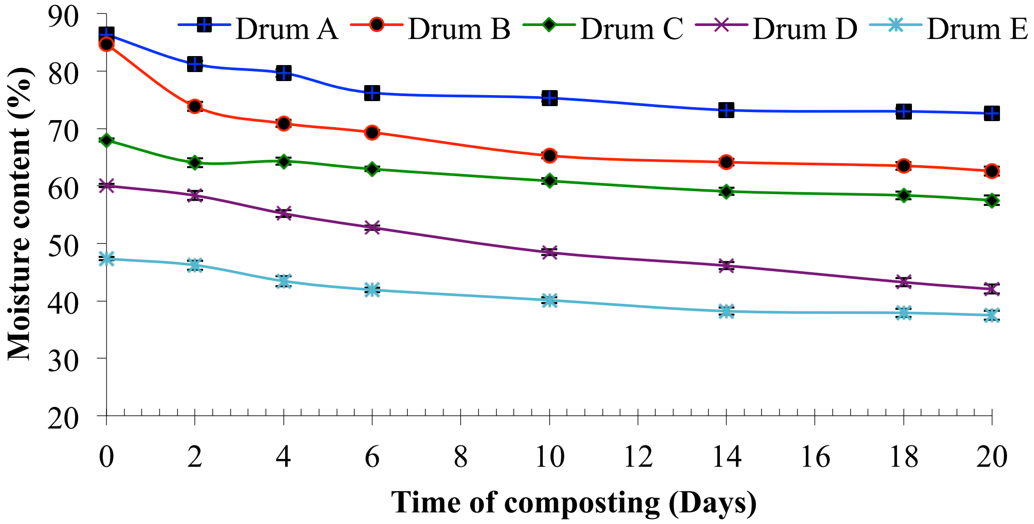


Fig. 4.10. Moisture reduction during composting of different organic wastes

The higher moisture content also increases the bulk density of the mixtures. The composting process causes loss of moisture content during the decomposition of organic wastes due to microbial activity. Maximum reduction was achieved during the composting process was in thermophilic phase in all the drums (A-E).

The percentage reduction observed in thermophilic phase was about 55, 76, 67, 64, and 59%, respectively, for all the drums (A-E). The reason for this reduction of moisture content can be explained owing to loss of vapors due to biologically produced heat. The addition of sawdust that is moderately dry in nature also aid in reducing moisture content and provided sufficient free air space within the composting mixtures (Eftoda and McCartney, 2004; Singh and Kalamdhad, 2014).

The moisture content at the end of the process was recorded as 72, 62, 57, 42, and 37.5 for drums (A-E), respectively. Thus rotary drum composter significantly observed to be effective technology to treat various organic wastes with significant reduction in moisture content in 20 days. However, conventional composting technologies (windrow/pile methods) take 30-120 days to achieve such reduction in moisture content (Khalil et al., 2008; Zhang et al., 2013).

- ***Bulk density***

Besides above discussed parameters (temperature, moisture content and volatile solids) the other physical parameters (bulk density, free air space, porosity, particle density, void ratio) of compost are considered to be the most important and composting process regulating parameters. These parameters hold a strong relationship with each other and may cause strong impact on the process if not monitored or controlled (Diaz et al., 2002; Iqbal et al., 2010). Bulk density evaluation is necessary to understand the extent of volume reduction of the composting mixtures. The volume reduction occurs as a result of organic matter degradation by the microorganisms. Moreover, bulk density determination also provides brief idea on the container to be hauled and for designing of the compost handling systems. The initial bulk density for drums (A-E) was recorded as 400, 308 312, 658, and 674 kg m^{-3}. The bulk density values for each waste are different and depend on the weight of particular wastes. The lighter the weight of wastes the lesser the bulk density and a vice versa and the present study followed same trend.

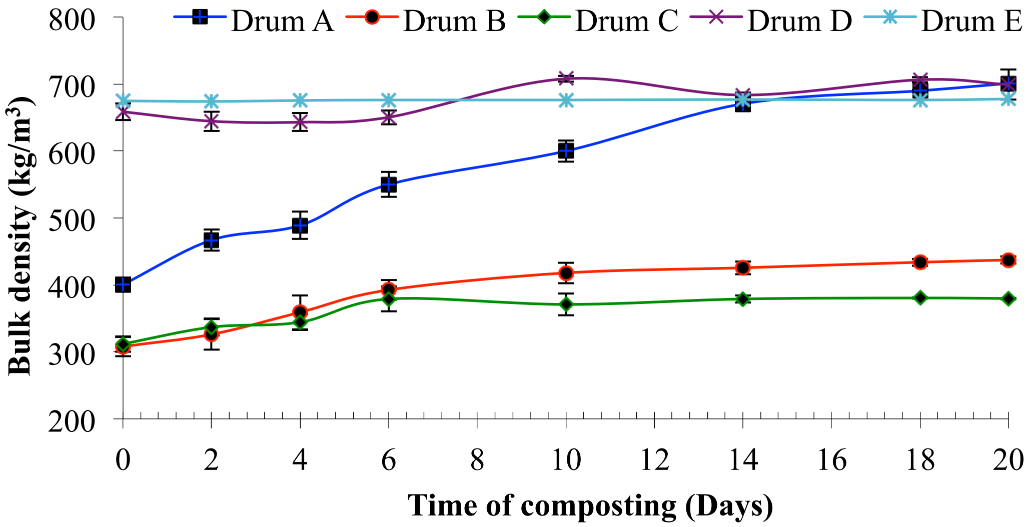


Fig. 4.11. Bulk density variation during composting of different organic waste

Table 4.3. Parameter values of the first-order equation describing organic content decomposition.

Trial names	A (%)	k (days^{-1})	RMSE	F
Drum A	45.2	0.019	6.221	3.8648**
Drum B	64	0.033	11.722	10.82506**
Drum C	34.9	0.014	2.223	3.2501**
Drum D	58.9	0.050	4.432	8.3261**
Drum E	19.7	0.011	2.211	1.02515**

where, A – Maximum degradation, k – rate constant, RMSE – Root mean square error, F – factor significant at $^{**}P < 0.01$

Table 4.4. Characteristics of final compost

Parameters (Units)	Final product in drums				
	A	B	C	D	E
Moisture content (%)	72±2	62± 2.5	57± 1.1	42± 0.4	37.5± 0.2
Volatile solids (%)	66±0.1	62±0.4	65±0.4	32± 0.4	41±0.2
Bulk density	761± 15	437±12	379±10.5	699±3.7	677±5.9
Free air space	35±1	59±0.5	66±0.0	44±0.2	51±0.1
Porosity	90.7±0.5	94.9±0.3	95.5±0.5	86.6±0.7	88.46±0.3
Total kjeldahl N (%)	3.3±0.1	2.1±0.1	2.3±0.1	0.3±0.05	0.9±0.1
Total P (g/kg)	4.3±0.2	2.6±0.2	1.21±0.1	2.66±0.3	0.9±0.1
K (g/kg)	35.1±1.1	5.6±0.5	25.2±0.2	9.94±0.1	2.3±0.3

The biological activity throughout the composting process causes reduction in organic matter, which in turn reduces volume of the wastes that increases the bulk density of the composting mixtures. The current study showed increase in bulk density by 70, 29, 20, 5, and 4% for drums (A-E), respectively, from the initial values. The final products were having bulk density as 728, 437, 379, 699, and 677 kg m^{-3}. The more the bulk density (> 1000 kg m^{-3}) the higher is the amount of moisture content and bulk density is less than 300 kg m^{-3} at the end of the process cause dryness of the compost. The determination of bulk density also aid while applying the compost in the soil.

- ***Free air space and porosity***

Free air space is the available voids of the air between the various raw materials used for the preparation of composting mixtures whereas porosity is referred to be the availability of air and water both within the pores of the composting mixtures. The microorganisms for their regular metabolic activity consume the oxygen. To determine water-holding capacity of the compost the information on size and distribution of the pores is essential (Agnew and Leonard, 2003). Free air space less than 30% initially is the indication that there is a very less microbial activity in the composting process. Moreover, composting process releases carbon-di-oxide, which is eliminated through appropriate airflow (Haug, 1993). Therefore, it is essential to monitor the free air space throughout the process. Free air space of the composting mixtures can be increased or maintained by the addition of various bulking materials. The current study recorded initial free air space as 86, 72, 72, 47, and 66% in drums (A-E), respectively. However, throughout the composting process the free air space was observed to be declining. The reason for declining FAS is due to decomposition of organic matter by biological activity. The microbes consumed the available air/oxygen which made the mixture more compacted i.e. volume reduction or increase in bulk density as a result FAS observed to be declined. The study indicated FAS in final product as 50, 59, 66, 44, and 51% in drums (A-E), respectively. The least value of FAS in Run A was due to the type of the organic waste used and lesser moisture reduction during the composting process. Higher the moisture reduction during composting the more is the FAS available for the biological activity. Moreover, besides such a significant variation in free air space and bulk density, the porosity exhibited very small or negligible change. In all drums (A-E) the porosity was perceived to be within the range of 88-98% in the final product. This range of porosity is acceptable, as many researchers have obtained such small variation (85-95%) in the porosity (Prasad and Maher, 1993; Gabriels et al., 1993; Raviv et al., 1997; Mohee and Mudhoo, 2005).

- ***Particle density***

The ratio mass: volume of compost solids is referred as the particle density. Particle density is also known as absolute or true density (Villar et al., 1993). The study observed the varied pattern for various composting mixtures. But most of them followed the declining pattern over the period of time.

The initial mean particle density was recorded as 1751, 1800, 578, 1562, and 610 kg m^{-3}, respectively. Some authors have found constant values of particle density for various composting mixtures excluding van Ginkle et al. (1999). The later stated that the composting mixtures varied the particle density throughout the composting period, however, Brouillette et al. (1996) observed a constant value of 1250 kg m^{-3} during composting of paper mill deinking sludge. A study carried out on composting of vegetable wastes by Mohee and Mudhoo (2005) observed variation in the particle density from 1050 to 2250 kg m^{-3}. In present study, after 20 days composting process the particle density was recorded as 1751, 1800, 578, 1562, and 610 kg m^{-3} for drums (A-E), respectively. Therefore, from above it is noted that amendment of various materials during composting may affect the variation in particle density.

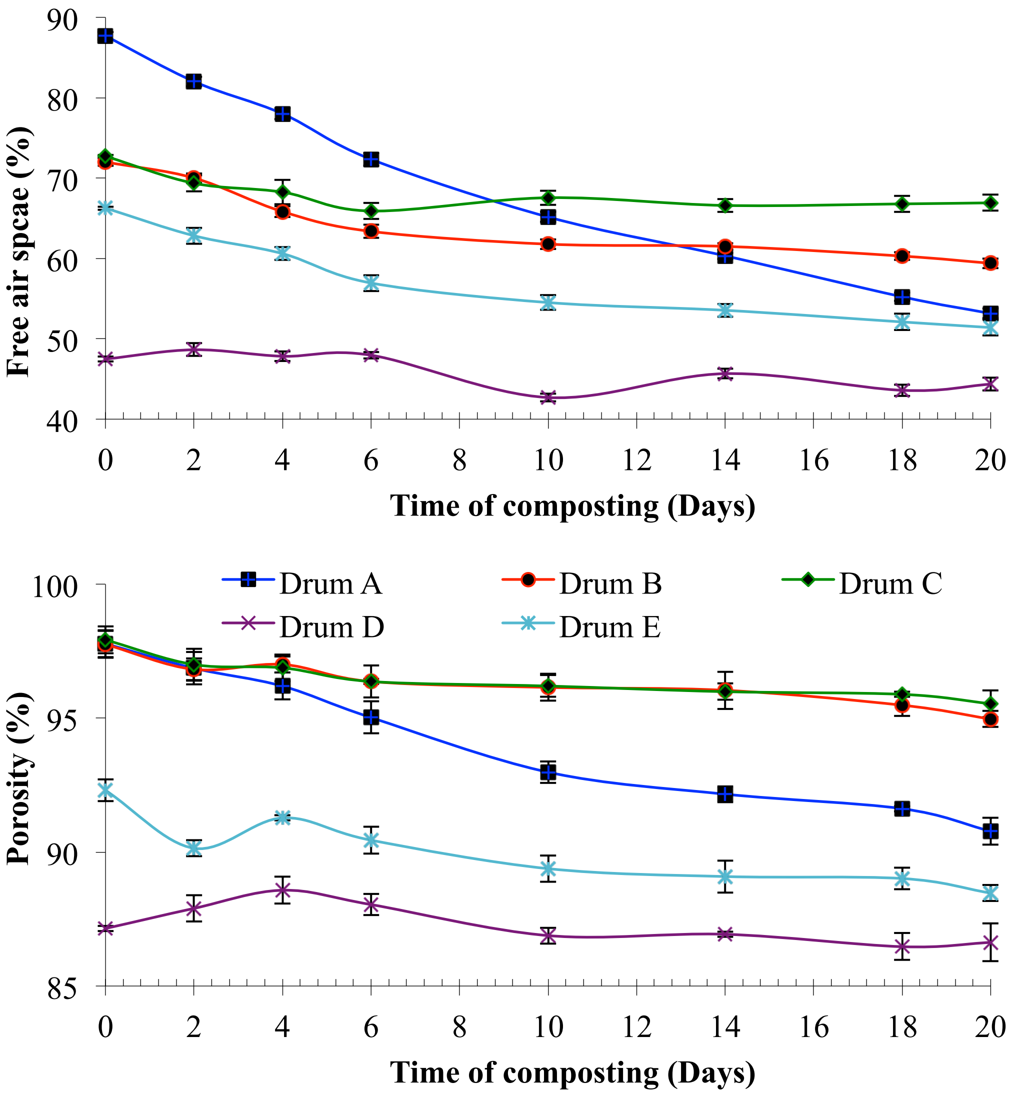


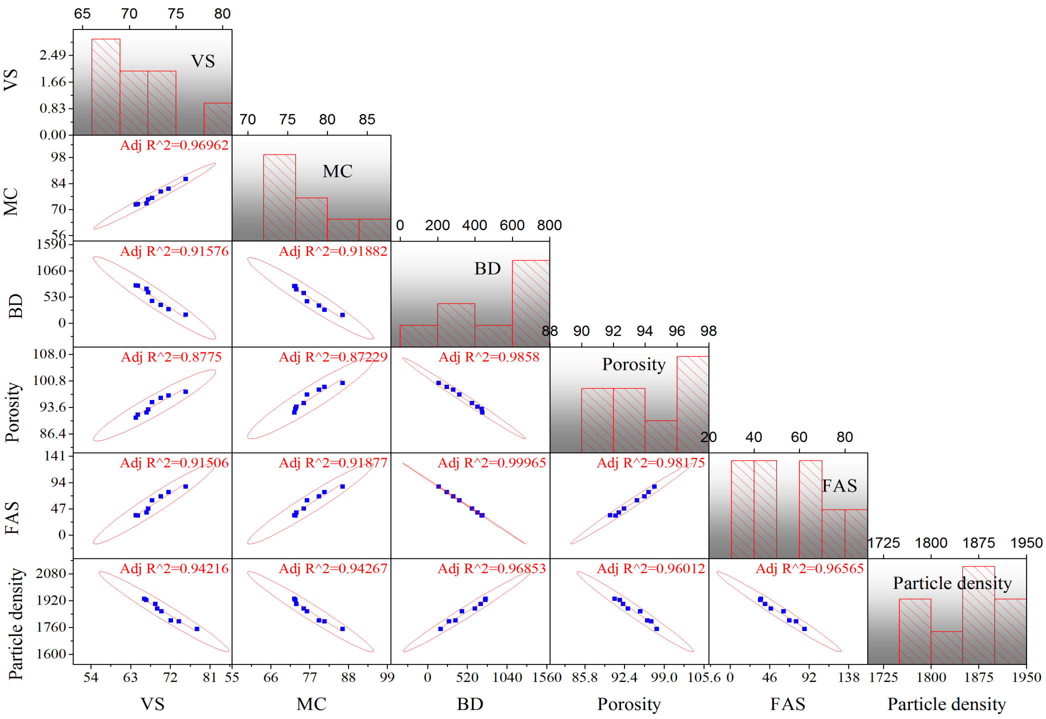
Fig. 4.12. Variation in FAS and porosity during composting process

4.2.2 Scatter plot matrix

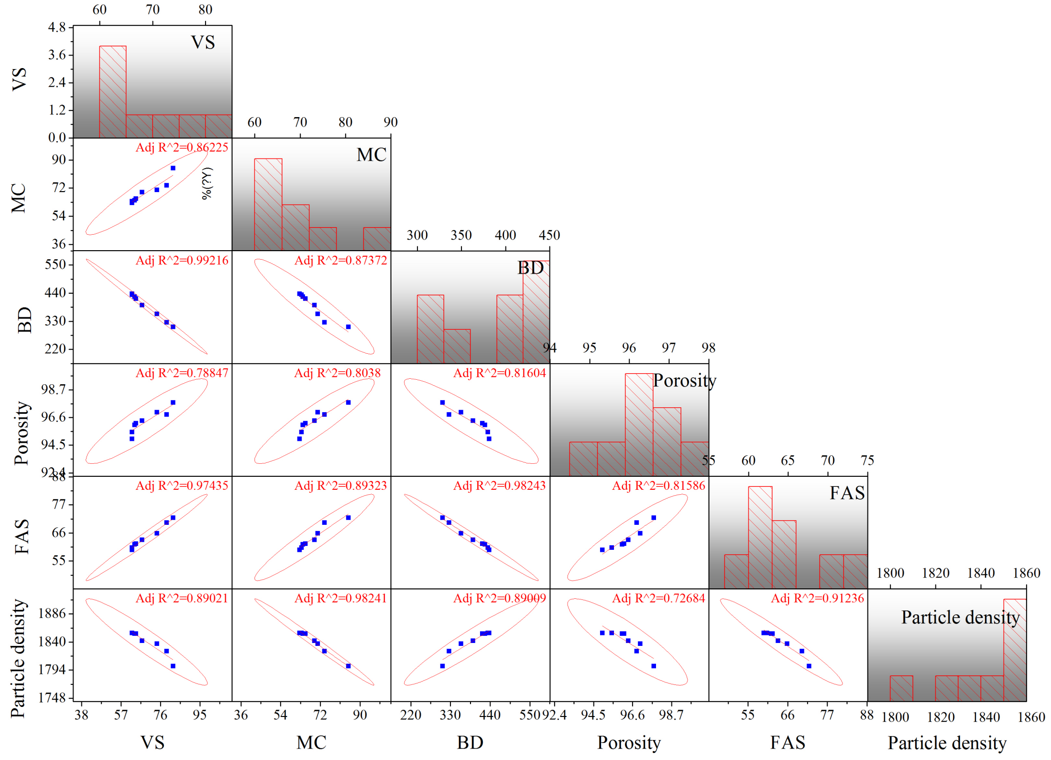
The various physical parameters are interacting with each other and aid in achieving best efficiency during composting process. It is therefore necessary to identify the correlation or involvement of various physical parameters that will be helpful to assess the extent of degradation for various organic wastes. A scatterplot is statistical tool that reveals association between two variables (Chambers, 1983). These relationships between two variables are also called as correlation. A scatterplot usually comprises of large amount of data. If the data points are closer and making a straight line then the plot is said to be having higher correlation between two variables or the deeper relationship and a vice-versa. Consider a given set of variables X_1, X_2, …., X_n. The scatterplot matrix comprises of all the pairwise scatterplots of the variables in a matrix format. It means suppose there are 'n' variable, the scatterplot matrix will have 'n' rows and columns and i^{th} row and j^{th} column of the matrix is the plot between X_i and X_j.

In this study, the scatterplot matrix was plotted between the physical parameters such as moisture content, bulk density, free air space, porosity, particle density and also volatile solids content to understand the effect of degradation on variation of parameters. For example, in Run B, i.e., the composting mixture having water hyacinth waste, the positive correlation was observed for variable (say volatile solids) with moisture content, free air space, and porosity, however, the negative correlation was observed with bulk density and particle density. Similar patterns were observed for the other organic wastes for the same variable, i.e., volatile solids with moisture content, free air space, and porosity, although the correlation coefficient was mostly greater in Run B. The similar observations can be made for various organic wastes to get an in-depth insight on correlations amongst other physical parameters. Another finding was observed from the scatterplot matrix that the drum D (sewage sludge composting) exhibited the lowest correlation amongst various physical parameters. The lowest correlation indicated that there was not enough organic matter available for biological degradation.

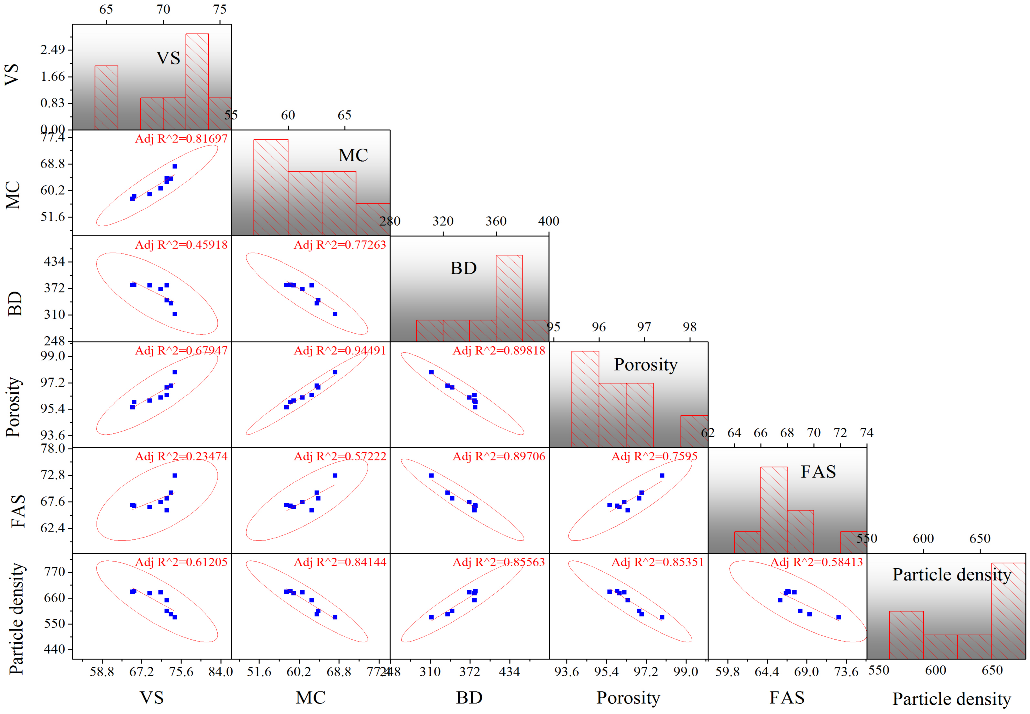
Therefore, it is understood that a small change in one variable may not cause significant impact on other variable, which in turn may not substantially affect the composting process for drum D. Hence; it is essential to perform such statistical studies on various organic wastes to understand the influence of single parameters on the other physical parameter.



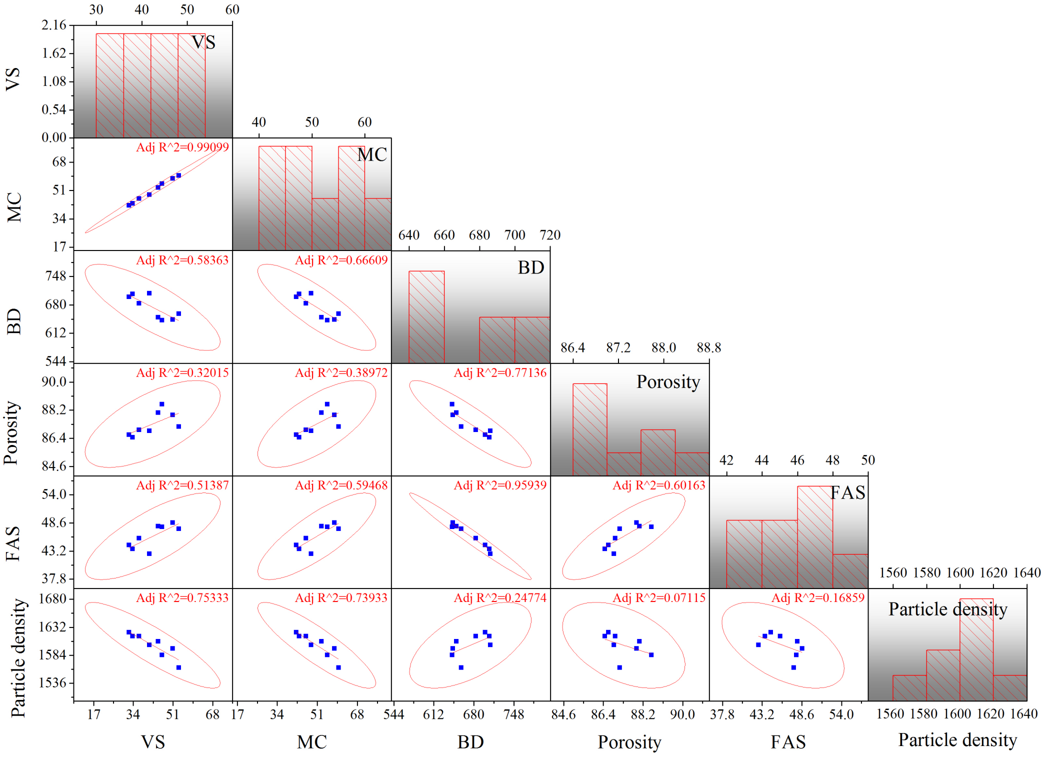
a. Scatter plot matrix amongst various physical parameters in Drum A



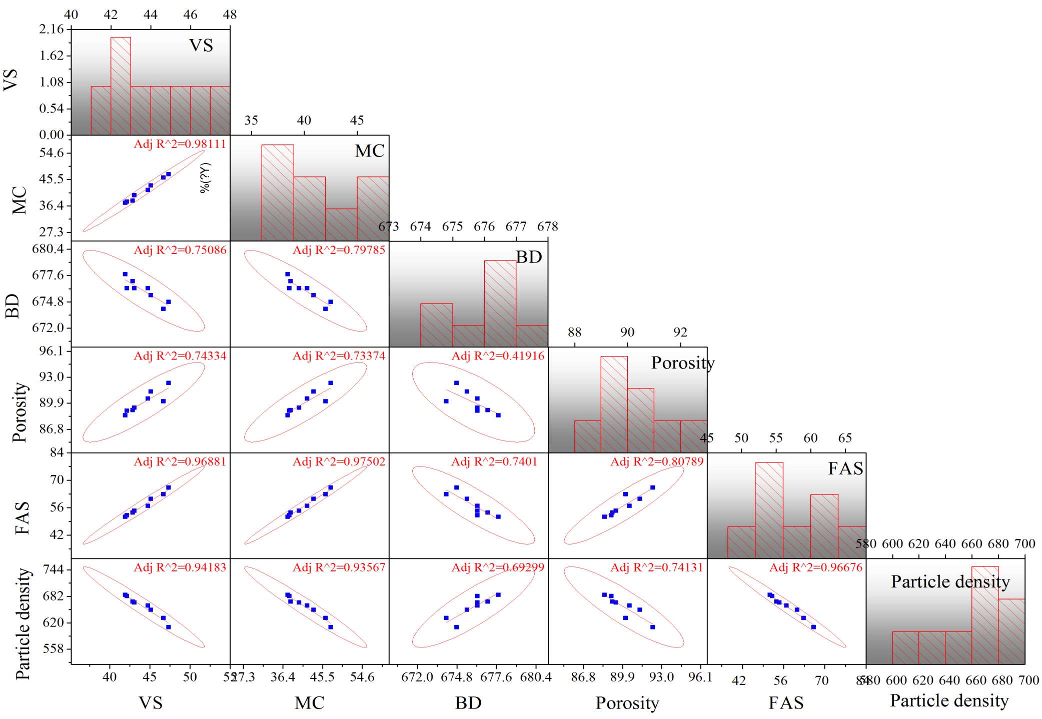
b. Scatter plot matrix amongst various physical parameters in Drum B



c. Scatter plot matrix amongst various physical parameters in Drum C



d. Scatter plot matrix amongst various physical parameters in Drum D



e. Scatter plot matrix amongst various physical parameters in Drum E

Fig. 4.13. Scatter plot matrix amongst various physical parameters

4.2.3 Principle component analysis (PCA)

To provide insight on composting physics, various physical parameters are to be determined since some researchers have reported that a solitary parameter is not adequate to assess final product (Gómez-Brandón et al., 2008). The compost quality parameters, measured at 20 days in 4-mm mesh-sieved products, are shown in Table 4.4. These data were subjected to a Principle Component Analysis (PCA). Since the PCA was trial on standardized variables, variable coordinates of every factor were the same as their correlation coefficient with each factor (Table 4.5). In this study, PCA was applied to two different data sets with the aim of studying composting of different organic wastes and physical as well as nutritional parameters during the composting process. Based on the PCA outcomes, two principal components (PCA$_1$ and PCA$_2$) having an eigenvalue more than or equal to 0.3 were obtained. The results are presented in Fig. 4.13. All the physical and nutritional parameters were observed in a circular-arc shape that explains the high correlation between the variables.

According to PCA, the first three axes indicated 82% of the total variation. The first axis indicated 42% and the variables most correlated with it were: TKN, P, K, Ca, MC and VS. The second axis explained 29%, with Na, VS, BD and FAS being the most correlated variables. The third axis indicated 11% was most correlated with Ca, Na, and PD as tabulated in Table 4.6.

Fig. 4.14 shows the simultaneous illustration of the variables and interpretations. The extremely correlated variables only integrated into the factorial planes. Interpretations only with good depiction quality were retained. For the better representation on the axis the data point (observation) should be closed to an axis. Hence, the squared cosine of the angle formed between the axis and the vector joining the origin and the data point can be used to evaluate the representation quality of an observation. When the sum of the relative contributions to each axis reached significantly high, it was considered that an observation was adequately represented on a given plane.

On the first factorial plane (Fig. 4.14 a), The drum with SS exhibited higher values of BD than that of drum comprising of IS that contains greater amount of lignocellulose matter. However, WH demonstrated higher nutritional values (e.g., TKN, K and P) compared to drum comprising of IS owing to accumulation of essential nutrients from the aquatic bodies. Although the Na and Ca was higher for WH than that of SS. The porosity, which is a physical parameter and is responsible for providing aeration for microbial activity was observed to be higher for VW and WH than that of IS and SS indicating the fact that FAS should be higher and is in accordance with the observation as shown in (Fig. 4.14 a).

On the second factorial plane (Fig. 4.14 b), the plot exhibited same drums which were observed in first factorial plane i.e., WT, VW, SS, IS, and WS. As observed for VW on the previous PCA plot, this PCA plot is also associated to highest Na content. The compost prepared from WH exhibited greater pH value, PD and P content. As anticipated the drum A exhibited highest porosity compared to other drums. Also reflected greater TKN and K content, which is due to its nutritional accumulation capacity.

In summary, Table 4.5 and PCA analysis show that, regardless of the type of material (compost), the composting of aquatic waste, i.e., WT and WH exhibited maximum nutrients content and higher porosity compared to other drums OM, while sludges, i.e. sewage and paper mill sludge exhibited lower nutritional values. The greatest VS values were obtained when the waste such as VW, WT and WH were composted. Moreover, IS and SS were exhibited highest BD values.

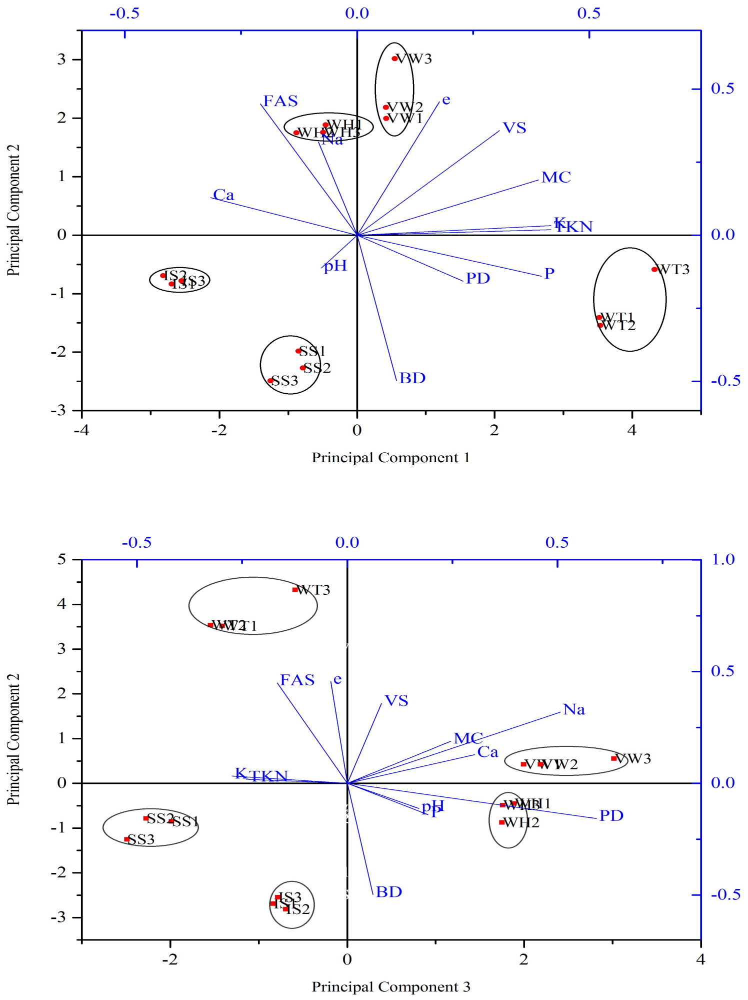


Fig. 4.14. Principle component analysis for five different organic wastes

Table 4.5. Eigen values of correlation matrix

No. of parameters	Eigen value	Percentage of Variance	Cumulative
1	5.00474	41.71	41.71
2	3.52502	29.38	71.08
3	1.28251	10.69	81.77
4	1.0774	8.98	90.75
5	0.68099	5.67	96.42
6	0.34486	2.87	99.30
7	0.05287	0.44	99.74
8	0.02367	0.20	99.93
9	0.00483	0.04	99.97
10	0.00178	0.01	99.99

11	0.0011	0.01	100.00
12	2.35×10^{-4}	0.00	100.00

Table 4.6. Extracted Eigen Vectors

Parameters	Coefficients of PC1	Coefficients of PC2	Coefficients of PC3
TKN	**0.42**	0.02	-0.24
P	**0.40**	-0.14	0.19
K	**0.42**	0.03	-0.27
pH	-0.08	-0.11	0.17
Ca	**-0.32**	0.13	**0.30**
Na	-0.08	**0.32**	**0.51**
MC	**0.39**	0.19	0.25
VS	**0.31**	**0.36**	0.08
BD	0.08	**-0.50**	0.06
FAS	-0.21	**0.45**	-0.17
PD	0.23	-0.16	**0.59**
e	0.18	**0.46**	-0.04

4.2.4 Concluding remarks

The results in the current study indicated the highest degradability rate in rotary drum composter for water hyacinth (Drum B) followed by *H. Verticillata* (Drum A) compared to other wastes. The paper mill sludge (Drum E) indicated the lowest degradability rate as confirmed from the lower k value. The maximum temperature depicted for Drum C was 64.2°C whereas the least depicted for Drum E. Amongst all the drums the Drum E was the one that did not achieve thermophilic (>45°C) temperatures which is the primary factor that affects composting process. Considering other physical properties such as moisture content and bulk density the maximum reduction in both properties achieved in the Drum A and Drum B. Despite such a considerable variation in the bulk density and moisture content the porosity in all the drums (A-E) showed minimal variation and observed in the range of 88-98%. From the scatterplot matrix plot, noted that most of these physical properties were correlated with each other.

Amongst all physical properties, the free air space and bulk densities were highly positively correlated in all the drums whereas the least correlation observed in porosity and bulk density. Therefore, it can be concluded the variation in bulk density has a substantial impact on the change in free air space and the small effect on porosity. Moreover, PCA study indicated the higher nutritional values in the compost obtained from the water hyacinth and water thyme whereas higher bulk density for the compost obtained from sewage sludge and paper mill sludge. The higher bulk density compost is not suitable for agricultural soil application.

4.3 PHASE 3 - ROLE OF VARIOUS CARBON-RICH AGENTS DURING COMPOSTING OF *Hydrilla verticillata*

This Phase 3 as mentioned in chapter 3 (3.1 Experimental design section) is on the role of carbon-rich agents during composting was carried out in two different parts. In first part, the locally available carbon-rich agents (dry leaves, grass clippings and wood chips) were utilized to minimize the effect of higher moisture content during composting of *H.verticillata.* Whereas in the second part, the novel carbon-rich agent, i.e., biochar was utilized in four different proportions as discussed in chapter 3 (section 3.4).

4.3.1 Role of locally available carbon-rich agents

Previous studies suggest that *H. verticillata* have tremendous potential to produce biogas or can be utilized as a feedstock for composting (Evans and Wilkie, 2010). However, its high moisture content and low C/N ratio do not provide possible composting conditions (Huang et al., 2004). The study on composting of the *H. verticillata* has reported higher moisture content in the final product. The higher moisture content in the compost makes it unfit for soil application (Varma and Kalamdhad, 2014; Singh et al., 2016). Moreover, lesser porosity and higher bulk density in compost may cause adverse effects on physical properties of soil. Many researchers reported that amendment of carbon-rich agents (CA) or bulking agents could be an option to achieve better reduction in moisture content as well as it improves physical properties. It absorbs excess moisture content from the substrate thus improving the degradation kinetics and composting performance (Chang and Chen, 2010). It also modifies the physical characteristics of the composting feedstock and enhances the overall composting process. It provides structural support when the composting substrate is too wet to maintain air availability within the compost matrix (Yamada and Kawase, 2006). Shao et al. (2014) stated that CA could improve the stability of organic wastes and reduce harmful pathogens and parasites.

Therefore the novelty and main aim of this study were to assess the use of the locally available CA for the composting of nitrogen-rich aquatic waste (*H. verticillata)*, which signifies an abundant organic waste. The three different locally available CA (dry leaves, grass clippings, and wood chips) were selected for composting of *H. verticillata* and compared with control (8:1:1) study : 1) This research work was conducted to study the composting physics and the degradation kinetics of the composting process that is added with CA; 2) how the addition of various carbon-rich agents affected the stability properties and nutritional quality of initial feedstock mixture and in end compost were studied, and 3) correlations between different physical parameters were evaluated.

- ***Temperature and moisture study***

The mean temperature in the core of the Run A, B, C and control were 43.5±5.5, 48.6±7.8, 41.5±2.8°C and 33.2±0.6°C, respectively. The ambient temperatures varied between 22±0.7 to 26±0.5°C (Fig. 4.15a). Heat is evolved as microbial decomposition initiation and temperature is raised due to the accumulation of metabolically generated temperature. The regulation of the temperature is essential for controlled composting (Bernal et al., 2009). Typically, the heat of the composting matrix was increased shortly after the establishment of the composting environments. For runs (A-C), as anticipated, the temperature increase was relatively rapid until it began to plateau; the thermophilic condition (>45°C) was attained within 24 h of feeding the feedstock's in the composter. The addition of CA aid to elevate the temperature of runs (A-C). But the control (without addition) exhibited slower increase as no addition. The highest temperatures for runs (A-C) and control were recorded as 55.0, 68.4, 51, and 45.1°C respectively. This increase in temperature was higher in runs (A-C) due to the addition of inoculum (cow dung) and CA. Both have enhanced the biological activity and elevated the temperature of the composting process (Karadag et al., 2013). Thermophilic phase (>45°C) lasts longer for 5, 9 and 3 days, respectively for runs (A-C) mainly due to addition of CA, whereas control showed only 1-day thermophilic phase. Shortly after that, the temperature started falling and the mesophilic phase developed in Run A, Run B, Run C and control. The heat loss is principally through suppressed heat associated with evaporation of water (Yamada and Kawase, 2006). During the first 7 days of the composting process, temperatures of Run A, Run B, Run C and control exhibited the higher noteworthy difference ($p<0.05$), which might have established from the improved biological activities. The temperature continued reducing until the 20th day of the composting process and was noted closer to ambient (27°C) temperature. There was no noteworthy variation observed between the runs and control when the overall composting duration (20 days) was considered. The existence of microbial consortia in the inoculum improved the degradation process and significantly concentrated the volume of the waste during composting. The addition of inoculum and CA increases air availability and water holding of the initial feedstock, which enhanced the degradation process and aid to maintain elevated temperatures (Eyheraguibel et al., 2008).

A study reported on composting of vegetable wastes added with dry leaves, and cow dung indicated the peak of temperature (69.1°C) using rotary drum composter (Varma et al., 2014). In current study only Run B satisfies the temperature condition as given by Zhang et al. (2013) that reported the composting process should withstand the temperature range between 55-60°C for minimum 3 days, to obtain pathogen-free compost. Runs A, C and control showed temperatures (<=55°C) that indicated they did not meet the sanitation requirement and thus may contain pathogens.

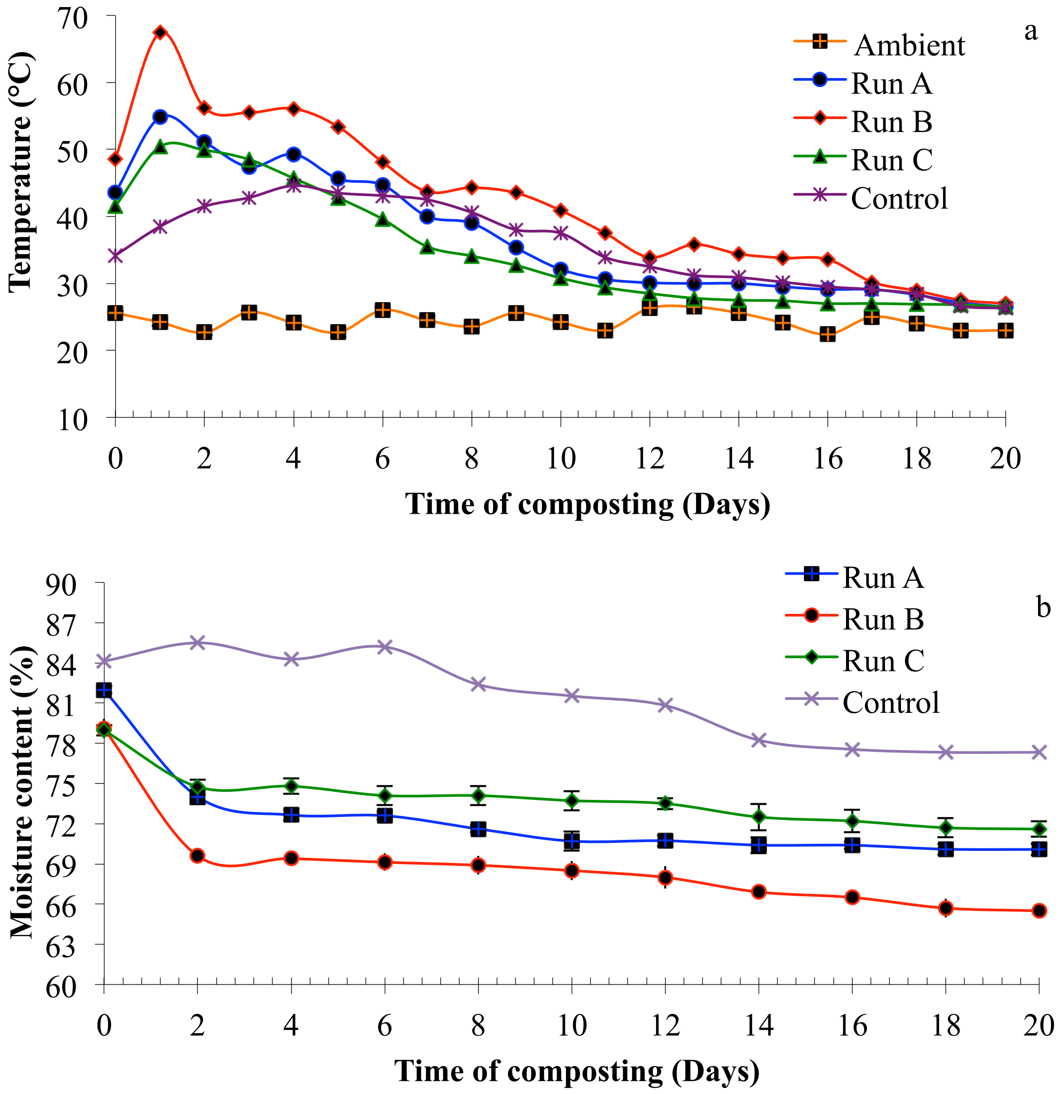


Fig. 4.15. Variation in a) Temperature, b) Moisture content during composting

The moisture content of *H. verticillata* (92-94%) and cow dung (86-88%) was very high but lower in CA. Silva et al. (2014) reported that the composting process is severely affected by moisture content that plays a significant role to maintain feasible conditions of composting.

The study reported by Huerta-Pujol et al. (2010) indicates that the moisture content of the compost matrix considerably impacts microbial activity. The moisture content recorded initially was 82.0 ± 0.3, 79.1 ± 0.7, 78.9 ± 0.4 and 84.1±0.5% for Run A, Run B, Run C and control, respectively. Degradation processes by biological activity of microbes cause loss of moisture content in compost mixtures (Varma et al., 2014). CA moreover, having the affinity to provide aeration for attaining a faster rate of degradation. It was witnessed that added CA lowered the moisture content of compost matrix by 14, 17, 9 and 8% for runs (A-C) and control, respectively at the end of the composting process as illustrated in Fig. 4.15b. Due to the accessibility of readily biodegradable organic matter, thermophilic temperatures (>45°C) were recorded within 24 h, and leachate formation was not witnessed during the composting process, but control exhibited a little quantity of water on day 4 (personal observation). A study on rotary drum composting of vegetable wastes reported the significance of CA for reducing moisture content (Kalamdhad et al., 2009; Varma et al., 2014). In the present study, the moisture content of the end compost was recorded as 70, 65, 71 and 77% for Run A, B, and C, and control respectively. Thus CA played an important function in arresting moisture content thus prevented leachate production in all runs (A-C) during the composting process. According to Khalil et al. (2008) and Zhang et al. (2013), conventional composting requires 90–270 days to produce a stable and matured compost product. In the current study, though, the production of a mature and steady compost by the rotary drum composter required only 20 days with the optimum combination of CA (10%), indicated that it significantly reduced the time required to obtain a stable compost. The similar pattern was observed during composting of *H. verticillata* added with biochar. The moisture content of Run A, B, and C, and control exhibited the greater noteworthy difference ($p<0.05$).

- ***Volatile solids reduction (VS) and carbon (C) decomposition***

The initial volatile solids (Fig. 4.16a) content were persuaded by the properties of the CA utilized for preparing the composting mixtures. The maximum reduction occurred during thermophilic stage (>45°C). The highest VS values were found in control (76.3%), Run A (73.6%) and B (71.8%), whereas the mixture prepared added with wood chips, i.e., Run C had an initial VS content of 69.9%. Rendering to the preliminary characterization of each material utilized in the initial feedstocks, it is possible to note, the lower initial volatile solids levels of wood chips, a Run C was with the lowermost levels for this parameter during the initial stage of the process.

Minimum volatile solids reduction was observed for Run C (7.3%), which was added with wood chips as a carbonaceous agent after control (6.9%). At the end of the composting process the VS dropped to 65, 57, 65 and 71% respectively, for Run A, B, and C, and control. The VS content of runs (A-C) and control exhibited the greater noteworthy difference ($p<0.05$).

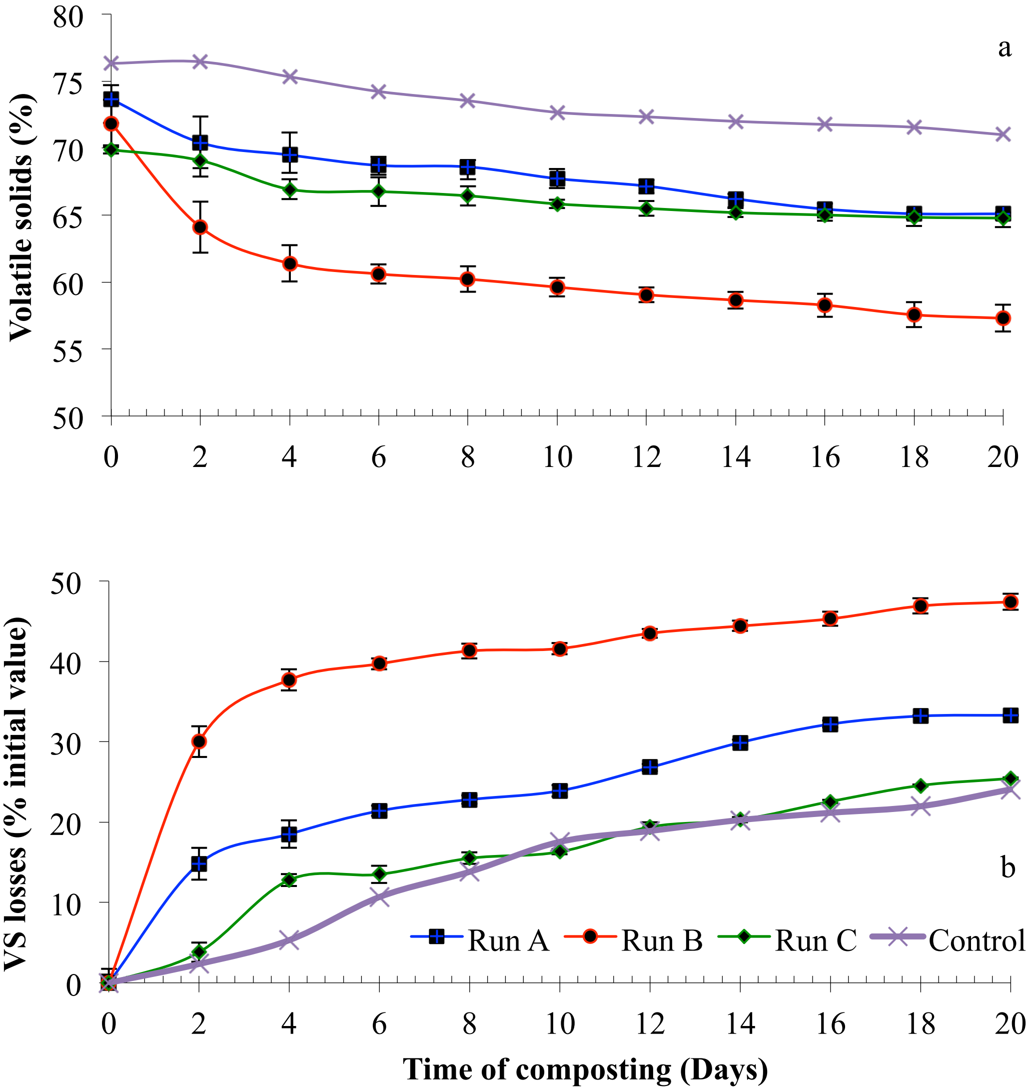


Fig. 4.16. Variation in a) Volatile Solids and, b) VS losses during composting process

Initially the total organic carbon in the three Run A, B, and C, and control was logged as 40.2±0.6, 39.2±1.0, 38.2±0.2 and 41.7±0.1%, respectively. Several researchers have presented attainment of the stabilization of the organic matter associated with the category and quality of the carbonaceous agent utilized for the preparation of initial feedstocks, where the supplement of organic materials characterized by more refractory carbon, decreases the decomposition of the organic matter. It also improves the humification and the superiority of the final product (Singh and Kalamdhad, 2014). The highest TOC reduction was observed for Run B (20%) whereas Run A, C and control showed 11, 7 and 6% reduction and tabulated in Table 4.7. Throughout the composting process, total organic carbon of Run A, B, and C, and control exhibited the greater noteworthy difference ($p<0.05$). Moreover, it was prominent that addition of CA added more organics and volatile solids. Therefore, reprocess of CA is advisable. Varma et al. (2014) conducted a study on composting of vegetable wastes added with dry leaves suggested that removal of CA from compost could provide the better reduction in organics and volatile solids. The study reported by Kalamdhad et al. (2009) using 3.5 m^3 capacity rotary drum composter, sieved the end compost for dry leaves through 0.6 mm sieve, which was reused afterward.

Table 4.7. Variation in total organic carbon reduction during composting process

Days	Run A	Run B	Run C	Control
0	40.91±0.6	39.92±1.0	38.83±0.2	41.71± 0.1
2	39.12±1.1	35.61±1.1	38.38±0.7	41.78±0.2
4	38.61±0.9	34.11±0.7	37.18±0.4	41.16±0.2
6	38.17±0.4	33.67±0.4	37.09±0.6	40.56±0.1
8	38.11±0.3	33.45±0.5	36.91±0.4	40.19±0.1
10	37.63±0.4	33.12±0.4	36.58±0.2	39.71±0.2
12	37.31±0.3	32.81±0.3	36.39±0.3	39.53±0.15
14	36.79±0.2	32.58±0.4	36.21±0.2	39.34±0.1
16	36.36±0.2	32.38±0.5	36.12±0.1	39.22±0.2
18	36.17±0.1	31.98±0.5	36.02±0.1	39.10±0.1
20	36.16±0.1	31.83±0.5	35.99±0.1	38.80±0.1

- *Kinetics of composting*

To evaluate organic matter (OM) biodegradability and produce a useful degree for an organic matter loss during composting, it is essential to define composting kinetics from the data obtained by experimental analysis. The decomposition of OM as a function of time follows first-order kinetics expressed as (Haug, 1993; Hamoda et al., 1998; Kulcu and Yaldiz, 2004)

$$\frac{d(VS)}{dt} = -k(VS) \tag{4.4}$$

where: VS is the amount of decomposable volatile solids at any period of the process in kilograms, t represents duration in days, k is the first-order reaction rate constant (days^{-1}).

Integrating above equation 5 by putting VS = VS_0 at t = 0, the value of organic matter at any period in the compost mixture can be expressed as follows:

$$Ln\left(\frac{VS}{VS0}\right) = -kt \tag{4.5}$$

Simplifying above equation 6 we get,

$$\text{VS loss} = VS_0(1 - e^{-kt}) \tag{4.6}$$

Curve fitting of the experimental data provided the parameter values as tabulated in Table 4.8.

Table 4.8. Parameter values of the first-order equation describing organic matter degradation

Trial Names	A(%)	k (days^{-1})	RMSE	F
Run A	33.3	0.013	3.632	2.2163**
Run B	47.4	0.0234	8.432	4.15204**
Run C	25.4	0.00766	2.81	1.08532**
Control	24.1	0.00632	2.74	1.0539**

where, A – Maximum degradation, k – rate constant, RMSE – Root mean square error, F – factor significant at **$P < 0.01$

The equations were significant at $P < 0.01$, while the OM bio-degradation kinetics of Run A and Run B fitted this equation better than the results obtained for Run C, as indicated by the smaller F value and greater residual mean square (RMSE) of the later. The organic matter decomposition rate was greater when carbon source was grass clippings (Run B), as determined by the greater value of k. The wood chips as carbonaceous agent during composting (Run C) instead of grass clippings or dry leaves (Run B or Run A) substantially reduced the VS decomposition rate, subsequently the value of k was approximately 3 times lower for Run C compare to Run B. This poorer decomposition rate may be due to the larger particle size of the wood chips compared with the other CA (grass clippings or dry leaves).

- ***Bulk density, free air space (FAS) and porosity***

The degradation process is significantly affected by factors such as particle sizes, bulk density and FAS (Kulcu and Yaldiz, 2004; Iqbal et al., 2010). FAS, porosity, and bulk density is closely associated to airflow endurance in the initial feedstock. Airflow provides the oxygen source for eliminating CO_2, surplus moisture and to threshold excess heat accretion (Haug, 1993). The study directed by Zhang and Sun (2016) testified that CA plays a substantial role in adjusting bulk density. In the current study, the results of bulk density were observed to be highly significant between days and runs ($p<0.05$), interpreted using ANOVA. The bulk density noted for the Run A, B, and C, and control were 137.2±5.1, 150.4±1.0, 143.5±0.8 and 418±2.7 kg m^{-3}, respectively. As expected, due to OM decomposition, the volume of the composting mixtures reduces that are corresponding in opposite to an increase in bulk density. The bulk density followed increasing trend during the composting process and found to be a greater increase for Run B (57%) as shown in Fig. 4.17(a). Throughout the process, the bulk density of Run A, B, and C, and control and control exhibited the greater noteworthy difference ($p<0.05$). The increase in bulk density can also be described by the maximum reduction in volume, which is seen prominent during the composting process that followed Run B > Run A > Run C > control. Madejón et al. (2002) enlightened theory concerning the bulk density and significance of particle size for CA. The author further indicated that use of CA usually increases bulk density. A similar pattern was observed for bulk density during composting of nitrogenous organic waste added with the various amount of biochar. On the other hand, FAS of composting feedstocks was witnessed to be declining in the following manner Run B > Run A > Run C > control.

Factors such as moisture content, bulk density, and FAS hold a favorable bond amongst them for the feasible decomposition of the organic wastes. A CA provides optimal free air space (Haug, 1993). In the present study, FAS was seen reducing from 82 to 66, 87 to 72, 90 to 73 and 76 to 61% for Run (A-C) and control, respectively during rotary drum composting (Fig. 4.17(b)). It was noted that maximum decrease occurred in thermophilic phase. A study demonstrated by Jolanun et al. (2008) revealed that substrate: CA ratio could impact the free air space in batch composting process which was perceived in the present study. FAS values for various end composts informed in literature findings are presented in Table 4.9. During the composting process, free air space values of Run A, B, and C, and control exhibited the greater noteworthy difference ($p<0.05$).

As expected, the initial mean porosity noted for runs (A-C) and control was 98.3, 97.2, 96.4 and 95.8%, respectively. Moreover, despite such great change in free air space, porosity exhibited a very little change throughout composting process and was observed to be within the range of 92-94% in and end compost for Runs (A-C) (Table 4.10).

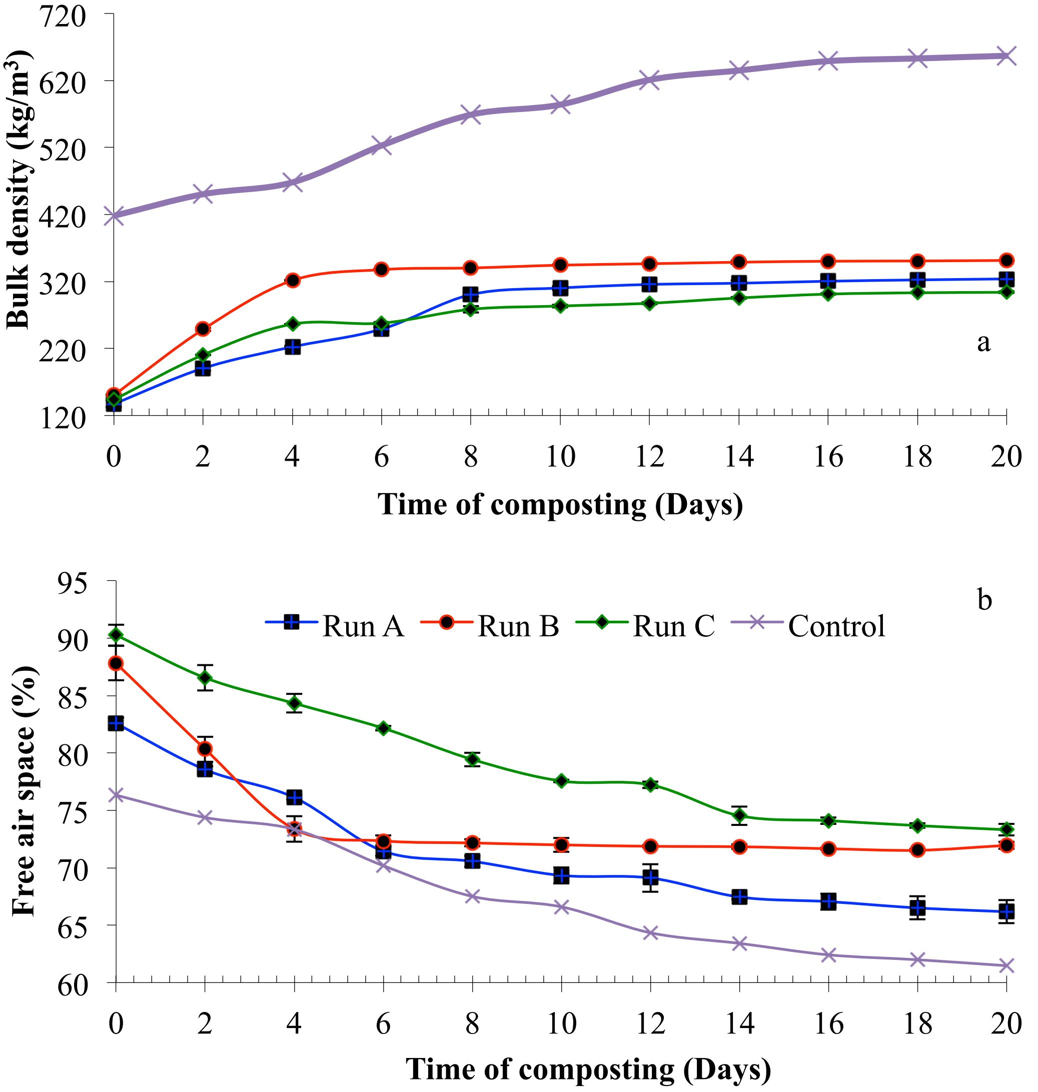


Fig. 4.17. Variation in a) Wet bulk density, and b) Free air space during composting process

The percentage change observed during composting process agrees to the range of 3-5% during all Runs (A-C). As expected, in the Run A, B, and C, the decrease in porosity was fewer competed to control, due to the accessibility of larger moisture in control, which is not a good sign of effective composting. Hence, CA aid in avoiding loss of nutrients by leaching owing to greater porosity in Run A, B, and C.

Throughout the composting process, the porosity of Run A, B, and C, and control exhibited the greater noteworthy variation between days ($p=0.006$) and between Runs ($p<0.05$).

Table 4.9. Free air space studied for different end composts

End compost mix	Free air space (%)	References
Five mixtures of garbage, sludge cake, paper and vermiculite	>30	Schulze (1962)
Bark and peat compost	18.2	Gabriels et al. (1993)
Peat moss compost	49.3	Prasad and Maher (1993)
Woodchips, cattle manure and mixed vegetables	40	Mohee and Mudhoo (2005)
Pruning waste compost	44.1	Benito et al. (2006)
Run A	66.2	This study
Run B	72	This study
Run C	73.3	This study
Control	61.4	This study

Table 4.10. Variation in porosity during composting process

Days	Run A	Run B	Run C	Control
0	98.34±0.5	97.21±1.5	96.45±0.4	95.87±0.1
2	95.45±0.5	94.92±1.1	94.54±0.0	95.67±0.0
4	94.69±0.2	94.31±1.1	94.10±0.5	95.41±0.3
6	94.56±0.4	93.76±0.5	93.56±0.2	94.34±0.2
8	94.11±0.5	93.58±0.3	93.42±0.4	93.45±0.2
10	93.87±0.1	93.49±0.6	93.21±0.1	93.21±0.4
12	93.76±0.3	93.42±0.1	93.01±0.3	92.57±0.0
14	93.55±0.2	93.38±0.2	92.88±0.1	92.11±0.0
16	93.45±0.5	93.35±0.1	92.76±0.3	91.89±0.1
18	93.31±0.1	93.31±0.1	92.66±0.2	91.21±0.2
20	93.31±0.1	93.00±0.3	92.62±0.5	91.22±0.1

- ***Stability parameters***

Fig. 4.18(a) shows a change in oxygen uptake rate during 20 days composting process. The oxygen uptake rate (OUR) of Run (A-C) decreased from 15.7, 15.9, 15.5

and 13.8 mg g^{-1} volatile solids (VS) d^{-1} to 2.5, 1.5, 3.2 and 2.5 mg g^{-1} volatile solids (VS) d^{-1} respectively. Noteworthy variations in OUR values were seen between days ($p<0.05$) and runs ($p=0.0009$). The change in percentage after 20 days composting process in OUR values from initial value was found to be 84, 90, 79 and 76% respectively, in Run (A-C) and control.

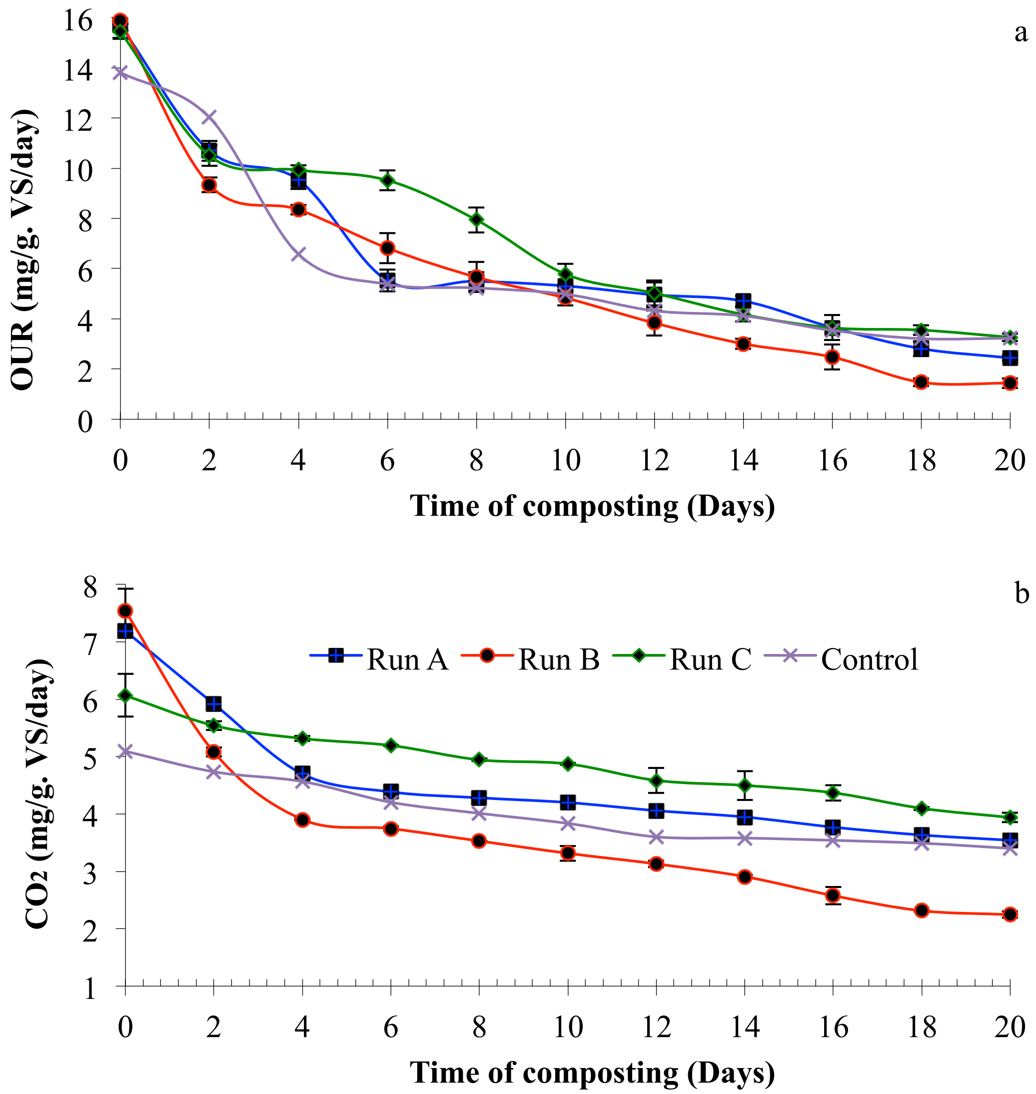


Fig. 4.18. Variation in a) Oxygen uptake rate, and b) CO_2 evolution rate during composting process

In the present study, except for Run B, a decrease in CO_2 evolution rate of respiration observed to become very slow after 15 days of composting, indicating Run B as stable and mature end compost. The CO_2 evolution rates decreased from 7.2, 7.5, 6.1 and 5.1 mg g^{-1} (VS) d^{-1} to 3.5, 2.2, 3.9 mg g^{-1} and 3.4 (VS) d^{-1} respectively, for Run A, B, C and control.

Final results showed that 50, 70, 35 and 33% decrease in the rate of respiration achieved in Run A, B, C, and control; respectively (Fig. 4.18(b)). Results assessed by ANOVA showed notable variations in CO_2 evolution between days and different runs ($p<0.05$).

- ***Chemical properties of the final product***

During initial rise of temperatures, the pH increased quickly and observed to be in between 7.5-7.6 for all Runs (A-C) and control Fig. 4.19a. The pH was nearer to an optimum range (7-8) as anticipated for composting process and observed to remain constant as composting process end indicating stabilization of process and lower microbial activities (Zhang and Sun, 2016). CA are also considered as the buffering material that increases the pH in the composting process.

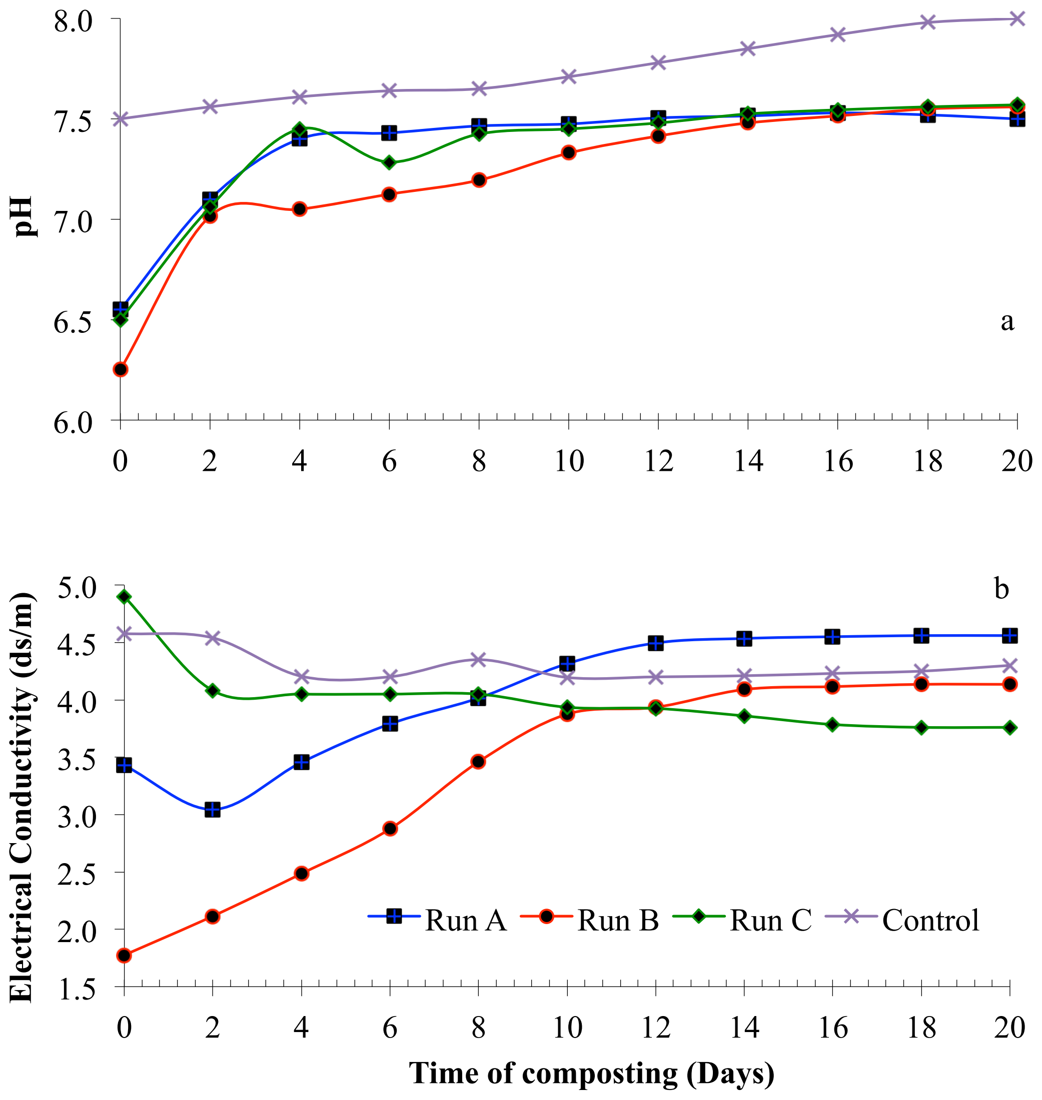


Fig. 4.19. Variation in a) pH, and b) Electrical conductivity during composting process

Moreover, the mineral cation content rises with the breakdown of organic waste (Varma et al., 2014; Francou et al., 2005).. From the initial values, the addition of CA (dry leaves and grass clippings) considerably abridged the electrical conductivity of the Run A and Run B. However, control and Run C followed a similar trend of electrical conductivity and found to be declining from 4.9 to 3.76 dS m^{-1} and 4.578 to 4.3 dS m^{-1}, respectively, which might be due to the existence of ammonium ions. The final electrical conductivity was noted as 4.5, 3.9, 3.7 and 4.3 (dS m^{-1}). The study conveyed by Banegas et al. (2007) testified that addition of CA might also upsurge ion retention in the compost product. The electrical conductivity beyond 4 dS m^{-1} is a sign of increased salinity of end product as it can be possibly phytotoxic for the growth of the plants (Singh and Kalamdhad, 2014). However, electrical conductivity for run B and C was only seen to be less than 4 dS m^{-1}. Noteworthy variations in electrical conductivity values were seen between days and different runs ($p<0.05$).

Nutritional parameters such as N, P, K, Ca, and Na were measured for initial compost matrix and end product. It was detected that all nutritional parameters were seen to be rising during the composting process. The total potassium concentration was observed to increase from 12.5, 14.8, 17.9 and 17.6 g kg^{-1} to 29.9, 38.1, 22.9 and 25.4 g kg^{-1}, respectively for Run A, B, and C, and control (Table 4.11). The addition of CA absorbed the comparatively greater quantity of moisture and due to whole structural integrity, which might be a reason to counteract the loss of potassium during the composting process. According to Kalamdhad and Kazmi (2009) and Varma et al. (2014), the total Kjeldahl nitrogen increases due to a net loss of dry mass regarding CO_2 and moisture loss by evaporation that causes evolvement of the heat during oxidization of OM.

In the present study, total Kjeldahl nitrogen was observed to be following an increasing trend. Increment percentage of total nitrogen was found to be 26, 48, 17 and 13% during composting of runs (A-C) and control. The characteristics of final product of the composting feedstocks Run A, Run B, Run C and control are tabulated in Table 4.11. On the other hand, phosphorus has shown more or less similar increment in Run A and B, i.e. (58 and 60%) whereas Run C and control study showed 50% increment. The total phosphorus was found to be 7.1, 8.5, 9.1 and 4.8 g kg^{-1} in an end product. Similarly, other nutrients such as calcium, potassium, and sodium showed increase in concentration by 25, 27 and 52% in Run A, Run B showed the change as 21, 16, and 20%, Run C showed percent change of 21, 21 and 25%, whereas control showed 23, 22 and 30% (% increment), respectively, during the process.

Concentrations of all nutrients are tabulated in Table 4.11.

Table 4.11. Characteristics of final compost

Parameters (Units)	Final compost			
	Run A	Run B	Run C	Control
Moisture content (%)	70.8±0.4	65.2±0.4	71.6±0.6	77.3±0.2
Volatile solids (%)	65.1±0.1	57.3±1.0	64.8±0.1	71.0±0.2
Ash content (%)	34.9±0.1	42.7±1.0	35±0.1	29.0±0.2
pH	7.5±0.01	7.56±0.01	7.57±0.01	8±0.1
Electrical cond. (dS/m)	4.56±0.1	3.9±0.4	3.7±0.2	4.32±0.0
TKN (%)	2.66±0.1	3.25±0.1	2.8±0.1	3.3±0.1
TP (g/kg)	7.1±0.05	8.5±0.03	9.1±0.1	4.3±0.07
K (g/kg)	21.3±0.8	21.0±1.2	22.9±0.4	25.4±0.3
Na (g/kg)	1.5±0.06	1.6±0.2	2.2±0.1	2.24±0.01
Ca (g/kg)	5.7±0.1	5.4±0.05	5.6±0.07	5.4±0.2

Table 4.12. Pearson's correlation between physical properties during composting process

		Moisture Content (MC)	Bulk Density (BD)	Free Air space (FAS)	Volatile Solids (VS)
Run A	MC	1	-0.90737	0.89451	0.90869
	BD		1	-0.98157	-0.93807
	FAS			1	0.96719
	VS				1
Run B	MC	1	-0.92151	0.90272	0.97586
	BD		1	-0.99837	-0.97776
	FAS			1	0.96604
	VS				1
Run C	MC	1	-0.94806	0.92652	0.91304
	BD		1	-0.93855	-0.97189
	FAS			1	0.97152
	VS				1
Control	MC	1.00	-0.94806	0.91951	0.9131
	BD		1	-0.99919	-0.98918
	FAS			1	0.99006
	VS				1

Correlation is significant at the 0.05 level (2-tailed)

- ***Pearson's correlation***

The Pearson's correlation coefficient matrix, represent all the validations about the correlation amongst physical properties such as moisture content, FAS, bulk density and VS as it plays the significant functions in achieving the best efficiency of the process developing the aerobic environments and required microbial activity throughout the composting process. During composting, control and Run A, B, and C showed correlation coefficient between moisture and bulk density as -0.90, -0.92, -0.94 and -0.94 respectively, that shows the (-ve) correlation, i.e., as the moisture decreased the bulk density increased. The factors such as FAS and bulk density were also correlated, and it can be implicit that FAS is negatively correlated with bulk density. The (+ve) correlation between the FAS and moisture content indicated that with a decrease in moisture content the FAS between compost materials were decreased.

4.3.2 Concluding remarks

The amendment of different CA during composting of *H. verticillata* aid in minimizing the effect of ammonia volatilization and achieved a higher reduction in moisture content. The prominent impact was seen in the Run B (H. verticillata, cow dung, and sawdust) added with 10% of grass clippings which depicted the maximum temperature of 68.1°C and had the highest degradability rate with moisture reduction of 17% and 20% reduction in volatile solids compared to other added CA. The bulk density at the end of the composting process was observed between 300-360 kg m^{-3}, whereas it was seen much higher (657 kg m^{-3}) in the control mixture

4.3.3 Role of biochar as a carbon-rich agent

More recent studies have successfully utilized biochar as a plausible CA for composting organic waste. The pyrolysis (low oxygen conditions) of organic waste leads to the end product known as biochar that ensures the sustainable use of the resources by incorporating biochar production into waste management (Lopez-Cano et al., 2016). As a result of renewable energy production, biochar is an economical and sustainable resource that can improve soil structure and enhance plant growth (Zhang and Sun, 2014). The strategy behind addition of biochar is to improve the composting process by enchancing aeration and sorption of available carbon compounds (Jindo et al., 2012; Steiner et al., 2015; Lopez-Cano et al., 2016; Liu et al., 2017). Steiner et al. (2015) explained the improved efficiency of the composting process and quality of end product owing to use of biochar. Sanchez-Garcia et al. (2015) showed that biochar enhances the degradation rate of organic matter during composting process and increased agronomical value of compost. A study on utilization of biochar (bamboo charcoal) during sludge composting indicated a reduction in nitrogen losses by enhancing the absorption of NH_4^+-N (Hua et al., 2009; Thies and Rillig, 2009). Biochar also increases plant nourishment further its surface has “weathered,” or becomes more responsive in the soil (Borchard et al., 2012; Schmidt et al., 2014). Prost et al. (2013) explained that addition of biochar with mixture (farmyard manure + straw) resulted in increasing potential CEC during the composting process. The studies were also carried out on use of biochar as carbon source during composting of various organic wastes (manures, olive mill wastes, sewage sludge) using either pile method or windrow method (Dias et al., 2010; Jindo et al., 2012; Malinska et al., 2014; Lopez-Cano et al., 2016; Jindo et al., 2016; Liu et al., 2017). Effects of biochar on nitrogen transformation, microbial community, and heavy metals have been studied so far. However, an effect of biochar on composting physics or physical parameters during composting of *H. verticillata* has rarely been studied. No studies have been investigated on the effect of biochar on *H. verticillata* using rotary drum composter as composting technology.

The amendment of biochar as a CA in composting of *Hydrilla Verticillata* (L.f. Royle) has not been previously studied. Hence, the novelty of this study was to assess the use of the biochar as CA for the composting of nitrogen rich aquatic weed *Hydrilla Verticillata*, which represents a substantial organic waste generated as a result of eutrophication in aquatic systems. The biochar were amended with *H. verticillata* in different amounts and results were compared. (1) The effects of biochar as CA during the composting process were evaluated based on the changes in various physical and nutritional parameters; (2) the influence of varying concentrations of biochar on microbial degradative rates and kinetics, and (3) inter-relationship amongst physical parameters are investigated.

- ***Composting temperature and moisture content***

At the start of the composting process, the mean temperature in the core of the three trials (A-C) and control were 33±0.2, 33±0.7, 33±0.6°C and 34.2±0.8°C, respectively. Maximum and minimum ambient air temperatures during the complete composting process ranged from 22±0.7 and 26±0.5°C (Fig. 4.20a). All trials and control showed a similar pattern of temperature increase with a rapid activation of the composting process (Fig. 4.20a). Generation of heat is the result of the initiation of microbial decomposition and temperature rises owing to the increase of metabolically generated energy. Temperature monitoring is essential to understand the composting process conditions (Bernal et al., 2009). The temperature of the composting mixtures started to increase just after the establishment of suitable composting conditions. This increase in temperature was more owing to the addition of amendment (cow dung) and biochar as CA that enhances the composting reactions and thus enhances the temperature of the composting mixtures (Karadag et al., 2013; Liu et al., 2017). For all trials (A-C), as anticipated, the temperature increased rapidly until it began to plateau. The thermophilic condition (>45°C) was attained after 3 days for trial B, and the maximum temperatures (59°C) occurred on day 5, whereas trial A (46.4°C), C (46.2°C), and control (45.1°C) showed maximum peak of temperatures on day 4, 7, and 4, respectively on degradation in the rotary drum composter. During the initial seven days of composting process, temperatures of all trials (A-C) and control showed the higher significant difference ($p<0.05$), which might have developed from the enhanced biological activities. However, when the overall composting duration was considered, there was no significant difference observed between the trials and control.

The daily turning of drum resulted in the loss of heat, and the temperature of the composting mixtures was started decreasing. The trials (A-C) reached to mesophilic phase on day 7, 10, 9, and 6, respectively during composting of *H. verticillata*. The temperature observed to be declining till the 20th day and was recorded nearer to ambient (27°C) temperature. The biochar addition increased the time period for thermophilic phase during the composting of *H. verticillata*, which was not seen for control (0% biochar).

The similar trend for temperatures was observed in literature studies using biochar as additives for manure composting (Jindo et al., 2012; Wang et al., 2013; Wei et al., 2014; Sanchez-Garcia et al., 2015). Studies carried out on composting of various organic wastes revealed that the composting process should retain the temperature range of 55-60°C for more than 3 days, for reduction in pathogens and to achieve standard sterilization (Sadaka and El-Taweel, 2003; Margesin et al., 2006, Zhang et al., 2013; Liu et al., 2017). In this study, trial B met the requirement of temperatures (55-60°C) and lasted for 3 days in thermophilic phase (Fig. 4.20a). Trial A and C showed temperatures (>45°C) for more than three days whereas control showed for 1 day. The temperatures data of current study indicated that trials A, C and, control, respectively, did not meet the sanitation condition and may contain pathogens. Out of all trials, trial B reached the highest temperature due to the higher addition of biochar indicating the quick establishment of microbial activity during the composting process. These data suggest that optimized addition of biochar, i.e., trial B (5%) enhanced the composting process by providing readily available carbon for microorganisms. The decomposition of organic wastes could be enhanced by increasing the C/N ratio to an optimum value by addition of readily biodegradable carbonaceous compounds (Nakasaki et al., 1992). In the present study, trial C having the highest quantity of biochar shown less temperature rise when compared to trial B. The increase in carbon content in trial C affected the composting process that inhibited biological activity. The literature studies carried out on various organic wastes stated increase in C/N ratio shows the lesser increase in temperature, lower maximum temperature and even shorter thermophilic phase (Huang et al., 2004; Zhang et al., 2006; Kalamdhad and Kazmi, 2008). The compost microorganisms require optimum carbon and nitrogen for their cell growth (Chen et al., 2010; Singh and Kalamdhad, 2013).

The initial moisture contents were high in *H. verticillata* (90-92%), and cow dung (85-87%) but lower in sawdust (14-16%) and biochar (1.5-2.5%). The higher moisture content displaces the air availability in the pore spaces of the organic waste materials. The composting process is strongly affected by environment conditions (moisture content, pH, and aeration) as it plays a substantial role to maintain suitable composting conditions (Silva et al., 2014). Moreover, moisture content disturbs microbial activity as well as the physical structure and thus has a central influence on the biological decomposition of organic waste materials (Ahn et al., 2008; Han et al., 2014).

Several organic materials can be effectively composted in the range (about 25–80% on a wet basis) (Willson, 1989; Haug, 1993; Richard et al., 2002; Cronje et al., 2004; Singh and Kalamdhad, 2013). In this present study,the initial moisture content of the composting process was recorded as 83.1 ± 0.3, 82.5 ± 0.7, 76.6 ± 0.4 and 86.3±0.5% for trials (A-C) and control, respectively. Decomposition of organic waste materials by microbial activity typically causes loss of moisture content within compost mixture (Varma et al., 2014). The addition of biochar that is a carbonaceous and fibrous material with lower moisture amount as a CA is to provide the optimum free air space and control the moisture level of the organic waste to be composted (Eftoda and McCartney, 2004; Singh and Kalamdhad, 2014).

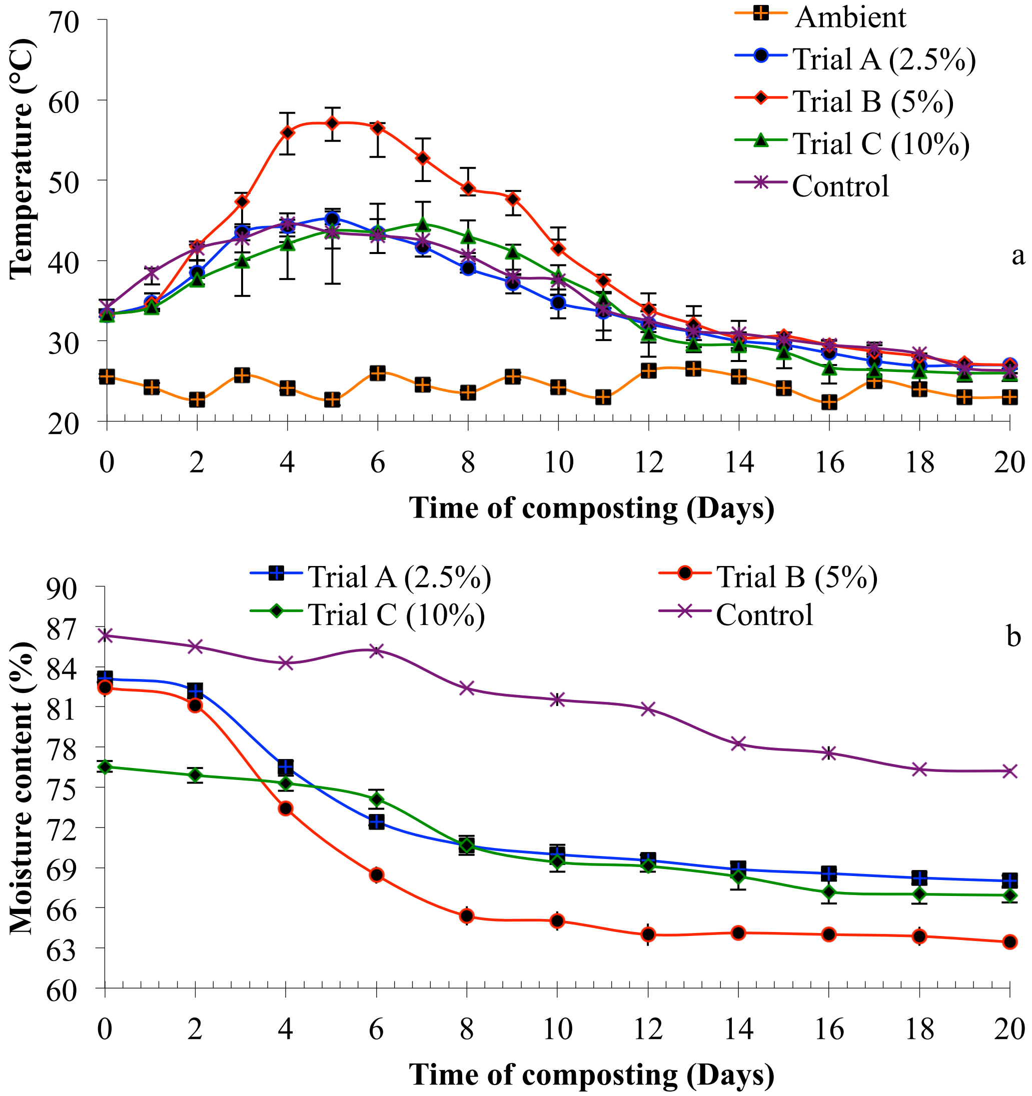


Fig. 4.20. Variation in a) Temperature, and b) Moisture content during composting

It was observed that addition of biochar as a BA lowered the moisture content of compost mixture by 18, 23 and 12% for trials (A-C), respectively as illustrated in Fig. 4.20b, whereas control trial showed reduction of 11% during the composting process. Owing to the availability of readily biological decomposable organic content, thermophilic temperatures (>45°C) were noted after 3 days for trial B whereas 4 and 5 days for trial A and trial C, respectively. No formation of leachate was witnessed during the composting process for trials (A-C), whereas control showed little amount of water on day 4 (personal observation). The moisture levels of end product on 20th day were recorded as 68, 63, 66 and 76% for trials (A-C) and control, respectively. During the composting process, moisture content of all trials (A-C) and control showed the higher significant difference ($p<0.05$).

Biochar played a significant role in absorbing moisture content and thus prohibited leachate formation during the composting process. The current study required just 20 days to obtain stable and matured compost as en end product compared to studies carried out on other organic wastes that took almost 90–270 days (Khalil et al., 2008; Zhang et al., 2013). The study revealed that addition of biochar as a CA in rotary drum composter significantly reduced the time needed to acquire matured compost. As anticipated, trial B showed maximum moisture reduction due to the optimized addition of biochar, whereas control showed the least reduction. The higher amount of biochar (dry material) as CA negatively affected trial C as it has inhibited required microbial activity for decomposition of composting materials. These results indicate that addition of biochar significantly reduced the moisture content that followed as trial B < A < C < control.

- ***Volatile solids and ash content***

Composting process is a biodegradation process in which the organic matter is progressively degraded by microbes (Jindo et al., 2016). Lopez-Cano et al. (2016) explained about the mineralization of all trials were categorized by an initial stage of rapid organic matter degradation, leading to the highest values of organic matter losses. He further stated that a second stage (at the end of the thermophilic phase) was characterized by a reduction in the organic matter losses that suggested an advanced stabilization of the composting mixtures. In the present study, the initial volatile solids content (Fig. 4.21a) concentrations were influenced by the proportion of the biochar added in the composting mixture. Another concept on the volatile solids shown by Singh and Kalamdhad (2014) states that it is an indicator of organic matter content and reduces during the composting process due to decomposition of the organic matter by the microbial activity and loss of carbon (C) in the form of CO_2. The highest volatile solids content were found in trial C (83.4%) and B (80.1%), whereas the mixture prepared added 2.5% biochar as CA (trial A) and control had an initial volatile solids content of 79.1% and 78.1%. There were no momentous variations in the concentration of the volatile solids in all the trials during the initial two days of the composting process. However, the maximum reduction occurred after 2 days, and the pattern is in agreed with a temperature profile of the three trials (A-C), i.e., during thermophilic stage (>45°C) of composting mixtures. Maximum volatile solid reduction was observed in trial B (31%) containing 5% biochar as bulking agent and this was due to the presence of more degradable organic matter. In trial A the reduction of volatile solids content was 14% whereas in trial C and control, as anticipated, achieved a reduction of only 10% due to the slower microbial activity which is not a good sign of efficient composting. There was no further observable reduction in all the three trials after 16 days indicating the decrease in microbial activity. After 20 days composting process the volatile solids declined to 68, 55, 75 and 71% respectively, for trials (A-C) and control. During the composting process, volatile solids data of all trials (A-C) and control showed the higher significant difference ($p<0.05$), analyzed statistically using ANOVA.

The current study results, when compared to the study, carried out on composting of other aquatic weed (water hyacinth) and sawdust as CA revealed 30% as maximum reduction using rotary drum composter (Singh and Kalamdhad, 2013). However, pile method showed 40% as maximum reduction during composting of water hyacinth added with saw dust (Prasad et al., 2013). Another study carried out by Singh and Kalamdhad (2014) on phumdi biomass (aquatic weed) added with rice husk as CA showed 19% as maximum volatile solids reduction during composting. This indicates that the *H. verticillata* biomass can be degraded quickly when combined with 5% biochar as CA and stable compost can be produced.

At the start of the composting process, the ash content in the three trials (A-C) and control were 20.9±1.0, 19.9±1.8, 16.5±0.3 and 21.9±0.4%, respectively. Ash content is an essential parameter to understand nutrient dynamics during composting which is likely to originate (salts, soil particles, and recalcitrant compounds) from organic matter (carbon or nitrogen, theoretically liable to decomposition) (Larney et al., 2004). The variation in ash content followed a pattern as per temperature variations, presenting three phases: (1) Days 0–8, when most of the organic matter degraded; (2) Days 8 to 15 a mesophilic period; and (3) Day 15 to the end of the experiment (day 20), during which the maturation phase initiated and the rate of organic matter degradation was extremely small. The ash content was observed to increase with composting period and recorded as 32, 45, 25 and 29% for trial (A-C) and control, respectively. During the composting process, ash content of all trials (A-C) and control showed the higher significant difference ($p<0.05$). The increase in ash content is owing to the loss of organic matter through microbial degradation (Varma and Kalamdhad, 2014). The decrease in volatile solids synchronized with an increase in the mass ash of treatments.

- *Kinetics of composting*

To assess waste biological decomposition and make a useful measure for the loss of organic content during composting process, it is necessary to state kinetics of composting process (degradation kinetics) using numbers obtained by investigational study. The degradation of organic content as a function of composting period (time) follows first-order kinetics expressed as (Hamoda et al., 1998; Kulcu and Yaldiz, 2004; Qdais and Widyan, 2016)

$$\frac{\mathrm{d(BVS)}}{\mathrm{dt}} = -\mathrm{k(BVS)} \qquad (4.7)$$

where: BVS is the quantity of biodegradable volatile solids at any time of the composting process in kilograms, t is time in days, k is the first-order reaction rate constant (days^{-1}).

Integrating Eq. 5 by letting BVS = $\mathrm{BVS_0}$ at t = 0, the concentration of organic matter at any time in the compost matrix can be expressed as follows:

$$Ln\left(\frac{\mathrm{BVS}}{\mathrm{BVS0}}\right) = -\mathrm{kt} \qquad (4.8)$$

Simplifying eq.6 we get,

$$\text{BVS loss} = BVS_0(1 - e^{-kt}) \qquad (4.9)$$

Curve fitting of the investigational statistics gave the parameter values shown in Table 4.13. All equations were significant at $P< 0.05$, although the organic content degradation kinetics of trial A and B fitted this equation superior than the outcomes achieved for trial C and control, as shown by the lower F and higher residual mean square values of the latter. The rate of organic content degradation was better when biochar (5%) (trial B) were used as the CA, as demonstrated by the higher value of k (Table 4.13). The use of 10% biochar as CA (trial C) rather than 2.5% or 5% (trial A or trial B) considerably reduced the organic content degradation rate, since the value of k was approximately 3 and 3.5 times is lower for trial C and control than for trial B, respectively.

This lower decomposition rate may have been owing to the excess amount of carbonaceous matter in case of trial C due to which inadequate nitrogen was available for microbial activity. Poor rate of degradation was observed as anticipated, in case of control (0% biochar). The graphical representation of VS losses occurred during experiments illustrated in Fig. 4.21b.

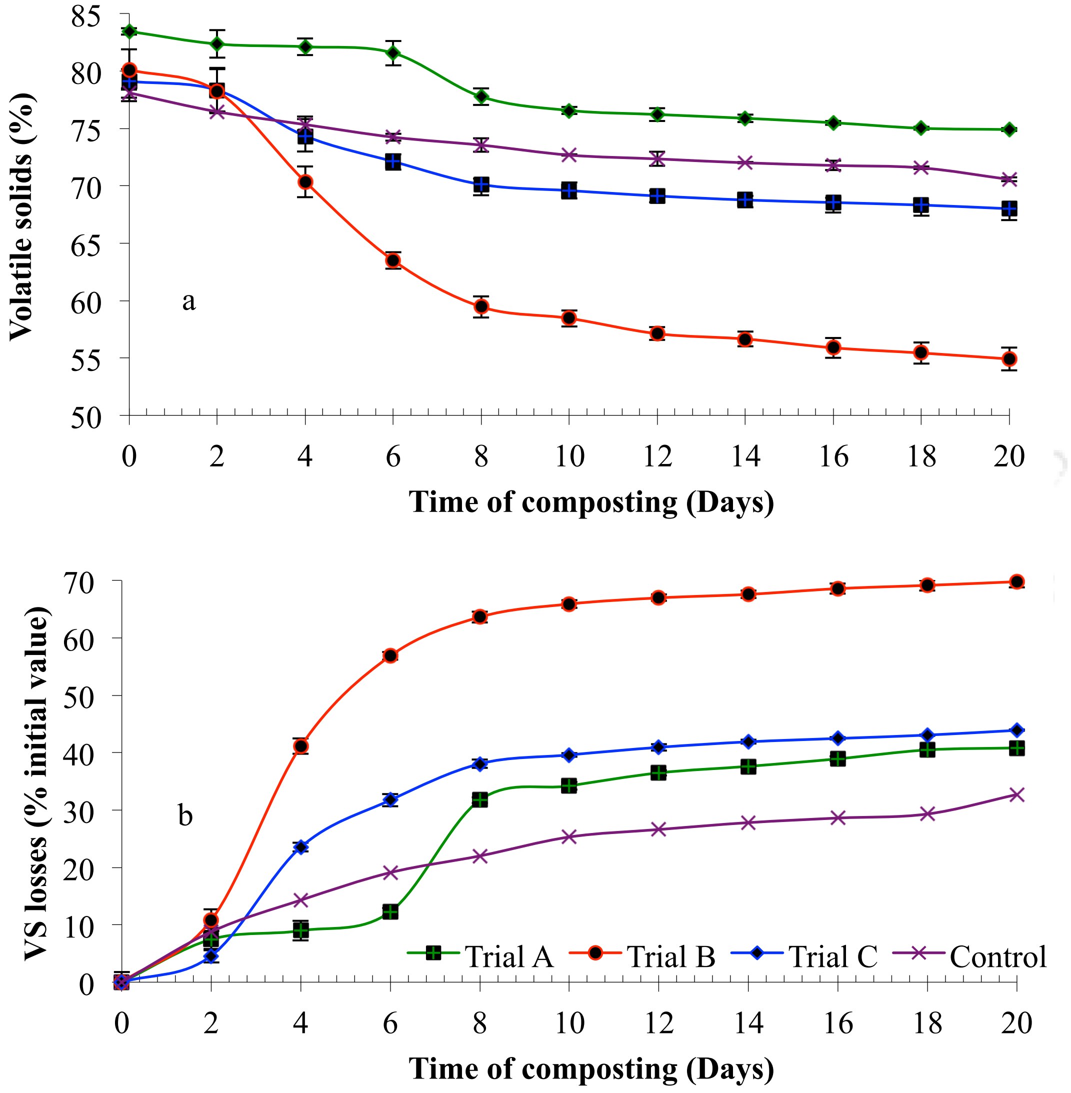


Fig. 4.21. Variation in a) Volatile solids content, and b) VS losses during composting

- ***Bulk density, porosity, free air space, and particle density***

Bulk density evaluation is an essential tool in composting process control (Huerta-Pujol et al., 2010). Diaz et al. (2002) and Iqbal et al. (2010) indicated an importance of physical properties evaluation (bulk density, free air space, particle sizes) as it greatly influences the composting process.

Table 4.13. Parameter values of the first-order equation describing organic content decomposition

Trial Names	A (%)	k ($days^{-1}$)	RMSE	F
Trial A (2.5%)	43.9	0.017	7.002	5.8744**
Trial B (5%)	69.8	0.044	25.641	14.6294**
Trial C (10%)	40.8	0.014	5.484	2.2168**
Control	32.8	0.012	3.329	2.2045**

A – Maximum degradation, k – rate constant, RMSE – Root mean square error, F – factor significant at **$P<0.05$ (2-tailed)

Zhang and Sun (2016) during a study on composting of green waste explained theory on the significance of CA in regulating bulk density. Bulk density evaluation could be of importance during composting process as it represents extent of volume reduction, also in the estimation of other physical parameters deep within composter (such as thermal conductivity, porosity, or resistance to air flow), or in the design of storage structures and materials-handling systems (Schaub-Szabo and Leonard, 2013). Biochar aid to decrease in initial bulk density and improves aeration as well as increase water holding capacity (Zhang and Sun, 2014). In studying the composting process, the mean bulk density was recorded for the three trials (A-C) and control were 350±11.7, 331±10.4, 308±20.8 kg m^{-3} and 418±11.7, respectively. As anticipated, due to organic matter degradation, volume decreases that are synchronized in reverse with increase in bulk density. During the composting process, bulk density was observed to be increasing as shown in Fig. 4.22a. Maximum bulk density increment was observed for trial B (56%) that was added with biochar (5%) as a CA and this is due to the maximum volume reduction. In trial A the increment in bulk density was 50% whereas in trial C and control, as anticipated, achieved the least increase of only 41 and 36% due to slower microbial activity. The significance of particle size for fibrous (bulking agents) materials are well explained in a study carried out by Madejon et al. (2002) concerning the behavior of bulk density. Moreover, he explained that utilizing CA usually increases bulk density. After 20 days composting process the bulk density was recorded as 698, 760, 530 and 657 kg m^{-3}. The values for bulk density were within the range as recommended by FCO (2003), i.e., less than 1000 kg m^{-3} respectively, for trials (A-C). During the composting process, bulk density of all trials (A-C) and control showed the higher significant difference ($p<0.05$).

According to Agnew and Leonard (2003) free air space is related to oxygen availability within composting mixtures during the composting process. However, porosity indicates an availability of air (oxygen) and water filled in the pores. Water holding capacity (WHC) that is related to structure of composting mixtures also depends on size and distribution of pores (Agnew and Leonard, 2003).

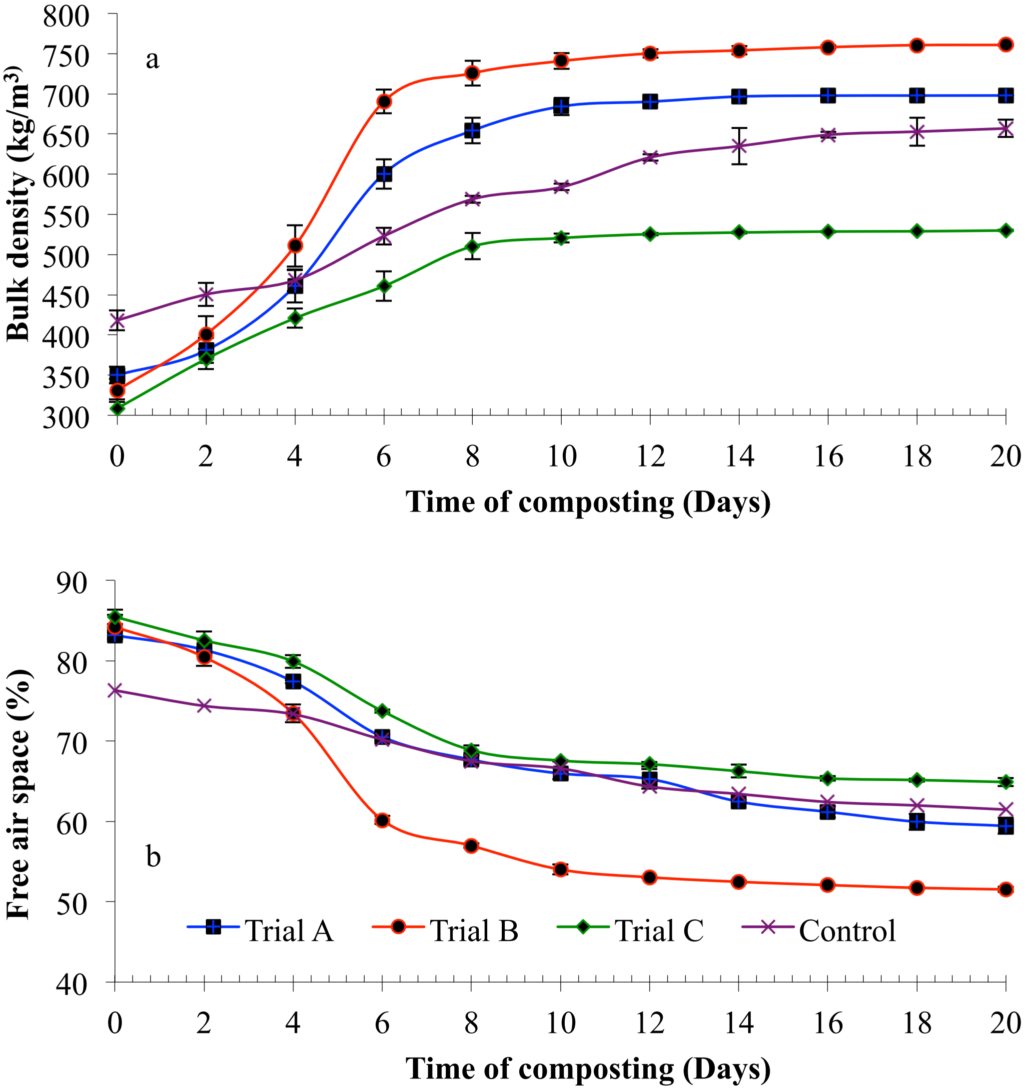


Fig. 4.22 Variation in a) Bulk density, and b) free air space during composting

The higher porosity and surface area of biochar aid to bind nutrients and thus avoid loss by leaching (Zhang and Sun, 2014). As anticipated, in studying the composting process, the mean porosity was recorded for trials (A-C) and control were 99.1, 99.2, 99.3 and 95.8%, respectively. It was observed that porosity showed a minimal change during composting process of trials (A-C). The final values for porosity that has been achieved during composting of *H. verticillata* that has been added with 2.5, 5 and 10%

of biochar was 98.6, 98.7 and 97.8%, respectively. The control showed a significant reduction in porosity when compared to that added with biochar and observed to be 91% in end compost. During the composting process, porosity of all trials (A-C) and control showed the higher significant difference between days ($p=0.006$) and between trials ($p<0.05$). The study carried out by few researchers on various organic wastes revealed porosity values within 85-95% (Raviv et al., 1997; Prasad and Maher, 1993; Gabriels et al., 1993; Mohee and Mudhoo, 2005). As anticipated, in the trial (A-C) the reduction of porosity was less compared to control, due to the availability of higher moisture content in control, which is not a good indicator of efficient composting. Therefore, biochar addition aid in preventing loss of nutrients via leaching due to higher porosity in trials (A-C).

Carbon dioxide releases during the composting process that can be eliminated with appropriate airflow, which provides oxygen, and it also helps to reduce surplus moisture (Haug, 1993). Bulk density, free air space, and moisture content hold a healthy relationship with each other for the proper degradation of organic matter in the compost mixture. Bulking agents (biochar) are carbonaceous material that provides optimal free air space (Haug, 1993). The initial mean free air space was noted for the three trials (A-C) and control were 83.1±0.5, 84.2±1.5, 85.3±0.9 and 76.3±1.2, respectively. As bulk density increased the free air space between the composting mixtures was observed to be followed decreasing trend. Maximum free air space reduction was observed for trial B (38%) that was added with biochar (5%) and control showed (19%) reduction (Fig. 4.22b). Microbes utilize the air (oxygen) for biological activity (decomposition) that decreases the free air space within composting mixture. As anticipated, the maximum decrease in free air space was observed between days 0-8 when the process was in thermophilic phase. After 20 days composting process the free air space was recorded as 59.5, 51.5, 64.9 and 61.5%. The free air space results were analyzed using ANOVA, significant variations were found between days and different trials ($p<0.05$). The maximum reduction pattern that has occurred is in agreement with a temperature profile of the all trials. A ratio of waste materials: bulking agent is essential to know as it impacts free air space in composting process and same has been observed during current study performed (Jolanun et al., 2008).

Particle density is density of the composts solids themselves and can be calculated as the mass of solids: volume of solids. It is also referred as true or absolute density (Wilson, 1983; Villar et al., 1993). The variation of particle density over composting duration can also be predicted by observing the variation of ash and volatile solids contents during the process (Agnew and Leonard, 2003). A researcher Schulze (1962) have obtained constant values for particle density (1200-1600 kg m^{-3}) during composting of mixtures (garbage, sludge cake, paper, and vermiculite). However, van Ginkle et al. (1999) reported that the particle density of the different compost substrates varied over the composting time while Brouillette et al. (1996) found that a constant value of 1250 kg m^{-3} was obtained for composting paper mill deinking sludge. In the present study, the particle density varied with the change in ash content over the composting duration and observed as trial A (1721-2080 kg m^{-3}), trial B (1570-2100 kg m^{-3}), trial C (1510-2120 kg m^{-3}) and control (1705-1765 kg m^{-3}) during the composting process. The particle density results were analyzed using ANOVA, significant variations were observed between days ($p<0.05$) and trials ($p<0.05$). A study carried out by on cattle manure composting showed a constant value of 1750-1820 kg m^{-3} (Inbar et al., 1993). A researcher Weindorf and Wittie (2003) observed higher constant values for particle density (2270-2310 kg m^{-3}) on composts from dairy manure. Another study carried out on composting of vegetable wastes by Mohee and Mudhoo (2005) observed variation in the particle density from 1050 to 2250 kg m^{-3}.

- ***Elemental and chemical analyses***

In the present study, the pH showed no change during initial 2 days. The initial mean pH values were noted for the three trials (A-C) and control were 7.6, 8.1, 8.5, and 7.2, respectively. However, with an increase in temperatures, pH showed decreasing trend in trials (A-C) and control showed increase in pH. After 2 days pH for trials (A-C) followed declining pattern as illustrated in Fig. 4.23a. The decrease in pH might be due to rapid decomposition of simple carbohydrates that transforms into small molecule organic content. Moreover, the formation of these low molecular weight fatty acids and release of CO_2 reduces pH during the composting process (Sun et al., 2016). But as composting process entered mesophilic phase, i.e., after eight days pH started rising and became stabilized after 15 days of the composting period. Bulking agents (biochar) are usually referred as the buffering agent that raises the pH during the composting process. The pH results were analyzed using ANOVA, significant variations were observed between days ($p=0.001$) and between trials ($p<0.05$). The pH rise can be attributed to increasing ash formation, and mineralization of organic nitrogen as a result of microbial activities (Bishop and Godfrey, 1983; Bang-Andreasen et al., 2017).

Electrical conductivity is an indicator of the salinity of the compost and is evaluated as high salinity compost that is not suitable for plant growth (Lin, 2008; Singh and Kalamdhad, 2014). The initial mean electrical conductivity values were noted for the three trials (A-C) were 2.14, 2.25, 2.43 and 4.58 dS m^{-1}, respectively. From the initial values the addition of biochar significantly reduced the electrical conductivity of the mixtures.

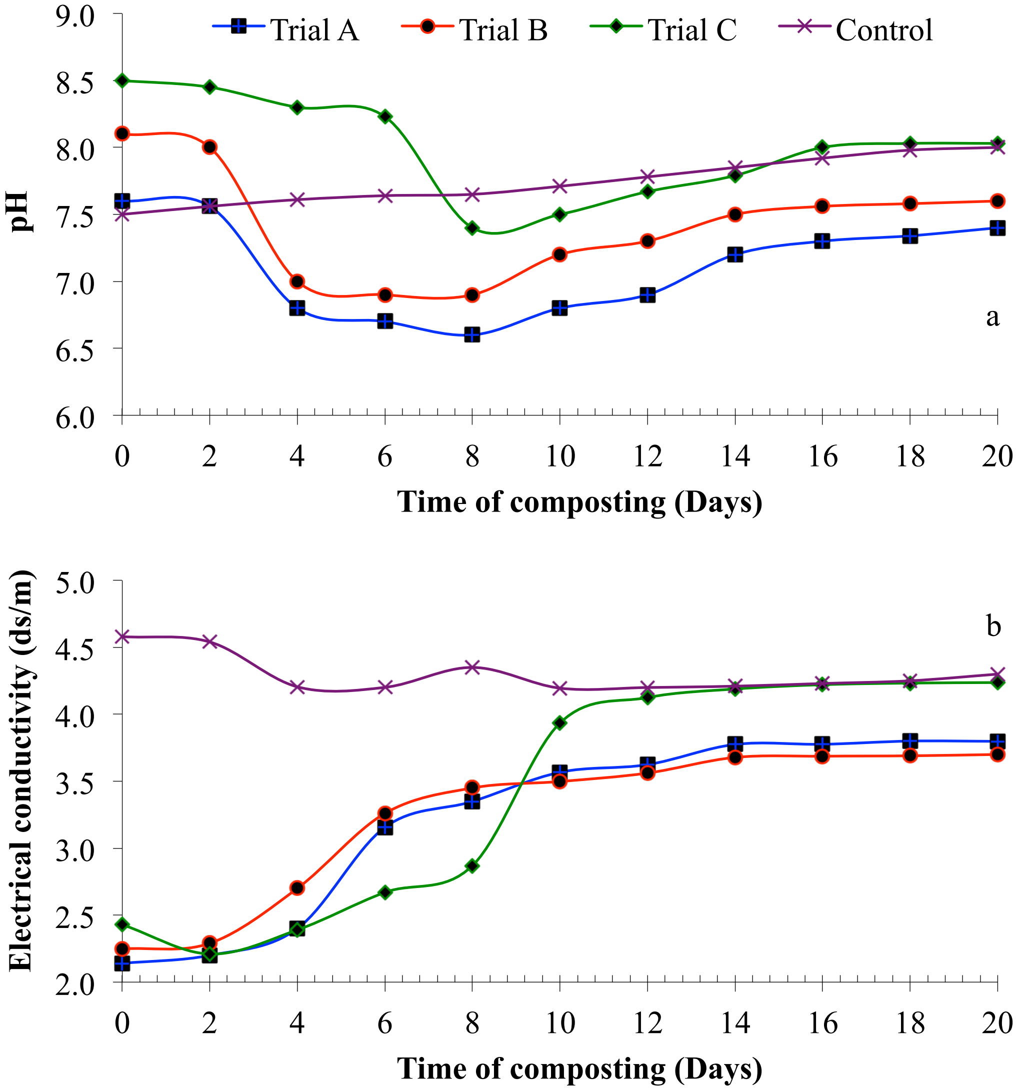


Fig. 4.23. Variation in a) pH, and b) Electrical conductivity during composting

The concentration of mineral cation is due to the presence of salts of sodium, potassium, nitrate, sulfate, and ammonia (Singh and Kalamdhad, 2014). The variation in electrical conductivity showed the same pattern during the composting process of all three trials (A-C) and observed to be increasing (Fig. 4.23b). In control electrical conductivity declined from 4.57 to 4.3 dS m^{-1} which could be due to presence of ammonium ions (Wong et al., 1995; Kalamdhad et al., 2008). After 20 days composting process the electrical conductivity was recorded as 3.9, 3.7 and 4.4 dS m^{-1} for trials (A-C), respectively. The increase in electrical conductivity is due to the decomposition of organic matter, which is not reduced by binding to stable organic complex (Varma et al., 2014; Francou et al., 2005). The electrical conductivity more than 4 dS m^{-1} is a indicator of bad quality or saline compost as this compost can be potentially phytotoxic for plant growth (Singh and Kalamdhad, 2014). The electrical conductivity results were analyzed using ANOVA, significant variations were observed between days ($p<0.05$) and between trials ($p<0.05$). The study carried out by Banegas et al. (2007) showed that addition of bulking agents (biochar) might also upsurge ion retention in the end product, i.e., compost. The change in total nitrogen during the composting process is illustrated in Fig. 4.24a. Chan et al. (2016) described that the volume of composting mass reduces more rapidly due to decomposition of organic matter and concentration of nutrients increases mainly due to a concentration effect. The initial mean total nitrogen was noted for the three trials (A-C) and control were 2.5, 2.4, 2.3 and 2.9% respectively. As volume of compost mixture reduced, the total nitrogen content was observed to be followed increasing trend in the manner as trial B > A > C > control.

Maximum total nitrogen content percent increase was observed for trial B (49%) that was added with biochar (5%) as a CA, and this is owing to maximum decomposition of organic matter during composting process. After composting, the total nitrogen contents in all three trials trial (A-C) and control, and was recorded as 4.5, 5.2, 4.1 and 3.3%, respectively. The total nitrogen results were analyzed using ANOVA, significant variations were observed between days and trials ($p<0.05$). Compared with the other trials, the total nitrogen content increased the least in trial C (43%) after control (13%). A possible increase in nitrogen content for trial B is due to the porosity of the biochar, making the airflow and moisture available to the compost mixture, which is favorable for the composting process that is speeding up the degradation rate of the organic matter in the composter (Sánchez-García et al., 2015). In addition, nitrogen increase in biochar amended compost has been attributed to nitrifying bacteria community to produce NO_3-N rather than NH_4^+-N due to more aerobic and oxidising conditions of biochar porosity (Zhang and Sun, 2014; Sanchez-Garcia et al., 2015). The amount of biochar addition in trial B was 5% (w/w), which was probably more suitable for the balance between the *H. verticillata* and biochar in the composting process.

The total phosphorus during composting of *H. verticillata* amended with biochar (2.5, 5 and 10%) was observed to increase with composting time. The initial concentration of total phosphorus for all three trials (A-C) and control was recorded as 1.7, 1.5, 0.8, and 2.5% also illustrated in Fig. 4.24b. The microbes consume phosphorous in organic matter for their metabolism, it is also an essential element for plant growth. The plants consume phosphorous in the soluble form as orthophosphate ions mainly hydrogen phosphate ions (HPO_4^{2-})(Singh and Kalamdhad, 2014). The addition of bulking agents absorbed the relatively large amount of moisture and owing to intact structural integrity and porosity, could be a reason to prevent loss of phosphorus during the composting process. The final values for total phosphorus were observed to be 3.4, 4.8, 4.8 and 4.3 g kg^{-1}. The total phosphorus results were analyzed using ANOVA, significant variations were found between days and trials ($p<0.05$). The concentration values for other nutrients (total potassium, calcium and sodium concentration) varied over composting time for all three trials (A-C) and control are tabulated in Table 4.14 (a,b and c). Similar to total phosphorus and nitrogen these nutrients, i.e., sodium, potassium, and calcium was observed to be increasing with progression in the composting process. The final characteristics of the composting mixtures of trials (A-C) and control are tabulated in Table 4.15.

Table 4.14a. Variation in calcium during composting process

Days	Calcium (g/kg)			
	Trial A (2.5%)	Trial B (5%)	Trial C (10%)	Control
0	7.7±0.2	6.9±0.2	8.1±0.1	4.2±0.1
2	8.0±0.4	8.0±0.4	8.2±0.1	4.4±0.1
4	15.6±0.4	20.9±1.1	8.2±0.1	4.6±0.1
6	27.6±0.7	33.5±1.7	8.3±0.1	4.9±0.05
8	35.3±0.2	42.8±1.6	27.4±0.7	4.9±0.1
10	40.5±0.4	46.8±0.4	36.1±0.3	5.0±0.05
12	44.7±1.1	46.9±0.3	36.1±0.6	5.0±0.1
14	44.9±0.2	48.5±0.3	36.1±0.3	5.2±0.01
16	45.1±0.1	48.5±0.1	36.5±0.4	5.3±0.05
18	45.2±0.0	48.6±0.0	37.0±0.4	5.4±0.01
20	45.2±0.0	48.6±0.1	37.0±0.1	5.4±0.02

Table 4.14b. Variation in potassium during composting process

Days	Potassium (g/kg)			
	Trial A (2.5%)	Trial B (5%)	Trial C (10%)	Control
0	12.5±0.3	14.8±0.0	17.9±0.01	17.6±0.0
2	14.7±0.2	15.6±0.0	18.4±0.2	18.4±0.2
4	15.2±0.1	20.7±0.1	18.7±0.2	19.0±0.0
6	20.5±0.1	27.6±0.03	19.9±0.2	20.4±0.1
8	25.6±0.1	32.8±0.05	21.2±0.2	21.7±0.1
10	25.9±0.3	33.4±0.1	21.8±0.1	22.5±0.0
12	27.6±0.3	36.4±0.1	22.5±0.4	23.5±0.1
14	28.8±0.1	36.4±0.0	22.7±0.1	23.5±0.2
16	29.4±0.1	37.8±0.3	22.6±0.1	24.7±0.1
18	29.8±0.1	38.1±0.4	22.8±0.1	25.4±0.1
20	29.9±0.0	38.1±0.0	22.9±0.1	25.4±0.2

Table 4.14c. Variation in sodium during composting process

Days	Sodium (g/kg)			
	Trial A (2.5%)	Trial B (5%)	Trial C (10%)	Control
0	0.67±0.01	0.55±0.01	0.82±0.01	1.71±0.03
2	0.67±0.01	0.57±0.01	0.74±0.01	1.83±0.03
4	0.69±0.01	0.67±0.03	0.78±0.01	2.00±0.01
6	0.87±0.05	0.94±0.08	0.8±0.01	2.12±0.05
8	0.92±0.03	1.22±0.02	1.21±0.01	2.12±0.05
10	0.95±0.02	1.36±0.03	1.24±0.01	2.13±0.01
12	1.0±0.05	1.38±0.01	1.0±0.01	2.15±0.01
14	1.05±0.01	1.41±0.01	1.27±0.01	2.19±0.02
16	1.1±0.01	1.41±0.01	1.29±0.01	2.22±0.03
18	1.12±0.01	1.43±0.01	1.3±0.01	2.24±0.01
20	1.13±0.01	1.43±0.01	1.31±0.01	2.24±0.01

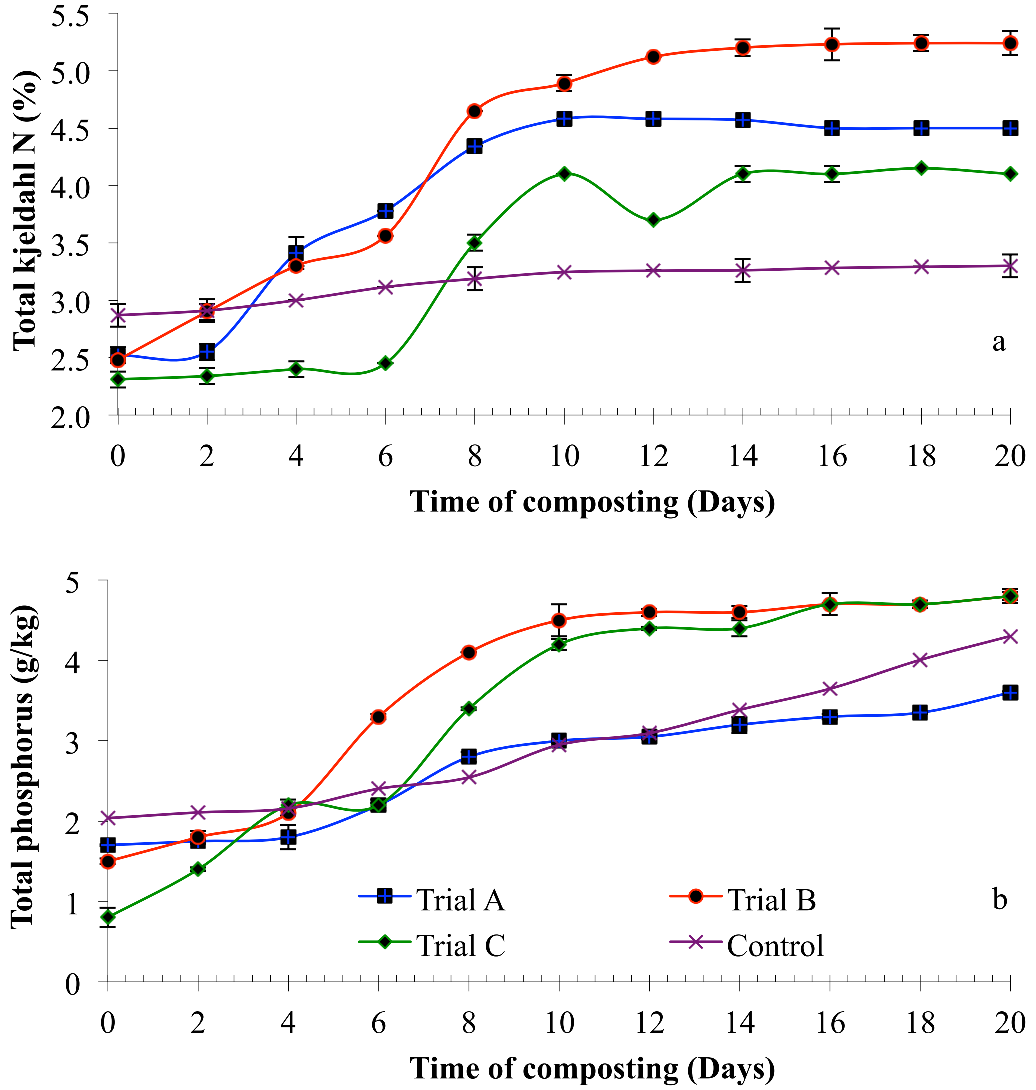


Fig. 4.24. Variation in a) Total Kjeldahl N and d) Total P during composting

Table 4.15. Characteristics of final compost

Parameters (Units)	Final compost			
	Trial A	Trial B	Trial C	Control
Moisture content (%)	68±0.4	63.4±0.4	66.9±0.6	76.2±0.2
Volatile solids (%)	68±0.1	55±1.0	75±0.1	70.5±0.2
Ash content (%)	32±0.1	45±1.0	25±0.1	29.5±0.2
pH	7.4±0.3	7.6±0.1	8±0.1	8±0.1
EC (ds m^{-1})	3.8±0.1	3.7±0.4	4.3±0.2	4.32±0.0
TN (%)	4.51±0.1	5.24±0.1	4.1±0.1	3.3±0.1
TP (g/kg)	3.6±0.05	4.8±0.03	4.8±0.1	4.3±0.07

- ***Pearson's correlation between various physical parameters***

Physical properties such as bulk density; moisture content, free air space, and particle density play the significant functions in attaining the best efficiency during monitoring of composting process as well as in utilization, handling and application of end product, i.e., compost. Optimizing compost characteristics for diverse end practices can require processing of the compost (screening, mixing, and moisture content adjustment). These operations comprise common materials-handling issues. However, process mixing ratios and turning or rotation can only be designed appropriately with a broad understanding of the physical properties of the waste materials concerned (Agnew and Leonard, 2003). According to Haug (1993), physical parameters (free air space, bulk density, and porosity) holds a healthy relationship within each other related to air flow resistance. A small variation in one parameter can affect variable essential parameters. It has been observed during the current study that as the bulk density increased the free air space tend to be rise during composting process, whereas particle density was perceived to be decreasing. The free air space and bulk density are also affected by variation in moisture content (Iqbal et al., 2010).

Table 4.16. Pearson's correlation between physical properties during composting process

		Moisture content (MC)	Bulk density (BD)	Free air space (FAS)	Particle density (PD)
Trial A (2.5%)	MC	1	-0.99201	0.98237	0.96379
	BD		1	-0.99185	-0.97804
	FAS			1	0.99439
	PD				1
Trial B (5%)	MC	1	-0.9922	0.99131	0.9894
	BD		1	-0.9945	-0.9877
	FAS			1	0.9982
	PD				1
Trial C (10%)	MC	1	-0.94318	0.9591	0.97919
	BD		1	-0.83973	-0.8799
	FAS			1	0.98729
	PD				1
Control	MC	1	-0.9454	0.92071	0.86756
	BD		1	-0.98929	-0.97549
	FAS			1	0.96924
	PD				1

Correlation is significant at the 0.05 level (2-tailed)

Hence, the Pearson's correlation coefficient matrix has been formed, as it represents all the confirmations about the relationship between the various physical parameters (bulk density, moisture content, particle density and free air space). Trial (A and B) and C and control exhibited correlation coefficient between moisture and bulk density as -0.99 and -0.94 respectively, that indicate the negative correlation between them, i.e., moisture and bulk density are interdependent as the moisture decrease the bulk density increases. The free air space is also positively correlated with the moisture contents of all the trials (A-C) and control as 0.99, 0.99, 0.98 and 0.96, respectively (Table 4.16). The correlation between those indicated that as particle density and moisture content decreases the free air space between compost mixtures decreases.

4.3.3 Concluding remarks

The amendment of biochar in varied amount during composting of *H. verticillata* aid in minimizing the effect of ammonia volatilization and achieved a higher reduction in moisture content. The prominent impact was seen in the trial B (H. verticillata, cow dung, and sawdust) added with 5% of biochar which depicted the maximum temperature of 59°C and had the highest degradability rate with moisture reduction of 23% and 31% reduction in volatile solids compared to other trials. The addition of biochar also benefitted in increasing the initial porosity of the mixes (99-99.3%), which was witnessed lesser (95.8%) in case of control.

4.4 PHASE IV - COMPOST APPLICATION IN SOIL

This Phase 4 mainly deals with the effect of compost application on two sandy soils (laterite and alluvial soil). This Phase IV as mentioned in chapter 3 (3.1 Experimental design section) also accomplishes the last objective of the study.

The study has been performed with the hypothesis that compost produced from *H. verticillata* with Biochar additive influences the nutritional value and soil physical health, but the influence can be studied with different application rates. Therefore the current research work is focused on determining the influence of different compost rates on two soils viz. alluvial and laterite soil. The study will also assess the effects of compost application on soil physical, organic matter, chemical, and nutritional properties.

4.4.1 Compost characteristics

Appropriate nutritional value characterized the compost prepared using *H. verticillata*, cow dung, sawdust, and biochar, enriched in nitrogen content as well as stabilized organic matter. The composting process also achieved thermophilic temperatures (68.1°C) thus indicating hygienic and pathogen-free compost.

The compost utilized in the present study for the application in alluvial and laterite soil depicted higher values of the mineral elements. The pH and electrical conductivity of the compost were within the range of 7-7.5 and 3.7-3.8, which is suitable for soil application as recommended by FCO (2009).

4.4.2 Effect on soil organic matter, pH and nutritional properties

The soils were characterized by a deficient soil organic matter (SOM) content, which was observed as 1.2 and 4.5% in LS and AS, respectively. However, the increasing compost application rates significantly increased the SOM content in all the treatments except control LS0 and AS0. The initial values for LS0-LS30 were 1.2, 17.8, 21.3 and 24.9% respectively. Similarly, in AS0-AS30 the initial values were noted as 4.5, 23.7, 27.3 and 31%, respectively. But with the due period, the SOM content was observed to be decreasing (Fig. 4.25a) and noted as 1.2, 9, 9.6 and 11.4% in LS0-LS30 and 4.6, 11.2, 13.8 and 12.6% in AS0- AS30, after 120 days, respectively. The treatment with the 20% of compost amount (L20) showed maximum reduction 55% whereas to the AS, it was observed for the AS30 59%.

The soil organic carbon (SOC) of raw LS and AS were depicted as very low. The

SOC of raw AS was observed three times higher as that of LS and noted as 2.3 and 0.7%, respectively. The prepared compost was characterized by a higher amount of total organic carbon approximately 30%. With the increasing application rates of the compost, the SOC was observed increasing in all the treatments except control (L0) and AS0. The day-0 values of SOC noted for LS0- LS30 were 0.7, 8.9, 10.6 and 12.4% and for AS0-AS30 were 2.4, 11.8, 13.6, and 15.5% respectively. The time study showed the significant decrease in the SOC when compared to control as shown in Fig. 4.25.

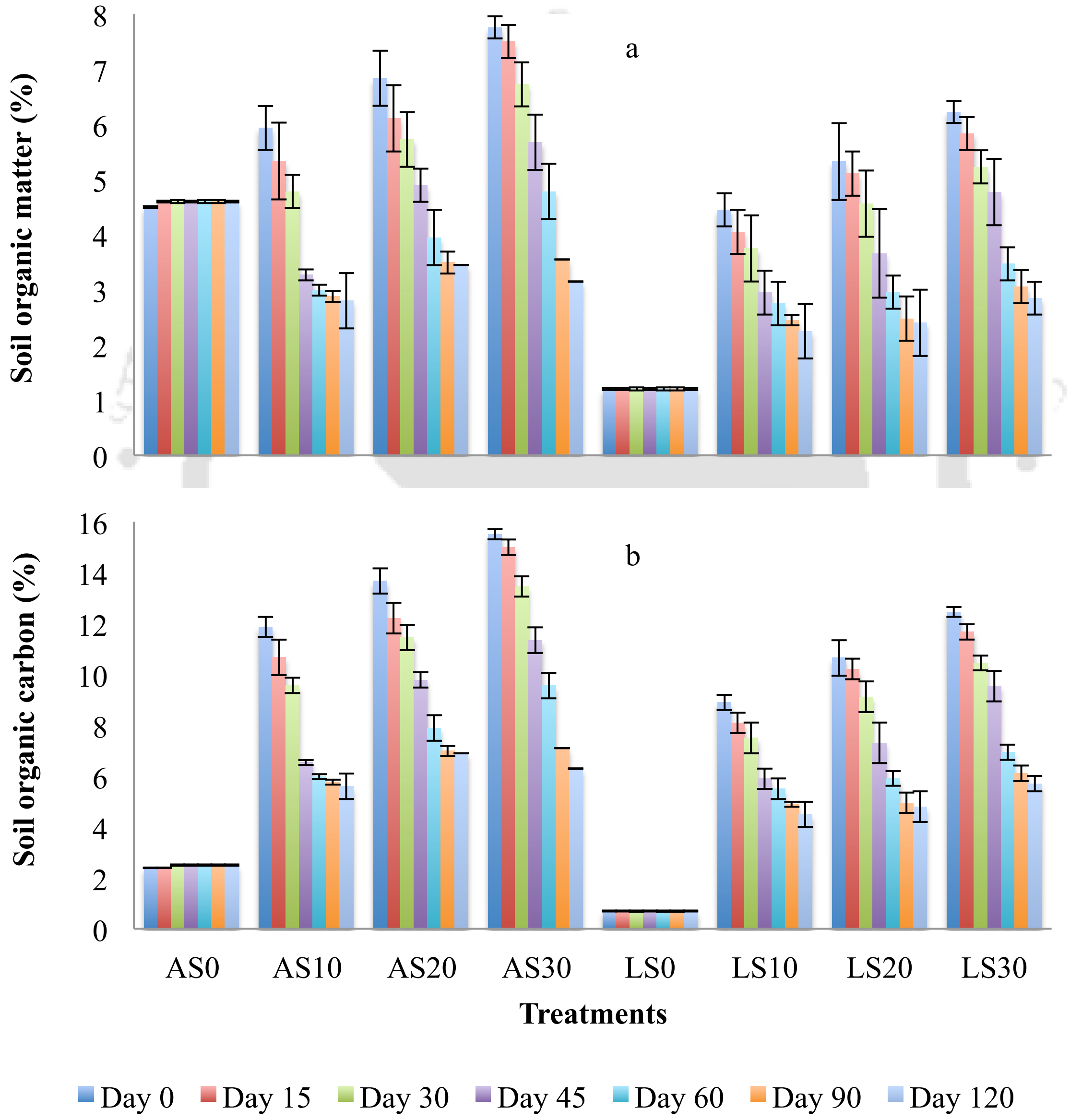


Fig. 4.25. Variation in a) Soil Organic matter and b) Soil Organic Carbon

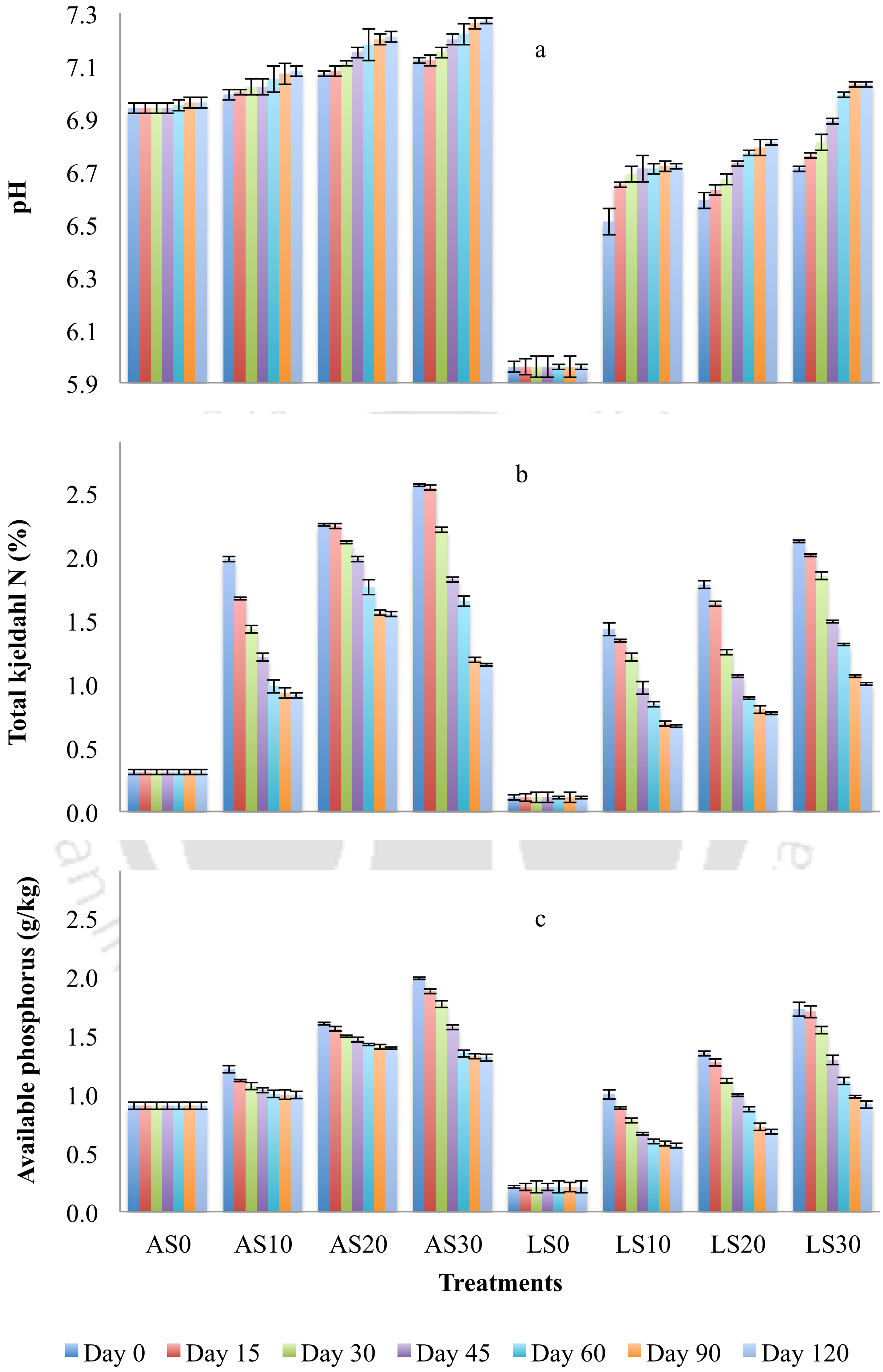


Fig. 4.26 Variation in a) pH, b) Total kjeldahl N and c) Available P

After 120 days the SOC values noted for LS0-LS30 were 0.7, 4.5, 4.8, and 5.7% and for AS0-AS30 were 2.5, 5.6, 6.9, 6.3%, respectively. The SOC reduction followed a similar pattern to that of SOM content for maximum reduction. Initially, the soils were characterized as the acidic soil with pH value 6.9 and 5.9 for AS and LS, respectively. However, the application of *H. verticillata* compost prepared using Biochar had a significant impact on soil pH as it aided for a direct rise from acidic towards neutral during the treatment of both soils, i.e., 5.9 to 7 when compost application rates increased from 0 to 30% in both the soils as shown in Table 4.15. The study indicated the final pH values for LS0- LS30 as 5.96, 6.72, 6.81 and 7.03 and for AS0-AS30 as 6.96, 7.08, 7.21 and 7.27, respectively, after 120 days, which was significantly higher than that of the control, i.e., LS0 and AS0 (Fig. 4.26a).

The total Kjeldahl nitrogen (TKN) and available phosphorus (AP) content of the treated soil samples were obtained from all the treatments, i.e., LS0-LS30 and AS0-AS30. The variation due to compost application in TKN and AP is shown in Fig. 4.26b and 4.26c. After the compost application an immediate effect on TKN and AP contents were seen for all the treatments as compared to control. Higher the application rates, the higher 0-day values of TKN and AP observed in this study. The TKN and AP contents of the AS10-AS30 treatments were higher compared to that of LS0- LS30. However, with the progression of the compost application time, both nutrients were observed to be reduced. The study indicated the final TKN values for LS0-LS30 as 0.11, 0.67, 0.77 and 1.0% and AS0-AS30 as 0.31, 0.91, 1.55, 1.15%, respectively after 120 days, which was significantly higher than that of the control, i.e., LS0 and AS0. Similarly, for AP the values were noted as 0.9, 0.99, 1.39 and 1.31 g/kg and 0.21, 0.56, 0.68 and 0.91 for AS0-AS30 and LS0- LS30, respectively. The study showed higher TKN and AP concentration in AS20 and LS30.

4.4.3 Effect on soil sorption properties

The sorption capacity of the compost prepared using Biochar indicated a high level of cation-exchange capacity (CEC) as well as water holding capacity (WHC), and therefore its application in soil (AS and LS) caused a considerable decrease of its potential acidity, increase in CEC and WHC (Table 4.17). This effect was not distinctly expressed in the first month of the experiment, while in the following months the CEC and WHC were increased as shown in Fig. 4.27.

All pots amended with composts showed significantly higher CEC and WHC compared with the control. CEC and WHC content was lower particularly those amended with the lower application rates in both soils. But it should be noticed that in the case of soil amended with 20% in AS, i.e., AS20 and 30% in LS, i.e., LS30 depicted the higher amount of CEC as well as WHC. The CEC and WHC were related to differential compost rates and distinctly changed with time. The increase was perceived within the 45 days. On day-120 CEC and WHC content found significantly higher, compared to the control, in all the treatments as shown in Table 4.17.

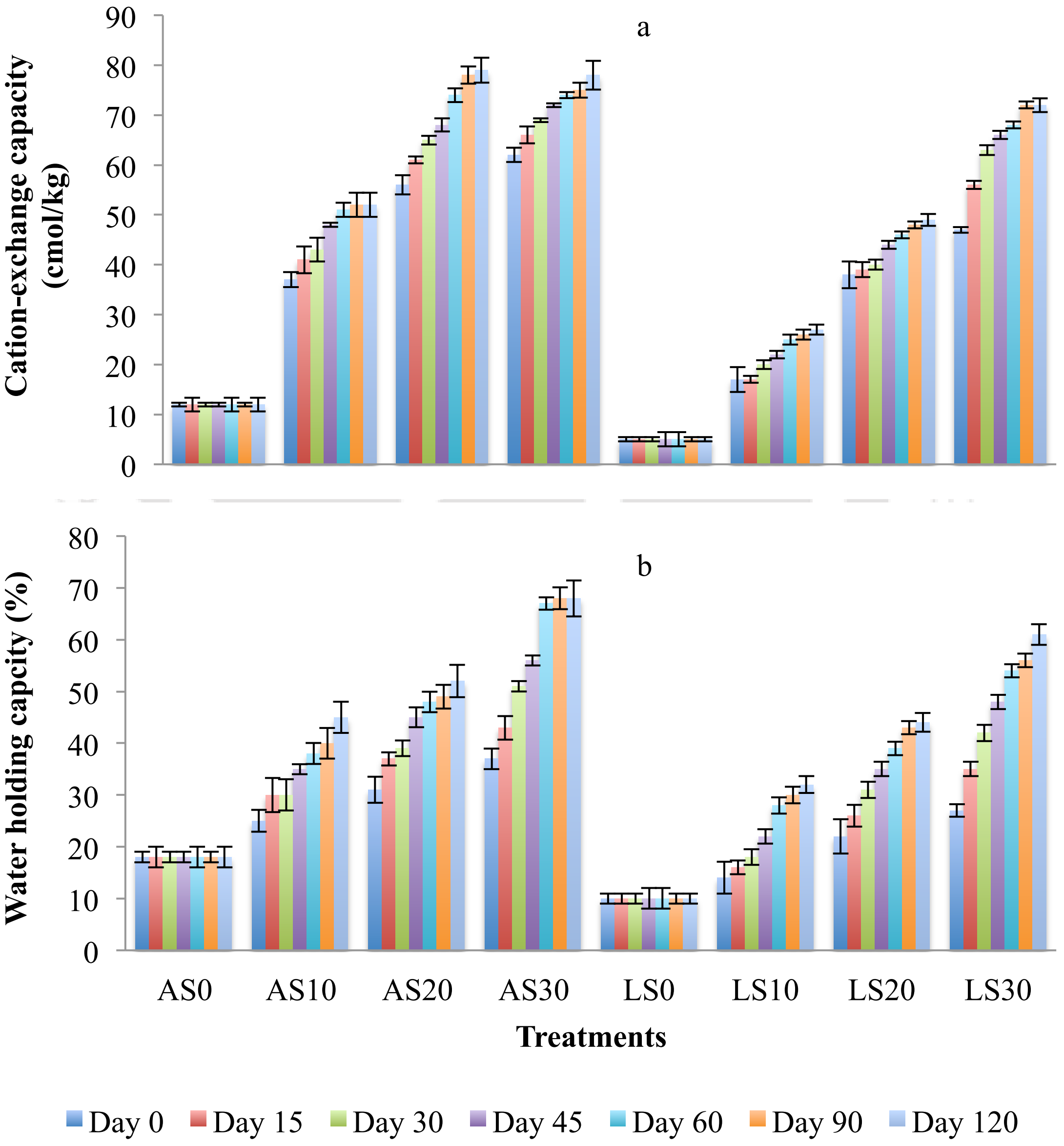


Fig. 4.27. Variation in a) Cation-exchange capacity and b) Water holding capacity

4.4.4 Effect on soil physical properties

The bulk densities (BD) of LS and AS were 1.36 and 1.67 g cm^{-3}, respectively. The compost application influenced the soil BD by lowering its initial value of raw soil. The BD for all treated soil samples were 1.67, 1.58, 1.34 and 1.21 in AS0-AS30 and 1.36, 1.21, 1.05, 0.987 g cm^{-3} in LS0- LS30, respectively. However, the type of soil showed an interaction with the application rates. Much smaller BD values were observed in all soil samples treated with the higher application rates with an average of 1.47 and 1.14 g cm^{-3} in treatments to the AS and LS, respectively (Fig. 4.28a).

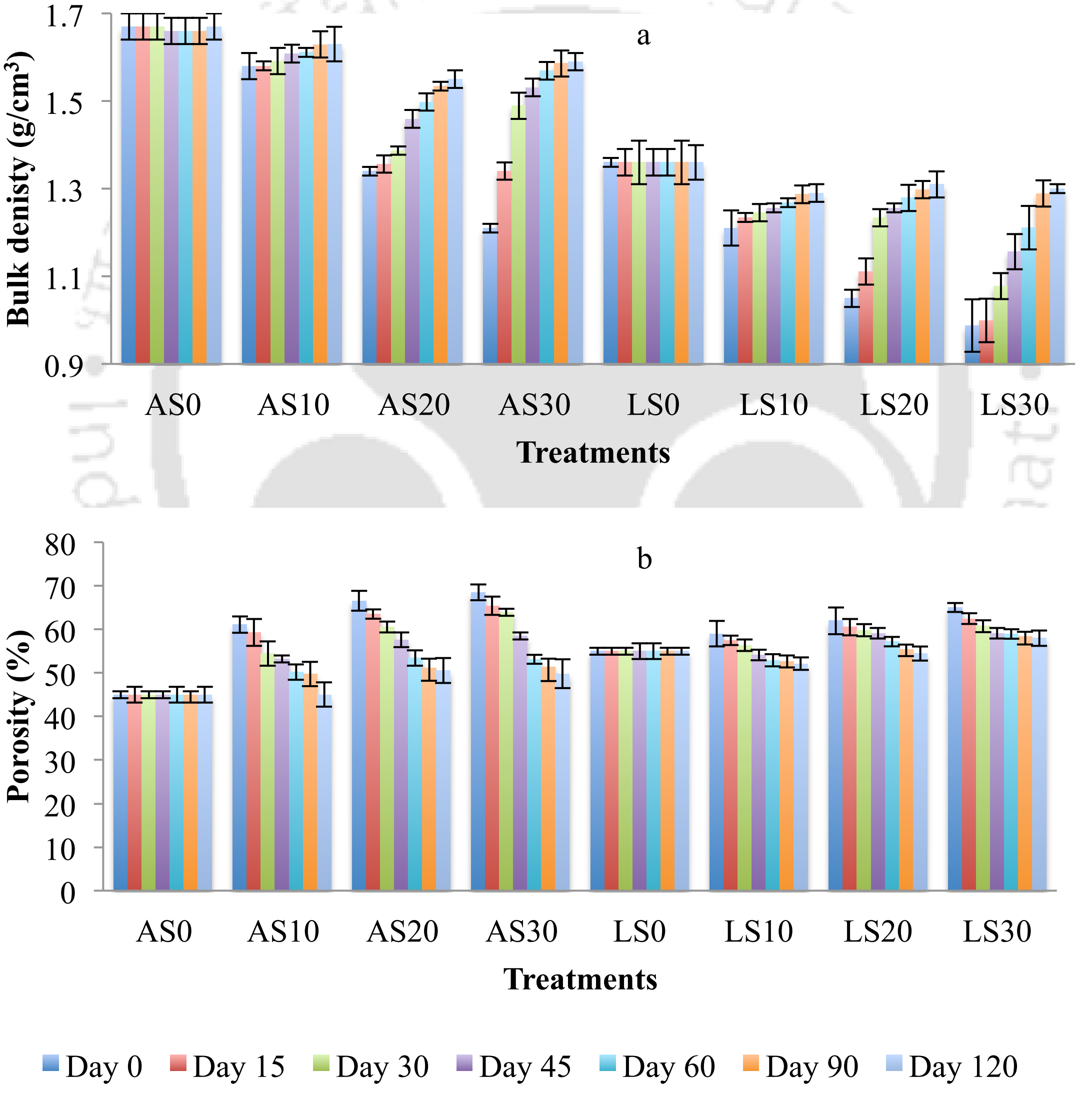


Fig. 4.28. Variation in a) Bulk Density and b) Total Porosity

However, when the lower application rates showed higher BD values in the soil samples (1.60 and 1.25 g cm^{-3} on an average in AS and LS, respectively). An opposite effect was perceived for TP when compared to the facts obtained for BD. The TP of the raw AS and LS was 45 and 55%, and it increased when increasing compost application rates were applied.

4.4.5 Discussion

The composts used in this research work showed enhanced mineral composition and nutrients characteristics compared to other composts prepared from different wastes such as sewage sludge, municipal solid, agro-industrial wastes which have been used so far as organic fertilizers (Paredes et al., 2005; Fernández-Hernández et al., 2014).

Soil Organic matter content is an essential element in the soil that supplies necessary plant nutrients, aid in reducing soil erosion, and improves soil aggregation as well as water holding capacity (Ryals et al., 2014). SOM is the primary source that provides carbon as energy to the soil microbes which regulates nutrients (Cooperband, 2002). The poor SOM content in both soils is mainly due to the heavy rainfall that occurs in the study area (Guwahati, Assam). The recurrent flood washes away the SOM from the topsoil surface. But the application of organic compost shown an immediate positive effect on both soils, i.e., SOM content had shown the significant increase with increasing application rates. However, when 120 days of study is considered the SOM content was found decreasing in all the treatments compared to control SOM content. This fact might be due to the mineralization process that has been occurred in the soil by the microbial biomass (Marschner and Kalbitz, 2003; Kemmitt et al., 2008). The SOM content can also decline because of erosion and repeated cultivation (Wolka and Melaku, 2015). Other researchers observed similar patterns for SOM during various compost amendments in sandy and different soils (Navas et al., 1998; Baiano and Morra, 2017; Goswami et al., 2017; Weber et al., 2007).

So, far many researchers have explained the fact of the increase in the SOC after the application of biochar (Lehmann et al., 2011; Kuppusamy et al., 2016). Biochar is a carbon-rich material. Hence, in the present study, the combination of *H. verticillata* and biochar significantly increased the SOC content with the increasing application rates in both soils. However, SOC was seen to be reducing with time in all the treatments. The carbon reduction from the substrates varies between 10-70% that depends on the soil micro-flora and the synthesized microbial cells.

Even after 120 days of the compost application, the SOC contents were observed as higher compared to the control pots of both soils, i.e., LS0 and AS0, respectively.

The pH values of the raw soil (LS and AS) used in this study were observed to be acidic. This study followed the similar pattern for the soil pH as observed in other studies on sandy soils (Fowles, 2007; Bass et al., 2016). However, it was contradictory to the study carried out by Abujabhah et al. (2016) on the temperate agricultural soil. The effect of compost application prepared from biochar on soil pH is reliant on the initial pH of the raw materials and the biochar itself, which is dependent on the type of the feedstocks and pyrolysis conditions used for biochar production (Lehmann et al., 2011; Abujabhah et al. 2016). As the biochar utilized in this research work had a slightly basic pH of 8, therefore, it was apparent to exhibit increase in the pH due to its higher buffering capacity. The decrease in organic matter may also the responsible for the rise in the soil pH due to the microbial activity. This pH pattern is following the other studies of compost application conducted on various soils (Jiang et al., 2006; Wolka and Melaku, 2015). According Jiang et al. (2016), the higher pH may increase the microbial community and can able to change its composition.

The LS soil exhibited lower nutritional (TKN and AP) values compared to that of AS. As anticipated, application of the compost enriched with various nutrients shown immediate positive effect during treatment of both soils. Multiple researchers observed the similar patterns for TKN and AP after compost application (Lehmann et al., 2011; Abujabhah et al. 2016; Baiano and Morra, 2017; Goswami et al., 2017). The TKN and AP were seen to be reducing with time in all the treatments. According to Wolka and Melaku (2015), the decline in nutrients might be due to leaching or nitrification process. The reduction also depends on the soil micro-flora and the synthesized microbial cells. Even after 120 days of the compost application, the TKN and AP contents were depicted higher compared to the control pots of both soils, i.e., LS0 and AS0, respectively. A fascinating observation was represented in this study that despite higher compost application rate in AS soil, i.e., AS30 showed lesser TKN and AP content compared to AS20. This fact is due to the more significant reduction in porosity, which caused substantial leaching of the nutrients. However, in the case of LS30, the higher amount of TKN and AP concentration was observed.

The impact of compost application on soil physicochemical properties may be measured concerning advantageous effects on soil sorption capacity, i.e., WHC and CEC. Various researchers observed the similar results for CEC and WHC after compost application (Gallardo-Lara and Nogales, 1987; Leifeld et al., 2002; Weber et al., 2007), however, regardless amounts of compost, amendments did not affect the soil reaction. The compost prepared using biochar had shown significant changes in the soil porosity that aid in improving its sorption or hydraulic properties. Curtis and Claassen (2005) reported a 2-fold increase in WHC after compost application at the rate of 24%. In the present study, WHC and CEC both increased with the increasing rate of application. This WHC pattern is following the other studies of compost application conducted on various soils (Aggelides and Londra, 2000). However, the study by Mamo et al. (2000) reported no significant effect on WHC after compost application.

Biochar is also known for its higher affinity for CEC and WHC. In the present study, also due to an addition of Biochar the CEC and WHC observed to be improved. Such increasing pattern of WHC in sandy soils was also reported (Abel et al., 2013). But according to Xu et al. (2012), improvements in soil WHC by Biochar additions are mainly restricted to coarse-textured soils. Previous studies suggest the improvement in physical properties of soil after compost application (Celik et al., 2004; Głąb, 2014). The significant impact on physical properties of the soil was observed in this study after compost application. According to Głąb et al. (2018), these changes in BD and TP are primarily due to an addition of less dense material (compost) with the soil. Similar patterns were also observed on fine and coarse-textured soils in the earlier studies (Celik et al., 2004; Głąb, 2014; Głąb et al., 2016). A review study also presents a healthy relationship between the compost application and its impact on physical properties (Hargreaves et al., 2008). The higher the compost application rates, the lower the BD and higher the TP. This variation pattern in BD and TP is following the other studies of compost application conducted on various soils (Aggelides and Londra, 2000; Pagliai et al., 2004). Variations in BD were suggested in the differential porosity of the soil. Thus compost application increased pore volume as compared to control. A similar effect was observed in the study conducted by Larney and Angers (2012) who noted that soil microporosity and macroporosity increased with the compost or livestock application. Moreover, an addition of the biochar during composting significantly aid in improving the physical health of the soil in relation to the control study after compost application in the LS and AS.

According to Tejada and Gonzalez (2008) and Jien and Wang (2013), the biochar amendment in soil contributes to altering soil aggregate sizes, which in turn decreases the bulk density of the soil. Even after 120 days of the compost application, the BD and TP contents were depicted lower compared to the control pots of both soils, i.e., LS0 and AS0, respectively.

Table 4.17. Results from a two-factor ANOVA testing for the effects of days and compost rates on two different soil parameters

Factors	df	Parameters[a]							
		SOM		SOC		pH		TKN	
		F	p	F	p	F	p	F	p
Treatments	7	26	< .05	47.7	< .05	514.2	< .05	66.6	< .05
Days	6	16	< .05	16.1	< .05	11.4	< .05	15.9	< .05

[a] SOM: Soil organic matter; SOC: Soil organic carbon; TKN: Total Kjeldahl Nitrogen;

Factors	df	Parameters[a]									
		AP		CEC		WHC		BD		TP	
		F	p	F	p	F	p	F	p	F	p
Treatments	7	78.4	< .05	374	< .05	69.6	< .05	64.8	< .05	20.1	< .05
Days	6	10.0	< .05	14.3	< .05	15.5	< .05	8.2	< .05	11.4	< .05

AP: Available Phosphorus; CEC: Cation-exchange capacity; WHC: Water Holding capacity; BD: Bulk density; TP: Total Porosity

4.4.6 Concluding remarks

The compost utilized was found to be rich in the essential mineral composition such as nitrogen (5.2%), available phosphorus (3.4 g kg^{-1}), and potassium (38.1 g kg^{-1}) that is beneficial for soil application. The immediate effect of the compost addition was seen on soil organic matter and organic carbon, which was observed increasing with higher application rates. The increase in organic carbon content to a greater extent is possibly due to the presence of biochar in the compost. The purely nitrogen-rich compost prepared using *H. verticillata* found to be beneficial to raise the nitrogen content in both soils with 1% in laterite soil possessing 30% compost whereas 1.5% in alluvial soil that owns 20% compost when measured after 120 days. Another significant effect of compost application was seen on sorption properties, i.e., water holding capacity and cation exchange capacity, which was increased with increasing application rates. The soil physical health is determined by understanding the composting effect on bulk density and total porosity.

The presence of biochar in the compost played a significant role in decreasing the bulk density whereas an inverse effect was seen to the total porosity. The lowest bulk density (1.21 and 0.98 g cm^{-3}) was depicted when the more significant amount of compost was applied in alluvial and laterite soil, respectively, when measured after 120 days. Therefore, after thorough understanding the effect of compost application on various soil properties, the authors recommend using this novel compost (prepared using *H. verticillata*, cow dung, sawdust, and biochar) on alluvial and laterite soil at the rate of 20% and 30%, respectively, to achieve better soil health.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

This chapter draws conclusion from the study carried out in four phases on the composting of *H. verticillata* biomass using rotary drum composting followed by study on composting physics; role of carbon-rich agents and its field application. This chapter also recommends scope of the future study.

5.1 CONCLUSIONS

The initial characterization of *H. verticillata* showed the potentiality of its conversion (composting) into the useful agricultural product (compost). But its high moisture content (89-94%) and low carbon: nitrogen ratio (10:1) indicated the need for the addition of cow dung and sawdust.

An appropriate amount of cow dung as inoculum and saw dust facilitated the rotary drum composting process of *H. verticillata* indicated by the thermophilic temperature (53°C) in the Trial 4 (8:1:1). The study also showed a higher reduction in moisture content, volatile solids, lower oxygen uptake rates (OUR) and carbon dioxide (CO_2) evolution rate, highest reduction in soluble biochemical oxygen demand (sBOD) as well as chemical oxygen demand (sCOD), enhanced pH values in the Trial 4 compared to other trials. However, the study showed higher nitrogen loss due to ammonia volatilization. Also moisture content in the end product was still higher (78-80%) than recommended values for the application. Moreover, moisture content is critical parameters that affect the degradation process and other essential properties (bulk density, porosity, free air space).

The comparative study on determination of physical properties conducted on five various wastes that include *H. verticillata*, water hyacinth, vegetable wastes, and sewage sludge and paper mill sludge. The study results indicated better results for rotary drum composting of *H. verticillata* and water hyacinth compared to other wastes. The maximum temperature depicted for Drum C (vegetable wastes) was 64.2°C whereas the least depicted for Drum E (paper mill sludge). Amongst the five drums only the Drum E did not achieve thermophilic (>45°C) temperatures, which is the primary factor for feasible composting process. The results also indicated that the moisture content of each waste had the impact on each of the physical properties. Similarly, the free air space and bulk densities were positively correlated in all the drums whereas the least correlation observed between porosity and bulk density. Hence, it is concluded that the variation in moisture content and bulk density has a substantial impact on the change in free air space and the small effect on porosity.

To minimize the effect of moisture content and to reduce the nitrogen loss during composting of *H. verticillata*, the various carbon-rich agents such as dry leaves (10%), grass clippings (10%), wood chips (10%) and varying biochar percentages (2.5, 5, 10%) were added to the mixture of *H. verticillata*, cow dung and sawdust of ratio Trial 4 (8:1:1). Although the higher thermophilic temperatures obtained for the Run B, i.e., with grass clippings (68°C), aesthetically it was not good due to the presence of partially degraded fibers of grass clippings in the final product. The study results further indicated higher moisture reduction (23%) as well as higher nitrogen content (5.4-5.6%) in the end product obtained from the Trial B, i.e, added with the biochar (5%). The biochar addition also fulfilled the criteria of carbon: nitrogen ratio due to the presence of highly stable carbon content. Further the study indicated higher reduction in volatile solids (31%), higher degradation rate, and recommended bulk density values (< 1000 kg m^{-3}), enhanced pH and electrical conductivity (< 4 ds m^{-1}) values in the Trial B, i.e, added with the biochar (5%) compared to other trials.

The application of the compost prepared from *H. verticillata* + biochar in alluvial and laterite soils shown a positive impact on the organic and physical properties as well as nutritional status of the soil. The study results indicated better results for alluvial soil with (20%) compost addition and 1.5% total Kjeldahl nitrogen and 1.21 g cm^{-3} bulk density was observed after 120 days. Similarly, 1% total Kjeldahl nitrogen and 0.98 g cm^{-3} bulk density observed for the laterite soil added with 30% compost. Therefore, after thorough understanding the effect of compost application on various soil properties, this study recommends addition of the compost prepared using *H. verticillata*, cow dung, sawdust, and biochar (5%) on alluvial and laterite soil at the rate of 20% and 30%, respectively, to achieve better soil health.

5.2 RECOMMENDATIONS

- Study on the vermicomposting of *H. verticillata* using different earthworm species.

- Determination or identification of microbial communities using rRNA and rDNA sequencing will be useful for understanding and controlling different stages of the composting process.
- To study variation in physical properties for various wastes such as other industrial and agricultural wastes.
- Study on the effect of different additives (corn stalks, rice straw etc.) can be performed to enhance the composting process.
- To study the effect of compost (prepared from *H. verticillata* + biochar) application on soil with various plant growth

REFERENCES

Abbasi, S. A., Nipaney, P. C., Schaumberg, G. D., 1990. Bioenergy potential of eight common aquatic weeds. Biological Wastes. 34(4), pp. 359-366.

Abbasi, S.A., 1988. Environmental analysis of cerium using N-p-Chlorophenyl-2-Furylacrylohydroxamic Acid with or without 1-(2-Pyridylazo)-2-Naphthol. Int. J. Environ. Anal. Chem. 34(3), pp. 181-190.

Abbasi, S.A., Chari, K.B., 2008. Environmental management of urban lakes, first ed. Discovery publishing house, New Delhi.

Abbasi, S.A., Nipaney, P.C., 1986. Infestation of the fern genus *Salvinia*: its status and control. Environ. Con. 13 (3), pp. 235-241.

Abdalla, A.A., Hafeez, A.T.A., 1969. Some aspects of utilization of water hyacinth (Eichhornia crassipes). Proc. of National Academy of sciences, 15(2), pp. 204–207.

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M.,Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma, 202, pp. 183-191.

Abujabhah, I. S., Bound, S. A., Doyle, R., Bowman, J. P., 2016. Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. App. Soil Ecol., 98, pp. 243-253.

Adhikari, B. K., Barrington, S., Martinez, J., King, S., 2009. Effectiveness of three bulking agents for food waste composting. Waste Manage., 29(1), pp. 197-203.

Adhikari, B., Barrington, S., Martinez, J., King, S., 2008. Characterization of food waste and bulking agents for composting. Waste Manage. 28, pp. 795-804.

Aggelides, S. M., Londra, P. A., 2000. Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. Bioresour. Technol., 71(3), pp. 253-259.

Agnew, J.M., Leonard, J.J., 2003. The physical properties of compost. Compost Sci. Util., 11(3), pp. 238-264.

Ahn, H. K., Richard, T. L., Glanville, T. D., 2008. Laboratory determination of compost physical parameters for modeling of airflow characteristics. Waste Manage., 28(3), 660-670.

Amlinger, F., Peyr, S., Geszti, J., Dreher, P., Karlheinz, W., Nortcliff, S., 2007. Beneficial effects of compost application on fertility and productivity of soils. Federal Ministry for Agricultural and Forestry, Environment and Water Management, Germany.

Angelidaki, I., Ellegaard, L., Ahring, B.K., 1999. A comprehensive model of anaerobic bioconversion of complex substrates to biogas. Biotechnol. Bioeng. 63(3), pp.363-372.

Amossé, J., Turberg, P., Kohler-Milleret, R., Gobat, J. M., Le Bayon, R. C., 2015. Effects of endogeic earthworms on the soil organic matter dynamics and the soil structure in urban and alluvial soil materials. Geoderma, 243, pp. 50-57.

An, C.J., Huang, G.H., Li, S., Yu, H., Sun, W., Peng, K., 2012. Influence of uric acid amendment on the in-vessel process of composting composite food waste. J. Chem. Technol. Biotechnol. 87(11), pp.1558-1566.

Anifowose, A. Y. B., 2000. Stabilisation of lateritic soils as a raw material for building blocks. B Eng Geol Environ., 58(2), pp. 151-157.

APHA, 2012. Standard methods for the examination of water and wastewater. 22nd edition, American Public Health Association, Washington DC.

Araki, S., Mukai, R., Makino, S., Nishikawa, T. and Saruwatari, H., 2003. The fundamental limitation of frequency domain blind source separation for convolutive mixtures of speech. IEEE Transactions on Speech and Audio Processing, 11(2), pp.109-116.

Baeta-Hall, L., Sàágua, M. C., Bartolomeu, M. L., Anselmo, A. M., Rosa, M. F., 2005. Bio-degradation of olive oil husks in composting aerated piles. Bioresour. Technol., 96(1), pp. 69-78.

Baiano, S., Morra, L., 2017. Changes in soil organic carbon after five years of biowaste compost application in a Mediterranean vegetable cropping system. Pedosphere, 27(2), pp. 328-337.

Balciunas, J. K., Minno., M. C., 1985. Insects damaging hydrilla in the USA. J Aquat. Plant Manage. 23, pp. 77-83.

Banegas, V., Moreno, J. L., Moreno, J. I., Garcia, C., Leon, G., Hernandez, T., 2007. Composting anaerobic and aerobic sewage sludges using two proportions of sawdust. Waste Manage. 27(10), pp. 1317-1327.

Bang-Andreasen, T., Nielsen, J.T., Voriskova, J., Heise, J., Rønn, R., Kjøller, R., Hansen, H.C., Jacobsen, C.S., 2017. Wood ash induced pH changes strongly affect soil bacterial numbers and community composition. Front. Microbiol., 8, pp.1400.

Barko, J.W., Smart, R.M., McFarland, D.G., Chen, R.L., 1988. Interrelationships between the growth of Hydrilla verticillata (L.f.) Royle and sediment nutrient availability. Aquat. Bot., 32(3), pp. 205-216.

Barnes M. A., Jerde C. L., Wittmann M. E., Chadderton W. L., Ding J., Zhang J., Purcell, M., Budhathoki, M., Lodge D. M., 2014. Geographic selection bias of occurrence data influences transferability of invasive Hydrilla verticillata distribution models. Ecol. Evol., 4, pp. 2584–2593.

Barrington, S., Choinière, D., Trigui, M., Knight, W., 2002. Effect of carbon source on compost nitrogen and carbon losses. Bioresour. Technol., 83(3), pp. 189-194.

Basiouny, F.M., Garrard, L.A., 1984. Studies on Mineral Nutrition of Hydrilla. Weed Sci. 32(5), pp. 681-685.

Bass, A. M., Bird, M. I., Kay, G., Muirhead, B., 2016. Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems. Sci. Total Environ., 550, pp. 459-470.

Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S.V., Pavlostathis, S.G., Rozzi, A., Sanders, W.T.M., Siegrist, H. and Vavilin, V.A., 2002. The IWA anaerobic digestion model no 1 (ADM1). Water Sci. Technol., 45(10), pp.65-73.

Beall, J., Swift, R., 2008. Natural micro sponge trial on hydrilla. Article in Wildland Weeds, 21.

Beinart, W., Wotshela, L., 2003. Prickly pear in the Eastern Cape since the 1950s-perspectives from interviews. Kronos, pp.191-209.

Bek, C. M., 1956. Controlled temperature forced air composting. Michigan State University. Department of Civil and Sanitary Engineering.

Benito, M., Masaguer, A., Moliner, A., De Antonio, R., 2006. Chemical and physical properties of pruning waste compost and their seasonal variability. Bioresour. Technol., 97(16), pp. 2071-2076.

Bernal, M. P., Alburquerque, J. A., Moral, R., 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. Bioresour. Technol., 100(22), pp. 5444-5453.

Best, E. P. H., Boyd, W. A., 1996. "A simulation model for growth of the submersed aquatic macrophyte hydrilla (Hydrilla verticillata (L.F.) Royle," Technical Report A-96-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bicudo, D. D. C., Fonseca, B. M., Bini, L. M., Crossetti, L. O., Bicudo, C. E. D. M., Araújo‐jesus, T. A. T. I. A. N. E., 2007. Undesirable side‐effects of water hyacinth control in a shallow tropical reservoir. Freshwater Biol., 52(6), pp. 1120-1133.

Bishop, P. L., Godfrey, C., 1983. Nitrogen transformations during sludge composting. Biocycle.

Blazy, V., de Guardi, A., Benoist, J.C., Daumoin, M., Lemasle, M., Wolbert, D., Barrington, S., 2014. Odorous gaseous emissions as influence by process condition for the forced aeration composting of pig slaughterhouse sludge. Waste Manage. 34, pp. 1125-1138.

Bock, D.G., Caseys, C., Cousens, R.D., Hahn, M.A., Heredia, S.M., Hübner, S., Turner, K.G., Whitney, K.D., Rieseberg, L.H., 2015. What we still don't know about invasion genetics. Mol. Ecol., 24(9), pp.2277-2297.

Borchard, N., Prost, K., Kautz, T., Moeller, A., Siemens, J., 2012. Sorption of copper (II) and sulphate to different biochars before and after composting with farmyard manure. Eur J Soil Sci, 63(3), pp. 399-409.

Boyd, C.E., 1969. The nutritive value of three species of water weeds. Econ. Bot. 23(2), pp. 123-127.

Brinton, W.F., 2001. How compost maturity affects plant and root performance in container grown media. Biodynamics, pp. 22-27.

Brouillette, M., Trepanier, L., Gallichand, J., Beaucham, C., 1996. Forced aeration. Can Agr Eng., 38(2), p. 115.

Brown, J.H., 1995. Macroecology. The University of Chicago Press. Chicago. USA.

Buckingham, G.R., Bennett, C.A., 1996. Laboratory biology of an immigrant Asian moth, Parapoynx diminutalis (Lepidotera: Pyralidae), on Hydrilla verticillata (Hydrocharitaceae). Fla. Entomol., 79, pp. 353-363.

Buckingham, G.R., Okrah, E.A., Omas, M.C., 1989. Laboratory host range tests with Hydrellia pakistanae (Diptera: Ephydridae), an agent for biological control of Hydrilla verticillata (Hydrocharitaceae). Environ. Entomol., 18, pp. 164-171.

Burkill, I.H., 1935. Economic Products of Malay Peninsula. 2 vols. Crown Agent for the Colonies, London.

Byju, G., Haripriya Anand, M., Moorthy, S. N., 2015. Carbon and nitrogen mineralization and humus composition following municipal solid waste compost addition to laterite soils under continuous cassava cultivation. Commun Soil Sci Plant Anal., 46(2), pp. 148-168.

Castaldi, P., Garau, G. and Melis, P., 2004. Influence of compost from sea weeds on heavy metal dynamics in the soil-plant system. Fresen. Environ. Bull., 13(11), pp.1322-1328.

Castlehouse, H., Smith, C., Raab, A., Deacon, C., Meharg, A.A. and Feldmann, J., 2003. Biotransformation and accumulation of arsenic in soil amended with seaweed. Environ. Sci. Technol., 37(5), pp.951-957.

Celik, I., Ortas, I., Kilic, S., 2004. Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. Soil Tillage Res., 78(1), pp. 59-67.

Chambers, J. M., Cleveland, W.S., Tukey, P. A., Kleiner, B., 1983. Graphical Methods for Data Analysis. Duxbury Press

Chan, M. T., Selvam, A., Wong, J. W., 2016. Reducing nitrogen loss and salinity during ‘struvite’food waste composting by zeolite amendment. Bioresour. Technol., 200, pp. 838-844.

Chang, J.I., Chen, Y.J., 2010. Effects of bulking agents on food waste composting. Bioresour. Technol., 101 (15), pp. 5917-5924.

Charudattan, R., 1972. Pathogenicity of fungi and bacteria from India to Hydrilla and Waterhyacinth. Fla Hyacinth Control J. 11, pp. 44-48.

Chen, X., Chen, Z., Wang, X., Huo, C., Hu, Z., Xiao, B., Hu, M., 2016. Application of ADM1 for modeling of biogas production from anaerobic digestion of Hydrilla verticillata. Bioresour Technol., 211, pp.101-107.

Chen, Y. X., Huang, X. D., Han, Z. Y., Huang, X., Hu, B., Shi, D. Z., Wu, W. X., 2010. Effects of bamboo charcoal and bamboo vinegar on nitrogen conservation and heavy metals immobility during pig manure composting. Chemosphere, 78(9), pp. 1177-1181.

Chislock, M. F., Doster, E., Zitomer, R. A.,Wilson, A. E., 2013. Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. Nature Education Knowledge, 4(4), 10

Chislock, M.F., Sarnelle, O., Jernigan, L.M. and Wilson, A.E., 2013. Do high concentrations of microcystin prevent Daphnia control of phytoplankton? Water Res., 47(6), pp.1961-1970.

Chowdhury, M. A., de Neergaard, A., Jensen, L. S., 2014. Prediction of changes in important physical parameters during composting of separated animal slurry solid fractions. Environ. Technol., 35(2), pp. 220-231.

Cocozza, C., Parente, A., Zaccone, C., Mininni, C., Santamaria, P. and Miano, T., 2011. Chemical, physical and spectroscopic characterization of Posidonia oceanica (L.) Del. residues and their possible recycle. Biomass Bioenergy, 35(2), pp.799-807.

Coetzee, J. A., Hill, M. P., Byrne, M. J., Bownes, A., 2011. A review of the biological control programmes on Eichhornia crassipes (C. Mart.) Solms (Pontederiaceae), Salvinia molesta DS Mitch.(Salviniaceae), Pistia stratiotes L.(Araceae), Myriophyllum aquaticum (Vell.) Verdc.(Haloragaceae) and Azolla filiculoides Lam.(Azollaceae) in South Africa. Afr. Entomol., 19(2), pp. 451-468.

Colle, D.E., Shireman, J.V., 1980. Coefficients of condition for largemouth bass, bluegill and redear sunfish in hydrilla-infested lakes. T Am Fish Soc., 109, pp.521-531.

Cook, C.D.K., Gut, B.J., Rix, E.M., Sclmeller, J., Seitz, M., 1974. Water Plants o f the World. A Manual for the Identification of the Genera of Frcshwatcr Macrophytes. Dr. W. Junk B.V., The Hague. 561 p.

Cook, C.D.K., Lüönd, R., 1982. A revision of the genus Hydrilla (Hydrocharitaceae). Aquat. Bot., 13, pp. 485-504.

Cooperband, L. R., 2002. Building soil organic matter with organic amendments: A resource for urban and rural gardeners, small farmers, turfgrass managers and large-scale producers. Center for Integrated Agricultural Systems.

CPHEEO, 2000. Manual on Municipal Solid Waste Management (First Edition),Central Public Health and Environmental Engineering Organisation, New Delhi, India.

Cronjé, A. L., Turner, C., Williams, A. G., Barker, A. J., Guy, S., 2004. The respiration rate of composting pig manure. Compost Sci. Util., 12(2), pp. 119-129.

Cuda, J.P., Coon, B.R., Dao, Y.M., Center, T.D., 2011. Effect of an herbivorous stem-mining midge on the growth of hydrilla. J. Aquat. Plant Manage., 49, 83-89.

Curtis, M. J., Claassen, V. P., 2005. Compost incorporation increases plant available water in a drastically disturbed serpentine soil. Soil Sci., 170(12), pp. 939-953.

D'Hose, T., Cougnon, M., De Vliegher, A., Vandecasteele, B., Viaene, N., Cornelis, W., ... & Reheul, D., 2014. The positive relationship between soil quality and crop production: A case study on the effect of farm compost application. Appl. Soil Ecol., 75, pp. 189-198.

Dalzell, H.W., Gray, K.R., Biddlestone, A.J., 1981. Composting in tropical agriculture. International Institute of Biological Husbandry, Ipswich.

Das, B., Pal, D., Haldar, A., 2015. Pharmacognostical and physiochemical study of the aquatic weed *Hydrilla* (L.f.) Royle known as nutrient powerhouse. Int. J. Res. Pharm. Sci. 5(1), pp. 1–5.

Davis, W., 1997. The Effects of Hydrilla Infestation on Selected Wintering Waterfowl: Santee Copper Lake System, South Carolina. Masters Thesis & Specialist Projects. Paper 773.

Dawson, R.M., 1998. The toxicology of microcystins. Toxicon, 36(7), pp.953-962.

de Sousa Lima, J. R., de Moraes Silva, W., de Medeiros, E. V., Duda, G. P., Corrêa, M. M., Martins Filho, A. P., ... & Hammecker, C., 2018. Effect of biochar on physicochemical properties of a sandy soil and maize growth in a greenhouse experiment. Geoderma, 319, pp. 14-23.

Dias, B. O., Silva, C. A., Higashikawa, F. S., Roig, A., Sánchez-Monedero, M. A., 2010. Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. Bioresour. Technol., 101(4), pp. 1239-1246.

Diaz, L. F., Savage, G. M., Golueke, C. G., 2002. Composting of municipal solid wastes. Handbook of solid waste management, 2, pp. 423-492.

Dixit, S., Dhote, S., 2010. Evaluation of uptake rate of heavy metals by Eichhornia crassipes and Hydrilla verticillata. Environ. Monit. Assess., 169(1-4), pp.367-74.

Dlugosch K. M., Parker I., 2008. Founding events in species invasions: Genetic variation, adaptive evolution, and the role of multiple introductions. Mol. Ecol., 17, pp. 431–449.

Doyle, R.D., Smart, R.M., 2001. Effects of drawdowns and dessication on tubers of hydrilla, an exotic aquatic weed. Weed Sci., 49, pp. 135–140.

Dwevedi, A., Kumar, P., Kumar, P., Kumar, Y., Sharma, Y. K., Kayastha, A. M., 2017. Soil sensors: detailed insight into research updates, significance, and future prospects. In New Pesticides and Soil Sensors, pp. 561-594.

Dwivedi, D., Riley, W. J., Torn, M. S., Spycher, N., Maggi, F., Tang, J. Y., 2017. Mineral properties, microbes, transport, and plant-input profiles control vertical distribution and age of soil carbon stocks. Soil Biol. Biochem., 107, pp. 244-259.

E.O. 13112 of Feb 3, 1999. "RamsarWetlands Information Sheet — Deepor Beel" (PDF). Ramsar Convention on Wetlands official website. Archived from the original(PDF) on 27 September 2007.

Easley, J.F., Shirley, R.L., 1974. Nutrient elements for livestock in aquatic plants. Fla. Sci., 39, pp. 240-245.

Edwards, P., 1980. Food potential of aquatic macrophytes. ICLARM Studies and Reviews 5, International Center for Living Aquatic Resources Management, Manila, Philippines.

Eftoda, G., D. McCartney, 2004. Determining the critical bulking agent requirement for municipal biosolids composting. Compost Sci. Util., 12(3), pp. 208-214.

Elserafy, Z.M., Sonbol, H.A., Eltantawy, I.M., 1980. The problem of water hyacinth in rivers and canals – production of compost from plant. J. Soil Sci. Plant Nutr., 26(1), pp. 135–138.

Evans, J. M., Wilkie, A. C., 2010. Life cycle assessment of nutrient remediation and bioenergy production potential from the harvest of hydrilla (Hydrilla verticillata). J Environ. Manage., 91(12), pp. 2626-2631.

Eyheraguibel, B., Silvestre, J., Morard, P., 2008. Effects of humic substances derived from organic waste enhancement on the growth and mineral nutrition of maize. Bioresour. Technol., 99(10), pp. 4206-4212.

FAO. (2003). Heavy metals regulations legal notice No. 66/2003.

Fernández-Hernández, A., Roig, A., Serramiá, N., Civantos, C. G. O., & Sánchez-Monedero, M. A., 2014. Application of compost of two-phase olive mill waste on olive grove: effects on soil, olive fruit and olive oil quality. Waste Manage., 34(7), pp. 1139-1147.

Fowles, M., 2007. Black carbon sequestration as an alternative to bioenergy. Biomass Bioenergy, 31(6), pp. 426-432.

Fox, A.M., Haller, W.T., Shilling, D.G., 1994. Use of fluridone for hydrilla management in the Withlacoochee River, Florida. J. Aquat. Plant Manag. 32, pp.47-55.

Francou, U., Poitrenaud, M., Houot, S., 2005. Stabilization of organic matter during composting: Influence of process and feedstocks. Compost Sci. Util., 13(1), pp. 72-83.

Frank, P.A. 1976. Distribution and utilization research on tropical and subtropical aquatic weeds in the United States, p. 353-359. In C.K. Varshney and J. Rzoska (eds.) Aquatic Weeds in South East Asia.

Gabhane, J., William, S. P., Bidyadhar, R., Bhilawe, P., Anand, D., Vaidya, A. N., Wate, S. R., 2012. Additives aided composting of green waste: Effects on organic matter degradation, compost maturity, and quality of the finished compost. Bioresour. Technol., 114, pp. 382-388.

Gabriels, R., Van Keirsbulck, W., Engels, H., 1993. A rapid method for the determination of physical properties of growing media. Acta Horticulturae, 342, pp. 243-247.

Gallagher, C., 2007. Aquatic Weed and Algae Control in Irrigation Canals. Alberta Agriculture and Food. Technical Report.

Gallardo-Lara, F., Nogales, R., 1987. Effect of the application of town refuse compost on the soil-plant system: A review. Biological wastes, 19(1), pp. 35-62.

Gaston K. J., 2003. The structure and dynamics of geographic ranges. Oxford, Oxford University Press.

Gavala, H.N., Yenal, U., Skiadas, I.V., Westermann, P., Ahring, B.K., 2003. Mesophilic and thermophilic anaerobic digestion of primary and secondary sludge. Effect of pre-treatment at elevated temperature. Water Res., 37(19), pp.4561-4572.

Getsinger, K., Dibble, E., Rodgers, J., Spencer, D., 2014. Benefits of controlling nuisance aquatic plants and algae in the United States. Council for Agricultural Science and Technology Issue Paper.

Gichuki, J., Omondi, R., Boera, P., Okorut, T., Matano, A. S., Jembe, T., Ofulla, A., 2012. Water Hyacinth Eichhornia crassipes (Mart.) Solms-Laubach dynamics and succession in the Nyanza Gulf of Lake Victoria (East Africa): implications for water quality and biodiversity conservation. The Scientific World Journal, 2012.

Głąb, T., 2014. Effect of soil compaction and N fertilization on soil pore characteristics and physical quality of sandy loam soil under red clover/grass sward. Soil Tillage Res., 144, pp. 8-19.

Głąb, T., Palmowska, J., Zaleski, T., Gondek, K., 2016. Effect of biochar application on soil hydrological properties and physical quality of sandy soil. Geoderma, 281, pp. 11-20.

Gómez-Brandón, M., Lazcano, C., Domínguez, J., 2008. The evaluation of stability and maturity during the composting of cattle manure. Chemosphere, 70(3), pp. 436-444.

Goswami, L., Nath, A., Sutradhar, S., Bhattacharya, S. S., Kalamdhad, A., Vellingiri, K., Kim, K. H., 2017. Application of drum compost and vermicompost to improve soil health, growth, and yield parameters for tomato and cabbage plants. J Environ. Manage. 200, pp. 243-252.

Grey, M., Henry, C., 1999. Nutrient retention and release characteristics from municipal solid waste compost. Compost Sci. Util., 7(1), pp. 42-50.

Grodowitz, M.J., Doyle, R., Smart, R. M., 2000. Potential Use of Insect Biocontrol Agents for Reducing the Competitive Ability of Hydrilla verticillata (No. ERDC/EL-SR-00-1). Engineer research and development center vicksburg MS environmental lab.

Gunnarsson, C.C., Petersen, C.M., 2007. Water hyacinth as a resource in agriculture and energy production: a literature review. Waste Manage. 27, pp. 117–129.

Haller, W. T., 2002. Hydrilla in Lake Izabal, Guatemala: Current Status and Future Prospects. Technical Report for the USAID-Guatemala. University of Florida, Florida.

Haller, W.T., 1978. Hydrilla: a new and rapidly spreading aquatic plant problem. Circular S-245. Gainesville: Institute of Food and Agricultural Sciences, University of Florida, Florida.

Haller, W.T., Sutton, D.L., Barlowe, W.C., 1974. Effects of salinity on growth of several aquatic macrophytes. Ecol., 55(4), pp. 891-894.

Hamoda, M. F., Qdais, H. A., Newham, J., 1998. Evaluation of municipal solid waste composting kinetics. Resour. Conserv. Recy., 23(4), pp. 209-223.

Han, W., Clarke, W., Pratt, S., 2014. Composting of waste algae: a review. Waste Manage., 34(7), pp. 1148-1155.

Hassen, A., Belguith, K., Jedidi, N., Cherif, A., Cherif, M., and Boudabous, A., 2001. Microbial characterization during composting of municipal solid waste. Bioresour. Technol. 80(3), pp. 217-225.

Haug, R. T., 1993. The practical handbook of compost engineering. Lewis Publishers. Boca Raton, FL USA.

Hazarika, J., Ghosh, U., Kalamdhad, A. S., Khwairakpam, M., Singh, J., 2017. Transformation of elemental toxic metals into immobile fractions in paper mill sludge through rotary drum composting. Ecol. Eng., 101, pp. 185-192.

Hentges, J. F., Salveson, Jr., R. E., Shirley, R. L., Moore, J.E., 1972. Processed aquatic plants in cattle diets. J. Animal Sci., 34, p. 360.

Hill, M. P., Coetzee, J., 2017. The biological control of aquatic weeds in South Africa: Current status and future challenges. Bothalia-African Biodiversity & Conservation, 47(2), pp. 1-12.

Hofstra, D.E., Clayton, J., 2001. Evaluation of Selected Herbicides for the Control of Exotic Submerged Weeds in New Zealand: I. The Use of Endothall, Triclopyr and Dichlobenil. J. Aquat. Plant Manage. 39, pp. 20-24.

Hofstra, D.E., Clayton, J., Green, J.D., Auger, M., 1999. Competitive performance of Hydrilla verticillata in New Zealand. Aquat. Bot. 63, pp. 305-324.

Holaday, A.S. and Bowes, G., 1980. C4 acid metabolism and dark CO2 fixation in a submersed aquatic macrophyte (*Hydrilla verticillata*). Plant physiology, 65(2), pp.331-335.

Holm, L. G., Weldon, L. W., Blackburn, R. D., 1969. Aquat. Weeds. Sci., 166(3906), pp. 699-709.

Hora, S.L., Pillay, T.V.R., 1962. Hand book of fish culture in the Indo-Pacific region. FAO Fish Tech. Pap., 14 (1962), p. 204

Houghton J. T., Ding Y., Griggs D. J., Noguer M., van der Linden P. J., Dai X., Maskell, K., Johnson, C.A., 2001. Climate change 2001: The scientific basis.

Hu, Z., Chen, Z., Li, G., Chen, X., Hu, M., Laghari, M., ... & Guo, D., 2015. Characteristics and kinetic studies of Hydrilla verticillata pyrolysis via thermogravimetric analysis. Bioresour. Technol., 194, pp. 364-372.

Hua, L., Wu, W., Liu, Y., 2009. Reduction of nitrogen loss and Cu and Zn mobility during sludge composting with bamboo charcoal amendment. Environ. Sci. Pollut. Res., 16, pp. 1-9.

Huang, G. F., Wong, J. W. C., Wu, Q. T., Nagar, B. B., 2004. Effect of C/N on composting of pig manure with sawdust. Waste Manage., 24(8), pp. 805-813.

Huerta-Pujol, O., Soliva, M., Martínez-Farré, F. X., Valero, J., López, M., 2010. Bulk density determination as a simple and complementary tool in composting process control. Bioresour. Technol., 101(3), pp. 995-1001.

Huet, J., Druilhe, C., Tremier, A., Benoist, J. C., Debenest, G., 2012. The impact of compaction, moisture content, particle size and type of bulking agent on initial physical properties of sludge-bulking agent mixtures before composting. Bioresour. Technol., 114, pp. 428-436.

Hussner, A., Stiers, I., Verhofstad, M. J. J. M., Bakker, E. S., Grutters, B. M. C., Haury, J., ... & Anderson, L. W. J., 2017. Management and control methods of invasive alien freshwater aquatic plants: a review. Aquat. Bot., 136, pp. 112-137.

Inbar, Y., Hadar, Y., Chen, Y., 1993. Recycling of cattle manure: The composting process and characterization of maturity. J. Environ. Qual., 22, pp. 857-863.

Jana, S., Choudhuri, M.A., 1980. Senescence in submerged aquatic weed angiosperms: changes in intact and isolated leaves during aging. New Phytol. 86, pp. 191-198.

Jayan, P. R., Sathyanathan, N., 2012. Aquatic weed classification, environmental effects and the management technologies for its effective control in Kerala, India. International J. Agr. Biol. Eng., 5(1), pp. 76-91.

Jayaweera, M. W., Kasturiarachchi, J. C., Kularatne, R. K., Wijeyekoon, S. L., 2008. Contribution of water hyacinth (*Eichhornia crassipes* (Mart.) Solms) grown under different nutrient conditions to Fe-removal mechanisms in constructed wetlands. J Environ. Manage. 87(3), pp. 450-460.

Jeppesen, E., Jensen, J. P., Søndergaard, M., Lauridsen, T., Møller, P. H., Sandby, K., 1998. Changes in nitrogen retention in shallow eutrophic lakes following a decline in density of cyprinids. Archiv fur Hydrobiologie, 142, pp. 129-151.

Jha, H.K., Singh, B.S., Varshney, A.K., 2015. Local survey of hydrilla (L.f.) royle : an invasive and valuable aquatic weed. J. Indian Bot. Soc. 94(1-2), pp. 149-152.

Jiang, X., Denef, K., Stewart, C. E., Cotrufo, M. F., 2016. Controls and dynamics of biochar decomposition and soil microbial abundance, composition, and carbon use efficiency during long-term biochar-amended soil incubations. Biol. Fertil. Soils, 52(1), pp. 1-14.

Jien, S. H., Wang, C. S., 2013. Effects of biochar on soil properties and erosion potential in a highly weathered soil. Catena, 110, pp. 225-233.

Jindo, K., Sánchez-Monedero, M. A., Hernández, T., García, C., Furukawa, T., Matsumoto, K., ... & Bastida, F., 2012. Biochar influences the microbial community structure during manure composting with agricultural wastes. Sci. Total Environ., 416, pp. 476-481.

Jindo, K., Sonoki, T., Matsumoto, K., Canellas, L., Roig, A., & Sanchez-Monedero, M. A., 2016. Influence of biochar addition on the humic substances of composting manures. Waste Manage., 49, pp. 545-552.

Jolanun, B., Towprayoon, S., Chiemchaisri, C., 2008. Aeration improvement in fed batch composting of vegetable and fruit wastes. Environ. Prog. Sustain. Energy., 27(2), pp. 250-256.

Jones P. D., Osborn T. J., Briffa K. R., 2001. The evolution of climate over the last millennium. Science, 292, pp. 662–667.

Kalamdhad, A. S., Kazmi, A. A., 2008. Mixed organic waste composting using rotary drum composter. Int. J Environ. Waste Manage., 2(1-2), pp. 24-36.

Kalamdhad, A. S., Pasha, M., Kazmi, A. A., 2008. Stability evaluation of compost by respiration techniques in a rotary drum composter. Resour. Conserv. Recy., 52(5), pp. 829-834.

Kalamdhad, A. S., Singh, Y. K., Ali, M., Khwairakpam, M., Kazmi, A. A., 2009. Rotary drum composting of vegetable waste and tree leaves. Bioresour. Technol., 100(24), pp. 6442-6450.

Kalamdhad, A.S., Kazmi, A.A., 2009. Effects of turning frequency on compost stability and some chemical characteristics during rotary drum composting. Chemosphere 74, pp.

1327-1334.

Kalita, P., Mukhopadhyay, P. K., Mukherjee, A. K., 2007. Evaluation of the nutritional quality of four unexplored aquatic weeds from northeast India for the formulation of cost-effective fish feeds. Food Chemistry, 103(1), pp. 204-209.

Kapetanios, E.G., Loizidou, M., Valkanas, G., 1993. Compost production from Greek domestic refuse. Bioresour. Technol. 43, pp. 13–16.

Karadag, D., Özkaya, B., Ölmez, E., Nissilä, M. E., Çakmakçı, M., Yıldız, Ş., Puhakka, J. A., 2013. Profiling of bacterial community in a full-scale aerobic composting plant. Int. Biodeterior Biodegradation, 77, pp. 85-90.

Kato, K., Miura, N., 2008. Effect of matured compost as a bulking and inoculating agent on the microbial community and maturity of cattle manure compost. Bioresour. Technol., 99(9), pp. 3372-3380.

Kemmitt, S. J., Lanyon, C. V., Waite, I. S., Wen, Q., Addiscott, T. M., Bird, N. R., ... & Brookes, P. C., 2008. Mineralization of native soil organic matter is not regulated by the size, activity or composition of the soil microbial biomass—a new perspective. Soil Biol Biochem., 40(1), pp. 61-73.

Kensa, V.M., Neelamegam, R., 2014. Evaluation of wound healing activity of Hydrilla (L.F.) Royle collected from unpolluted and polluted water sources. Int. J Curr. Microbiol. App. Sci. 3(12), pp. 417-423.

Khalil, A., Domeizel, M., Prudent, P., 2008. Monitoring of green waste composting process based on redox potential. Bioresour. Technol., 99(14), pp. 6037-6045.

Kirk, J. P., J. E. Henderson.,2006. Management of hydrilla in the Santee Cooper Reservoirs, South Carolina. J Aquatic Plant Manag., 44, pp. 98-103.

Knoepp, J.D., Vose, J.M., 2002. Quantitative Comparison of In situ soil CO2 Flux Measurement Methods. USDA Forest Service Research Paper SRS-28, Asheville, NC

Ko, T. H., 2014. Nature and properties of lateritic soils derived from different parent materials in Taiwan. The Scientific World Journal, 2014.

Koivula, N., Räikkönen, T., Urpilainen, S., Ranta, J., Hänninen, K., 2004. Ash in composting of source-separated catering waste. Bioresour. Technol., 93(3), pp. 291-299.

Kulcu, R., Yaldiz, O., 2004. Determination of aeration rate and kinetics of composting some agricultural wastes. Bioresour. Technol., 93(1), pp. 49-57.

Kumar, A., Holuszko, M., Espinosa, D. C. R., 2017. E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recy., 122, pp. 32-42.

Kuppusamy, S., Thavamani, P., Megharaj, M., Venkateswarlu, K., Naidu, R., 2016. Agronomic and remedial benefits and risks of applying biochar to soil: current knowledge and future research directions. Environ. Int., 87, pp. 1-12.

Lamsal, P., Pant, K.P., Kumar, L., Atreya, K., 2014. Diversity, Uses, and Threats in the Ghodaghodi Lake Complex, a Ramsar Site in Western Lowland Nepal. ISRN Biodiversity, 2014.

Langeland, K.A., 1996. Hydrilla (L.F.) Royle (Hydrocharitaceae), The Perfect Aquatic Weed. Castanea. 61, pp. 293-304.

Larney, F. J., Angers, D. A., 2012. The role of organic amendments in soil reclamation: A review. Can. J Soil Sci., 92(1), pp. 19-38.

Larney, F. J., Hao, X., 2007. A review of composting as a management alternative for beef cattle feedlot manure in southern Alberta, Canada. Bioresour. Technol., 98(17), pp. 3221-3227.

Larson, D. L., Phillips-Mao, L., Quiram, G., Sharpe, L., Stark, R., Sugita, S., Weiler, A., 2011. A framework for sustainable invasive species management: Environmental, social, and economic objectives. J Environ. Manage. 92(1), pp. 14-22.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota–a review. Soil Biol. Biochem., 43(9), pp. 1812-1836.

Leifeld, J., Siebert, S., Kögel‐Knabner, I., 2002. Biological activity and organic matter mineralization of soils amended with biowaste composts. J Plant Nutrition Soil Sci., 165(2), pp. 151-159.

Li, J., Huang, G. H., Zeng, G., Maqsood, I., Huang, Y., 2007. An integrated fuzzy-stochastic modeling approach for risk assessment of groundwater contamination. J Environ. Manage., 82(2), pp. 173-188.

Li, W., Loh, K. C., Zhang, J., Tong, Y. W., Dai, Y., 2018. Two-stage anaerobic digestion of food waste and horticultural waste in high-solid system. Appl. Energy, 209, pp. 400-408.

Li, Z. M., Peterson, M. M., Comfort, S. D., Horst, G. L., Shea, P. J., Oh, B. T., 1997. Remediating TNT-contaminated soil by soil washing and Fenton oxidation. Sci. Total Environ., 204(2), pp. 107-115.

Liu, W., Huo, R., Xu, J., Liang, S., Li, J., Zhao, T., Wang, S., 2017. Effects of biochar on nitrogen transformation and heavy metals in sludge composting. Bioresour. Technol., 235, pp. 43-49.

López-Cano, I., Roig, A., Cayuela, M. L., Alburquerque, J. A., Sánchez-Monedero, M. A. , 2016. Biochar improves N cycling during composting of olive mill wastes and sheep manure. Waste Manage., 49, pp. 553-559.

López, M., Soliva, M., Martínez-Farré, F. X., Bonmatí, A., & Huerta-Pujol, O., 2010. An assessment of the characteristics of yard trimmings and recirculated yard trimmings used in biowaste composting. Bioresour. Technol., 101(4), pp. 1399-1405.

Lu, J., Zhu, L., Hu, G. Wu, J., 2010. Integrating animal manure-based bioenergy production with invasive species control: A case study at Tongren Pig Farm in China. Biomass Bioenergy., 34(6), pp. 821-827.

Lu, W., Ma, M., Zhang, X., Zhang, B., Guo, Y., Wang, C., 2015. Comparison of high calorific fuels obtained from fresh and dried Hydrilla verticillata: Effects of temperature, residence time, catalyst content and material state. J Anal Appl Pyrolysis, 111, pp. 76-87.

Macdonald, G.E., Shilling, D.G., Doong, R.L., Haller, W. T., 1993. Effects of Fluridone on Hydrilla Growth and Reproduction. J Aquat. Plant Manage. 31, 195–198.

Maceina, Michael, J., Slipke, J.W., 2004. The Use of Herbicides to Control Hydrilla and the Effects on Young Largemouth Bass Population Characteristics and Aquatic Vegetation in Lake Seminole, Georgia. J Aquat Plant Managet, 42, pp. 5-11.

Madeira, P., Van, T., Steward, D., Schnell, R., 1997. Random amplified polymorphic DNA analysis of the phenetic relationships among world-wide accessions of Hydrilla. Aquat. Bot. 59(3-4), pp. 217-236.

Madejón, E., Díaz, M. J., López, R., Cabrera, F., 2002. New approaches to establish optimum moisture content for compostable materials. Bioresour Technol., 85(1), pp. 73-78.

Madsen, J.D., 1997. Chapter 12. Methods for Management of Nonindigenous Aquatic Plants, 145-171. In:J.O. Luken and J.W. Thieret, eds. Assessment and Management of Plant Invasions. Springer, New York. 324pp.

Malińska, K., Zabochnicka-Świątek, M., Dach, M. 2014 Effects of biochar amendment on ammonia emission during composting of sewage sludge. Ecol. Eng., 71, pp. 474–478.

Mamo, M., Moncrief, J. F., Rosen, C. J., Halbach, T. R., 2000. The effect of municipal solid waste compost application on soil water and water stress in irrigated corn. Compost Sci Util., 8(3), pp. 236-246.

Mangkoedihardjo, S., 2006. Revaluation of maturity and stability indices for compost. J Appl. Sci. Environ. Manage. 10(3), pp. 83-85

Margesin, R., Cimadom, J., Schinner, F., 2006. Biological activity during composting of sewage sludge at low temperatures. Int Biodeterior. Biodegradation, 57(2), pp. 88-92.

Marschner, B., Kalbitz, K., 2003. Controls of bioavailability and biodegradability of dissolved organic matter in soils. Geoderma, 113(3-4), pp. 211-235.

McCann, J.A., Arkin, L.N., Williams, J.D., 1996. Nonindigenous aquatic and selected terrestrial species of Florida: Status, pathway and time of introduction, present distribution, and significant ecological and economic effects. Southeastern Biological Science Center, National Biological Service, Gainesville, Florida.

Meier, E.J., Waliczek, T.M., Abbott, M.L., 2014. Composting Invasive Plants in the Rio

Grande River. Invasive Plant Sci. Manage. 7(3), pp. 473–482.

Mendo, T., Wosnitza, A., Barrantes, J.G., 2006. Utilization of seaweed Ulva sp in Paracas Bay (Peru): experimenting with compost. J. Appl. Phycol. 18, pp. 27–31.

Michel, A., Arias, R. S., Scheffler, B. E., Duke, S. O., Netherland, M. and Dayan, F. E. 2004. Somatic mutation-mediated evolution of herbicide resistance in the nonindigenous invasive plant hydrilla (Hydrilla verticillata). comparative study. Mol. Ecol. 13(10), pp. 3229-3237.

Mitra, E., Banerjee, A.C., 1976. Utilization of higher aquatic plants in fishery waters, p. 375-381. In C.K. Varshney and J. Rzoska (eds.) Aquatic Weeds in South East Asia. Dr. Junk, W., Academic Press, London. B.V., The Hague.

Mohee, R., Mudhoo, A., 2005. Analysis of the physical properties of an in-vessel composting matrix. J Powder Technol., 155, pp. 92–99.

Mullin, B.H., Anderson, L.W.Z., DiTomaso, J.M., Eplee, R.E., Getsinger, K.D., 2000. Invasive Plant Species. Issue Paper Number 13, Council for Agricultural Science and Technology, Washington, D.C. February 2000. 18pp.

Muñoz, R. and Guieysse, B., 2006. Algal–bacterial processes for the treatment of hazardous contaminants: a review. Water Res., 40(15), pp.2799-2815.

Nair, K.P.P., 2013. Cropping Zones and Production Technology. In The Agronomy and Economy of Turmeric and Ginger (pp. 347-373).

Nakasaki, K., Watanabe, A., Kitano, M., Kubota, H., 1992. Effect of seeding on thermophilic composting of tofu refuse. J Environ Qual., 21(4), pp. 715-719.

Natural Resource, Agriculture, and Engineering Service (NRAES), 1992. On-farm composting. In R. Rynk (Ed.), Ithaca, USA, NRAES Cooperative Extension.

Navas, A., Bermúdez, F., Machın, J.,1998. Influence of sewage sludge application on physical and chemical properties of Gypsisols. Geoderma, 87(1-2), pp. 123-135.

Nayak, A. K., Gangwar, B., Shukla, A. K., Mazumdar, S. P., Kumar, A., Raja, R., ... & Mohan, U., 2012. Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. Field Crops Res., 127, pp. 129-139.

Nayak, A. K., Kalamdhad, A. S., 2014. Feasibility of composting combinations of sewage sludge, cattle manure, and sawdust in a rotary drum reactor. Environ Eng Res., 19(1), pp. 47-57.

Ndimele, P.E., Kumolu-Johnson, C.A. and Anetekhai, M.A., 2011. The invasive aquatic macrophyte, water hyacinth {*Eichhornia crassipes* (Mart.) Solm-Laubach: Pontedericeae}: problems and prospects. Res J Environ Sci, 5(6), p.509.

Nelson, D. W., Sommers, L., 1982. Total carbon, organic carbon, and organic matter

1. Methods of soil analysis. Part 2. Chemical and microbiological properties, (methodsofsoilan2), pp. 539-579.

Netherland, M.D., 1991. Herbicide concentration/exposure time relationship for Eurasian watermilfoil and hydrilla. In: Proceedings, 25th Annual meeting, Aquatic plant control research program, 26-30 Nov., 1990, Orlando, Florida, pp. 205-209.

Netherland, M.D., 1997. Turion Ecology of Hydrilla. J. Aquat. Plant Manag. 35, pp. 1-10

Oviedo-Ocaña, E. R., Dominguez, I., Komilis, D., Sánchez, A., 2017. Co-composting of Green Waste Mixed with Unprocessed and Processed Food Waste: Influence on the Composting Process and Product Quality. Waste Biomass Valorization, pp. 1-12.

Owens, C.S., Madsen, J.D., 1998. Phenological studies of carbohydrate allocation in Hydrilla. J Aquat Plant Manag 36, pp. 40–44.

Page, A.L., Miller, R.H., Keeney, D.R., 1982. Methods of Soil Analysis. 2nd Edn., American Society of Agronomy, Madison, WI., USA.

Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil Tillage Res., 79(2), pp. 131-143.

Pal, D.K., Nimse, S.B., 2006. Little known uses of common aquatic plant, *Hydrilla verticillata* (Linn. f.) Royle.

Pan, E., Jamison, M., Yousufuddin, M., MacMillan, J.B., 2012. Ammosamide D an oxidatively ring opened ammosamide analog from a marine-derived Streptomyces variabilis. Org Lett 14(9), pp.2390–2393.

Paredes C., Bernal, M.P., Roig, A., Cegarra, J., Sánchez-Monedero, M.A., 1996. Influence of the bulking agent on the degradation of olive-mill wastewater sludge during composting. Int. Biodeter. Biodegr., 38, pp. 205–210.

Paredes, C., Cegarra, J., Bernal, M. P., Roig, A., 2005. Influence of olive mill wastewater in composting and impact of the compost on a Swiss chard crop and soil properties. Environ. Int., 31(2), pp. 305-312.

Pelicice, F.M., Agostinho, A.A. and Thomaz, S.M., 2005. Fish assemblages associated with Egeria in a tropical reservoir: investigating the effects of plant biomass and diel period. Acta Oecologica, 27(1), pp.9-16.

Pennington, T.G., Skogerboe, J.G., Getsinger, K. D., 2001. Herbicide / Copper Combinations for Improved Control of *Hydrilla verticillata*, pp. 56–58.

Pesacreta G., 1988. Water Chemistry from North Carolina Piedmont Impoundments with Hydrilla (Hydrilla (L.f.) Royle). Ph.D. dissertation, North Carolina State University, Raleigh.

Peterson A. T., Papeş M., Soberón J., 2008. Rethinking receiver operating characteristic analysis applications in ecological niche modeling. Ecol. Model, 213, pp. 63–72.

Peterson, A. T., 2003. Predicting the geography of species' invasions via ecological niche modeling. The quarterly review of biology, 78(4), pp. 419-433.

Pham, T.L., Utsumi, M., 2018. An overview of the accumulation of microcystins in aquatic ecosystems. J. Environ. Manage. 213, pp. 520-529.

Pizzorno Jr, J.E., Murray, M.T., 1990. Encyclopedia of Natural Medicine. Rocklin CA.

Prasad, R., Singh, J., Kalamdhad, A.S., 2013. Assessment of nutrients and stability parameters during composting of water hyacinth mixed with cattle manure and sawdust. Res J Chem Sci 3(4), pp. 1–4.

Prasad, M., Maher, M.J., 1993. Physical and chemical properties of fractionated peat. Acta Horticulturae, 342, pp. 257-264.

Prost, K., Borchard, N., Siemens, J., Kautz, T., Séquaris, J. M., Möller, A., Amelung, W., 2013. Biochar affected by composting with farmyard manure. J Environ. Qual., 42(1), pp. 164-172.

Qdais, H. A., Al-Widyan, M., 2016. Evaluating composting and co-composting kinetics of various agro-industrial wastes. Int J Recy Organic Waste Agr., 5(3), pp. 273-280.

Quilliam, R. S., van Niekerk, M. A., Chadwick, D. R., Cross, P., Hanley, N., Jones, D. L., ... & Oliver, D. M., 2015. Can macrophyte harvesting from eutrophic water close the loop on nutrient loss from agricultural land?. J. Environ. Manage. 152, pp. 210-217.

Rai, R.K., Scarborough, H., 2013. Economic value of mitigation of plant invaders in a subsistence economy: incorporating labour as a mode of payment. Environ Dev Econ, 18(2), pp.225-244.

Rakotomalala, M., 2014. Journée de l'artisanat–Les jacinthes d'eau deviennent des filons d'or. L'Express de Madagascar. Antananarivo, 10 june 2014.

Rascio, N., Navari-Izzo, F., 2011. Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting?. Plant science, 180(2), pp. 169-181.

Rasool, R., Kukal, S. S., Hira, G. S., 2008. Soil organic carbon and physical properties as affected by long-term application of FYM and inorganic fertilizers in maize–wheat system. Soil Tillage Res., 101(1-2), pp. 31-36.

Rattray, M.R., MacDonald, G., Shilling, D.G., Bowes, G., 1993. The mechanism of action of bensulfuron methyl on hydrilla. J. Aquat. Plant Manage. 31, pp. 39-42.

Raviv, M., S.Tarre, Z.Geler and G. Shelef. 1987. Changes in some physical and chemical properties of fibrous solids from cow manure and digested cow manure during composting. Biological Wastes, 19(4), pp. 309-318.

Ray, P., Hill, M. P., 2013. Microbial agents for control of aquatic weeds and their role in integrated management. CAB Reviews Perspectives in Agriculture Veterinary Science

Nutrition and Natural Resources, 8, pp. 1-9.

Rayment, G. E., Higginson, F. R., 1992. Australian laboratory handbook of soil and water chemical methods. Inkata Press Pty Ltd.

Reddy, K.R., DeBusk, W.F., 1985. Growth characteristics of aquatic macrophytes cultured in nutrient-enriched water: II. Azolla, duckweed and salvinia. Econ. Bot. 39(2), pp. 200-208.

Reddy, L.C.S., Reddy, K.V.R., Humane, S.K., Damodaram, B., 2012. Accumulation of Chromium in Certain plant Species Growing on Mine Dump from Byrapur, Karnataka. Res. J. Chem. Sci. 2(12), pp. 17-20.

Ren, X., Zeng, G., Tang, L., Wang, J., Wan, J., Liu, Y., ... & Deng, R. , 2018. Sorption, transport and biodegradation–an insight into bioavailability of persistent organic pollutants in soil. Sci. Total Environ., 610, pp. 1154-1163.

Richard, T. L., Hamelers, H. V. M., Veeken, A., Silva, T., 2002. Moisture relationships in composting processes. Compost Sci Util., 10(4), pp. 286-302.

Rodriguez, M.E., Narros, G.A., Molleda, J.A., 1995. Wastes of multilayer containers as substrate in composting processes. J. Air Waste Manage. Assoc. 45, pp. 156–160.

Romero-Oliva, C. S., Contardo-Jara, V., Pflugmacher, S., 2015. Time dependent uptake, bioaccumulation and biotransformation of cell free crude extract microcystins from lake amatitlan, guatemala by ceratophyllum demersum, egeria densa and hydrilla verticillata. Toxicon, 105, pp. 62-73.

Romero-Oliva, C.S., Contardo-Jara, V., Block, T. and Pflugmacher, S., 2014. Accumulation of microcystin congeners in different aquatic plants and crops–A case study from lake Amatitlán, Guatemala. Ecotoxicol Environ Saf, 102, pp.121-128.

Romero-Oliva, C.S., Contardo-Jara, V., Pflugmacher, S., 2015. Time dependent uptake, bioaccumulation and biotransformation of cell free crude extract microcystins from Lake Amatitlán, Guatemala by Ceratophyllum demersum, Egeria densa and *Hydrilla verticillata*. Toxicon, 105 (Suppl. C) (2015), pp. 62-73.

Ruskin, F.R., Shipley, D.W., 1976. Making Aquatic Weeds Useful: Some Perspectives for Developing Countries. National Academy of Sciences, Washington, D.C.

Ryals, R., Kaiser, M., Torn, M. S., Berhe, A. A., Silver, W. L., 2014. Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils. Soil Biology and Biochemistry, 68, pp. 52-61.

Rybicki, N.B., Landwehr, J.M., 2007. Long-term changes in abundance and diversity of macrophyte and waterfowl populations in an estuary with exotic macrophytes and improving water quality. Limnology and Oceanography, 52(3), pp.1195-1207.

Rynk, R., Sailus, M., Popow, J. S., Bernat, J., Grant, R., Van de Kamp, M., ... & Richard, T. L., 1994. On-farm composting handbook (No. 631.875 O-58o). New York, US:

Northeast Regional Agricultural Engineering Service, Cooperative Extension.

Sadaka, S., El-Taweel, A., 2003. Effects of aeration and C: N ratio on household waste composting in Egypt. Compost Sci. Util. 11, pp. 36–41.

Saha, S., Ray, A.K., 2011. Evaluation of nutritive value of water hyacinth (Eichhornia crassipes) leaf meal in compound diets for rohu, Labeo rohita (Hamilton, 1822) fingerlings after fermentation with two bacterial strains isolated from fish gut. Turkish J Fisheries Aquat. Sci., 11(2).

Sánchez-García, M., Alburquerque, J. A., Sánchez-Monedero, M. A., Roig, A., Cayuela, M. L., 2015. Biochar accelerates organic matter degradation and enhances N mineralisation during composting of poultry manure without a relevant impact on gas emissions. Bioresour. Technol., 192, pp. 272-279.

Schardt, J.D., 1997. Florida aquatic plant survey report. Florida Department of Environmental Protection, Bureau of Aquatic Plant Management, Tallahassee, FL. Report nr 942-CGA 86 pp.

Schaub-Szabo, S. M., Leonard, J. J., 1999. Characterizing the bulk density of compost. Compost Sci. Util., 7(4), pp. 15-24.

Schmidt, H. P., Kammann, C., Niggli, C., Evangelou, M. W., Mackie, K. A., Abiven, S., 2014. Biochar and biochar-compost as soil amendments to a vineyard soil: Influences on plant growth, nutrient uptake, plant health and grape quality. Agr. Ecosystems Environ., 191, pp. 117-123.

Schmitz, D.C., Nelson, B.V., Nall, L.E., Schardt, J.D., 1991. Exotic aquatic plants in Florida: A historical perspective and review of the present aquatic plant regulation program, in: Center, T. D., Doren, R. F., Hofstetter, R. L., Myers, R. L., & Whiteaker, L. D. (Eds.). Proceedings of the Symposium on Exotic Pest Plants. Denver, pp. 303-326.

Schulze, K.L. 1962. Continuous thermophilic composting. Compost Sci., 3, pp. 22-34.

Serramiá, N., Sánchez-Monedero, M.A., Fernández-Hernández, A., Civantos, C.G., Roig, A., 2010. Contribution of the lignocellulosic fraction of two-phase olivemill wastes to the degradation and humification of the organic matter during composting. Waste Manage. 30, pp. 1939–1947.

Shackleton, S., Delang, C.O. and Angelsen, A., 2011. From subsistence to safety nets and cash income: exploring the diverse values of non-timber forest products for livelihoods and poverty alleviation. In Non-timber forest products in the global context (pp. 55-81). Springer, Berlin, Heidelberg.

Shah, K.A., Sumbul, S., Andrabi, S.A., 2010. A Study on Nutritional Potential of Aquatic Plants. Vetscan. 5(1), pp. 1-5.

Shao, L. M., Zhang, C. Y., Wu, D., Lü, F., Li, T. S., He, P. J., 2014. Effects of bulking agent addition on odorous compounds emissions during composting of OFMSW. Waste Manage., 34(8), pp. 1381-1390.

Shardendu, Ambasht, R.S., 1991. Relationship of nutrient in water with biomass and nutrient accumulation of submerged macrophytes of a tropical wetland. New Phytol. 117, pp. 493-500.

Shearer, J. F., 1998. Biological control of hydrilla using an endemic fungal pathogen. J. Aquat. Plant Manage. 36, pp. 54-56.

Silva, M.E.F., de Lemos, L.T., Nunes, O.C., Cunha-Queda, A.C., 2014. Influence of the composition of the initial mixtures on the chemical composition, physicochemical properties and humic-like substances content of composts. Waste Manage. 34, pp. 21–27.

Singh, A., Kumar, S.C., Agarwal, A., 2012. Physiological study of combined heavy metal stress on Hydrilla (L.f.) Royle. Int. J Environ. Sci. 2(4), pp. 2234-2242.

Singh, J., Kalamdhad, A. S., 2012. Reduction of Heavy Metals during Composting-A. International Journal, 2(9), pp. 36-43.

Singh, J., Kalamdhad, A. S., 2013. Assessment of bioavailability and leachability of heavy metals during rotary drum composting of green waste (Water hyacinth). Ecol. Eng., 52, pp. 59-69.

Singh, J., Kalamdhad, A.S., 2013. Effect of rotary drum on speciation of heavy metals during water hyacinth composting. Environ. Eng. Res., 18(3), pp. 177-189.

Singh, J., Kalamdhad, A.S., 2016. Effect of lime on speciation of heavy metals during agitated pile composting of water hyacinth. Front. Environ Sci. Eng., 10(1), pp. 93-102.

Singh, J., Prasad, R., Kalamdhad, A.S., 2013. Effects of on bioavailabiity and leachability of heavy metals during rotary drum composting of water hyacinth. Research J Chemistry Environ., 17(8), pp. 26-34.

Singh, W. R., Kalamdhad, A. S., Singh, J., 2016. The preferential composting of water fern and a reduction of the mobility of potential toxic elements in a rotary drum reactor. Process Saf. Environ. Protect., 102, pp. 485-494.

Singh, W.R., Das, A., Kalamdhad, A.S., 2012. Composting of Water Hyacinth using a Pilot Scale Rotary Drum Composter. Environ. Eng. Res. 17(2), pp. 69-75.

Singh, W.R., Kalamdhad, A.S., 2014. Potential for composting of green phumdi biomass of loktak lake. Ecol. Eng., 67, pp. 119-126

Singh, W.R., Kalamdhad, A.S., Singh, J., 2016. The preferential composting of water fern and a reduction of the mobility of potential toxic elements in a rotary drum reactor. Process Saf Environ Protect., 102, pp. 485-494.

Singnar, L., Sil, A., 2018. Liquefaction potential assessment of Guwahati city using first-order second-moment method. Innovative Infrastructure Solutions, 3, pp. 1-17.

Sousa W. T. Z., Thomaz S. M., Murphy K. J., Silveira M. J., Mormul R. P., 2009. Environmental predictors of the occurrence of exotic Hydrilla verticillata (L.f.) Royle and native Egeria najas Planch. in a sub-tropical river floodplain: The Upper River Paraná, Brazil. Hydrobiologia, 632, pp. 65–78.

Sousa, W.T.Z., 2011. Hydrilla verticillata (Hydrocharitaceae), a recent invader threatening Brazil's freshwater environments: a review of the extent of the problem. Hydrobiologia, 669, pp. 1-20.

Spencer, D.F., Ryan, F.J., Ksander, G.G., 1997. Construction costs for some aquatic plants. Aquat. Bot. 56(3-4), pp. 203-214.

Srivastava, S., Mishra, S., Dwivedi, S., Tripathi, R., 2010. Role of thiol metabolism in arsenic 969 detoxification in Hydrilla (L.f.) Royle. Water Air Soil Pollut. 212(1), pp. 155-165.

Steiner, C., Sánchez-Monedero, M., Kammann, C., 2015. Biochar as an additive to compost and growing media. Biochar for environmental management: science, technology and implementation, pp. 717-736.

Steward, K.K., 1991. Growth of various hydrilla races in waters of differing pH. Fla. Sci. 54, pp. 117-125.

Steward, K.K., Van, T.K., 1987. Comparative studies of monoecious and dioecious hydrilla (Hydrilla) biotypes. Weed Sci. 35, pp. 204-210.

Stratman, K.N., Overholt, W.A., Cuda, J.P., Netherland, M.D., Wilson, P.C., 2013. Host range and searching behavior or Cricotopus lebetis (Diptera: Chironomidae), a tip miner of Hydrilla verticillata. Biocontrol Sci. Techn., 23, pp. 317-334.

Sun, W., Qian, X., Gu, J., Wang, X. J., Duan, M. L., 2016. Mechanism and effect of temperature on variations in antibiotic resistance genes during anaerobic digestion of dairy manure. Scientific reports, 6, pp. 302-337.

Sutton, D.L., Portier, K.H., 1983. Variation of nitrogen, phosphorus and potassium contents of Hydrilla in South Florida. J Aquat. Plant Manag., 21, pp. 87-92.

Suwatabandhu, K., 1950. Weeds in Paddy Fields in Thailand. Technical Bulletin No. 4. Department of Agriculture, Bangkok, Thailand. p. 21.

Tag El-Din, A.R., 1992. Utilization of water-hyacinth hay in feeding of growing sheep. Indian J. Anim. Sci. 62(10), pp. 989–992.

Taheruzzaman, Q., Kushari, D.P., 1989. Evaluation of some common aquatic macrophytes cultivated in enriched water as possible source of protein and biogas. Hydrobiol. Bull. 23(2), pp. 207-212.

Tchobanoglous, G., Theisen, H., Vigil, S. A., 1993. Integrated solid waste management: engineering principles and management issues. New York, New York, USA.

Tejada, M., Gonzalez, J. L., García-Martínez, A. M., Parrado, J., 2008. Effects of different green manures on soil biological properties and maize yield. Bioresource Technology, 99(6), pp. 1758-1767.

Thies, J. E., Rillig, M. C., 2009. Characteristics of biochar: biological properties. Biochar for environmental management: Science and technology, pp. 85-105.

Thomas, T.H., Eden, R.D., 1990. Water hyacinth – A major neglected resource. Material Science, Wind Energy, Biomass Technol., 3, pp. 2092–2096.

Tiquia, S.M., Tam, N.F.Y., 1998. Composting of spent pig litter in turned and forced-aerated piles. Environ. Pollut. 99, pp. 329-337.

Tiquia, S.M., Tam, N.F.Y., 2000. Fate of nitrogen during composting of chicken litter. Environ. Pollut. 110, pp. 535–541.

Tits, M., Elsen, A., Bries, J., Vandendriessche, H., 2014. Short-term and long-term effects of vegetable, fruit and garden waste compost applications in an arable crop rotation in Flanders. Plant and soil, 376(1-2), pp. 43-59.

Tsang, D. C., Olds, W. E., Weber, P. A., Yip, A. C., 2013. Soil stabilisation using AMD sludge, compost and lignite: TCLP leachability and continuous acid leaching. Chemosphere, 93(11), pp. 2839-2847.

USDA, Animal and Plant Health Inspection Service (APHIS), Plant Protection and Quarantine (PPQ). 2012. Federal noxious weed list (1 February 2012). USDA, APHIS, PPQ. Washington, DC.

van Apeldoorn, M.E., van Egmond, H.P., Speijers, G.J. and Bakker, G.J., 2007. Toxins of cyanobacteria. Molecular nutrition & food research, 51(1), pp.7-60.

van Ginkle, G.T., P.A.C. Raats and I.A. van Haneghem. 1999. Bulk density and porosity distributions in a compost pile. Netherlands Journal of Agricultural Science, 47:105-121.
Van, D. G., 1985. *Vallisneria* and its interactions with other species. Aquatics 7(3): pp. 6-10.

Vandecasteele, B., Reubens, B., Willekens, K., De Neve, S., 2014. Composting for increasing the fertilizer value of chicken manure: effects of feedstock on P availability. Waste Biomass Valorization, 5(3), pp. 491-503.

Vandecasteele, B., Willekens, K., Zwertvaegher, A., Degrande, L., Tack, F. M. G., & Du Laing, G., 2013. Effect of composting on the Cd, Zn and Mn content and fractionation in feedstock mixtures with wood chips from a short-rotation coppice and bark. Waste Manage., 33(11), pp. 2195-2203.

Vargas-Garcia, M. C., Suarez-Estrella, F., Lopez, M. J., Moreno, J., 2007. In vitro studies on lignocellulose degradation by microbial strains isolated from composting processes. Int. Biodeter. Biodegrad., 59(4), pp. 322-328.

Varma, V. S., Kalamdhad, A. S., 2014. Stability and microbial community analysis during rotary drum composting of vegetable waste. Int. J Recy. Org. Waste Agri. 3(2), 52.

Varma, V.S., Chatuphale, M. Kalamdhad, A.S., 2014. Effects of bulking agent in composting of vegetable waste and leachate control using rotary drum composter. Sustain Environ Res., 24(4), pp. 245-256.

Varma, V.S., Kalamdhad, A.S., 2013. Composting of municipal solid waste (MSW) mixed with cattle manure. Int. J Environ. Sci. 3(6), pp. 2068-2079.

Varma, V.S., Kalamdhad, A.S., 2014. Effects of leachate during vegetable waste composting using rotary drum composter. Environ Eng. Res., 19(1), pp. 1-7.

Varshney, C.K., Rzoska, J., 1976. Aquatic Weeds in South East Asia. The Hague, New Delhi.

Villamagna, A. M., Murphy, B. R., 2010. Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. Freshwater Biol., 55(2), pp. 282-298.

Villar, M. C., Beloso, M. C., Acea, M. J., Cabaneiro, A., González-Prieto, S. J., Carballas, M., ... Carballas, T., 1993. Physical and chemical characterization of four composted urban refuses. Bioresour. Technol., 45(2), pp. 105-113.

Vuorinen, M.H., Saharinen, S.H., 1997. Evolution of microbiological and chemical parameters during manure and straw co-composting in a drum composting system. Agri. Ecosyst. Environ. 66, pp. 19-29.

Wang, L., Xie, L., Yang, G., Yan, Q. and Ruan, W., 2009. Impact of different bulking agents and compound microbial inoculant on blue algae composting. Chin J Env Eng, 12, pp.2261-2265.

Wang, X., Selvam, A., Chan, M., Wong, J. W., 2013. Nitrogen conservation and acidity control during food wastes composting through struvite formation. Bioresour. Technol., 147, pp. 17-22.

Wang, Z., Calderon, M. M., 2012. Environmental and economic analysis of application of water hyacinth for eutrophic water treatment coupled with biogas production. J. Environ. Manage. 110, pp. 246-253.

Weber, J., Karczewska, A., Drozd, J., Licznar, M., Licznar, S., Jamroz, E., & Kocowicz, A., 2007. Agricultural and ecological aspects of a sandy soil as affected by the application of municipal solid waste composts. Soil Biol. Biochem., 39(6), pp. 1294-1302.

Wei, L., Shutao, W., Jin, Z., Tong, X., 2014. Biochar influences the microbial community structure during tomato stalk composting with chicken manure. Bioresour. Technol., 154, pp. 148-154.

Weindorf, D. C., Wittie, R., 2003. Determining particle density in dairy manure compost. Tex. J. Agric. Nat. Resour, 16, pp. 60-63.

Wetzel, R.G., 2001. Limnology: lake and river ecosystems. Gulf professional publishing.
Wile, I., Neil, J., Lumis, G., Pos, J., 1978. Production and utilization of aquatic plant compost. J. Aquat Plant Manage. 16, pp. 24-27.

Wilkie, A.C., Evans, J.M., 2010. Aquatic plants: an opportunity feedstock in the age of bioenergy. Biofuels 1(2), pp. 311-321.

Willekens, K., Vandecasteele, B., Buchan, D., De Neve, S., 2014. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Appl. soil Ecol., 82, pp. 61-71.

Williams, S.K., Kempton, J., Wilde, S.B., Lewitus, A., 2007. A novel epiphytic cyanobacterium associated with reservoirs affected by avian vacuolar myelinopathy. Harmful Algae, 6(3), pp. 343-353.

Wilson, G. B., 1989. Combining raw materials for composting. BioCycle, 29, pp. 82-85.

Wolka, K., Melaku, B., 2015. Exploring selected plant nutrient in compost prepared from food waste and cattle manure and its effect on soil properties and maize yield at Wondo Genet, Ethiopia. Environ System Res., 4(1), p. 9.

Wong, J.W.C., Li, S.W.Y., Wong M.H., 1995. Coal fly ash as a composting material for sewage sludge: Effects on microbial activities. Environ. Technol., 16(6), pp. 527-537.

Wu, L., Ma, L.Q., Martinez G. A., 2000. Comparison of Methods for Evaluating Stability and Maturity of Bio-solids Compost. J Environ. Qual. 29, pp. 424-429.

Xin, X., Zhang, J., Zhu, A., Zhang, C., 2016. Effects of long-term (23 years) mineral fertilizer and compost application on physical properties of fluvo-aquic soil in the North China Plain. Soil Tillage Res., 156, pp. 166-172.

Xu, Q.J., Nian, Y.G., Jin, X.C., Yan, C.Z., Liu, J., Jiang, G.M., 2007. Effects of chitosan on growth of an aquatic plant (Hydrilla verticillata) in polluted waters with different chemical oxygen demands. J Environ Sci, 19, pp. 217–221.

Xue, J., Zartarian, V., Wang, S.W., Liu, S.V., Georgopoulos, P., 2010. Probabilistic modeling of dietary arsenic exposure and dose and evaluation with 2003–2004 NHANES data. Environ Health Perspect., 118, pp. 345–350.

Yadav, R. L., Dwivedi, B. S., & Pandey, P. S., 2000. Rice-wheat cropping system: assessment of sustainability under green manuring and chemical fertilizer inputs. Field Crops Research, 65(1), pp. 15-30.

Yamada, Y., Kawase, Y., 2006. Aerobic composting of waste activated sludge: Kinetic analysis for microbiological reaction and oxygen consumption. Waste Manage., 26(1), pp. 49-61.

Yeo, R.R., McHenry, W.H., 1977. Hydrilla, a new noxious aquatic weed in California. California Agriculture, 31(10), pp.4-5.

Zehnsdorf. A., Hussner, A., Eismann, F., Rönicke, H., Melzer, A. 2015. Management options of invasive Elodea nuttallii and Elodea Canadensis. Limnologica, 51, pp. 110-117.

Zhang, L., Sun, X., 2014. Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar. Bioresour. Technol. 171 (1), pp. 274-284.

Zhang, L., Sun, X., 2014. Effects of rhamnolipid and initial compost particle size on the two-stage composting of green waste. Bioresour. Technol., 163, pp. 112-122.

Zhang, L., Sun, X., 2016. Influence of bulking agents on physical, chemical, and microbiological properties during the two-stage composting of green waste. Waste Manage., 48, pp. 115-126.

Zhang, L., Sun, X.Y., Tian, Y., Gong, X.Q., 2013. Effects of brown sugar and calcium superphosphate on the secondary fermentation of green waste. Bioresour. Technol. 131, pp. 68–75.

Zhang, Y., He, Y., 2006. Co-composting solid swine manure with pine sawdust as organic substrate. Bioresour. Technol., 97(16), pp. 2024-2031.

Zhu, J., Xu, X., Tao, Q., Yi, P., Yu, D., Xu, X., 2017. High invasion potential of Hydrilla verticillata in the Americas predicted using ecological niche modeling combined with genetic data. Ecol Evol, 7(13), pp. 4982-4990.

Zorpas, A.A., Loizidou, M., 2008. Sawdust and natural zeolite as a bulking agent for improving quality of a composting product from anaerobically stabilized sewage sludge. Bioresour. Technol., 99(16), pp.7545-7552.

Zorpas, A.A., Constantinides, T., Vlyssides, A.G., Haralambous, I., Loizidou M., 2000. Heavy metal uptake by natural zeolite and metals partitioning in sewage sludge compost. Bioresour. Technol. 72(2), pp. 113-119.

PUBLICATIONS

INTERNATIONAL JOURNALS (PUBLISHED/ACCEPTED)

1. Jain, M.S., Kalamdhad, A.S., 2018. A review on management of *Hydrilla verticillata* and its utilization as a potential nitrogen-rich biomass for compost or biogas production. Bioresour. Technol. Reports, 1, pp. 69-78.

2. Jain, M.S., Kalamdhad, A.S., 2018. Efficacy of batch mode rotary drum composter for management of aquatic weed (*Hydrilla verticillata* (L.f.) Royle). J Environ. Manage., 221, pp. 20-27.

3. Jain, M.S., Jambhulkar, R., Kalamdhad, A.S., 2018. Biochar amendment for batch composting of nitrogen-rich organic waste: Effect on degradation kinetics, composting physics and nutritional properties. Bioresour. Technol., 253, pp. 203-214.

4. Jain, M.S., Daga, M., Kalamdhad, A.S., 2018. Composting physics: A degradation process-determining tool for industrial sludge. Ecol. Eng., 116, pp. 14-20.

5. Jain, M.S., Daga, M., Kalamdhad, A.S., 2018. Composting physics: A science behind bio-degradation of lignocellulose aquatic waste amended with inoculum and bulking agent. Process Saf. Environ. Protect., 116, pp. 424-432.

6. Jain, M.S., Daga, M., Kalamdhad, A.S., 2018. Physical parameters evaluation during production of soil conditioner from aquatic waste: *Hydrilla verticillata* (L.f.) Royle. Environ. Technol. Innovation, 11, pp. 64-73.

7. Jain, M.S., Paul, S., Kalamdhad, A.S., 2019. Utilization of Biochar as an amendment during lignocellulose waste composting: Impact on composting physics and Realization (probability) amongst physical properties. Process Saf Environ. Protect., 121, pp. 229-238

8. Jain, M.S., Kalamdhad, A.S., 2019. Drum composting of nitrogen rich Hydrilla Verticillata with carbon-rich agents. Journal of Environmental Management, 231, pp. 770-779.

9. Jain, M.S., Daga, M., Kalamdhad, A.S., 2019. Variation in the key indicators during composting of municipal solid organic wastes. Sustain. Environ. Res.

ARTICLES (REVISION SUBMITTED)

10. Jain, M.S., Paul, S., Kalamdhad, A.S., 2019. Kinetics and physics during composting of various organic wastes: Statistical approach to interpret compost application feasibility. J Cleaner Prod.

ARTICLES (UNDER REVIEW)

11. Jain, M.S., Paul,S., Kalamdhad, A.S., 2019. Degradation process physics during composting of sewage sludge. Waste Manag.

12. Jain, M.S., Kalamdhad, A.S., 2019. Treatment of sandy soils using novel organic compost (Hydrilla verticillata and biochar) and its later effects on soil organic content, nutritional, sorption and physical properties. Soil Biol. Biochem.

13. Jain, M.S., Paul, S., Kalamdhad, A.S., 2019. Biochar amendment for batch composting of lignocellulose aquatic weed: Effect on physico-chemical, nutritional and total heavy metals. Chemosphere.

14. Jain, M.S., Jambhulkar, R., Kalamdhad, A.S., 2019. Vermicomposting: A novel treatment technology to manage aquatic weed Hydrilla verticillata. Environ. Int.

INTERNATIONAL CONFERENCE AND PROCEEDINGS

1. Jain, M.S., Kalamdhad, A.S., 2017. Rotary drum composting: A novel technology to treat aquatic weed (*hydrilla*). Proc. International Conference on Integrated Solid Waste Management Practices in Developing Countries (CSIR-NEERI-2017), 11-12 April, National Environmental Engineering Research Institute (NEERI), Nagpur, India.

2. Paul, S., Jain, M.S., Kalamdhad, A.S., 2018. Biochar as a capable bulking agent to improve nutritional properties during composting of lignocellulose aquatic weed. Proc. Research Conclave-2017, 8-11 March, Indian Institute of Technology Guwahati (IITG), Guwahati, India.

3. Jain, M.S., Kalamdhad, A.S., 2018. Composting physics: Degradation process regulating tool for sewage and industrial sludge. Proc. International Conference on Waste Management (Recycle 2018), 22-24 February, Indian Institute of Technology Guwahati, Guwahati, India.

4. Paul, S., Jain, M.S., Kalamdhad, A.S., 2018. Effect of biochar amendment on chemical and physical properties during rotary drum composting of water hyacinth. Proc. International Conference on Waste Management (Recycle 2018), 22-24 February, Indian Institute of Technology Guwahati, Guwahati, India.

5. Sihag, S., Jain, M.S., Kalamdhad, A.S., 2018. Amendement of biochar on laterite and alluvial soil: Effects on sorption and nutritional properties. Proc. International Conference on Waste Management (Recycle 2018), 22-24 February, Indian Institute of Technology Guwahati, Guwahati, India.

6. Jambhulkar, R., Jain, M.S., Kalamdhad, A.S., 2018. Application of biochar in agricultural soil: Effects on soil index and physical properties. Proc. International Conference on Waste Management (Recycle 2018), 22-24 February, Indian Institute of Technology Guwahati, Guwahati, India.

Book Chapter (Accepted)

1. Paul, S., Jain, M.S., Kalamdhad, A.S., 2019. Relevance of physicochemical and nutritional variables during rotary drum composting of water hyacinth with Biochar amendment. Recent Developments in waste management: Select Proceedings of Recycle 2018.