COMPOSTING OF FLOATING BIOMASS (PHUMDI AND *SALVINIA NATANS*) OF LOKTAK LAKE (MANIPUR, INDIA)

A thesis submitted

in partial fulfillment of the requirement for the degree of

Doctor of Philosophy

Submitted

By

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Candidate's Declaration

I hereby declare that the work presented in this thesis is to the best of my knowledge, original, except as acknowledged in the text. This material has not been submitted, either in whole or in part, for degree at any University.

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Certificate

This is to certify that the thesis entitled "**Composting of Floating Biomass (Phumdi and *Salvinia natans*) of Loktak Lake (Manipur, India)**" submitted by **Waikhom Roshan Singh** (Registration No. 09610417) to the Indian Institute of Technology Guwahati for the degree of Doctor of Philosophy is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion has reached the requisite standard fulfilling the requirement for award of the degree of Doctor of Philosophy. This work has not been submitted earlier for the award of any degree or diploma to the best of my knowledge and belief.

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Waikhom Roshan Singh

ABSTRACT

Mechanical and manual removal of phumdis (combination of different types of weeds and other plant species growing on floating detritus organic matter) and other invasive weeds such as *Salvinia natans* of the Loktak Lake, Manipur, India is carried out to check their proliferation and protect the freshwater lake. Composting can be the best alternative for utilization of the huge harvested green biomass because of the high organic contents, but there is a need for determination and understanding of the physico-chemical and bio-chemical parameters at various stages of the process in order to assess the performance and achieve process efficacy. Studies were carried out on the physico-chemical and bio-chemical transformations including the bioavailability of nutrients and heavy metals during agitated pile composting, drum composting and vermicomposting of phumdi as well as *Salvinia natans* biomass (both blended with cattle manure and rice husk or sawdust) all in five different trials. The weight of the materials for agitated pile composting and drum composting was 150 kg for each trial i.e. trial 1 (8 phumdi/*Salvinia natans*: 2 cattle manure:1 rice husk), trial 2 (7 phumdi/*Salvinia natans*:3 cattle manure:1 rice husk), trial 3 (6 phumdi/*Salvinia natans*:3 cattle manure:1 rice husk), trial 4 (5 phumdi/*Salvinia natans*:4 cattle manure:1 rice husk) and trial 5 (10 phumdi/*Salvinia natans*:0 cattle manure:0 rice husk). In the case of vermicomposting, the weight of the materials was 2.5 kg for each of the five trials and the earthworm *Eisenia fetida* was used for the process.

Trial 4 recorded the highest temperature (46.8ºC on the 8th day) during agitated pile composting of phumdi biomass with highest net volatile solids (VS) reduction (20.4%) after the process. The maximum temperatures recorded for trial 1, 2 and 3 during phumdi pile composting were 38.8, 39.2, and 45.8ºC on the 8th day with net VS reductions 13.9, 16.7 and 18.9% respectively. Trial 5 recorded maximum temperature (31.7ºC) on the 10th day of the pile composting process with net VS reduction of only 6.4%. The temperature profile was enhanced during drum composting of the phumdi biomass and the highest temperature (53.1ºC on the 6th day) with highest net VS reduction (22.2% after the process) was shown in trial 4. The maximum temperatures recorded for trial 1, 2, 3 and 5 during drum composting of phumdi biomass were 40, 48.4, 49.8 and 35.1ºC on 8th, 6th, 6th and 12th day with net VS losses of 24.3, 28.1, 29.9 and 8.9% respectively. During vermicomposting of the phumdi biomass, the highest gain of total earthworm biomass (1.3 folds) and maximum net VS reduction (23.4%) were also indicated in trial

4 on day 45. On the other hand, agitated pile composting of *Salvinia natans* showed highest temperature profile (52.2°C on 6th day) with highest net VS reduction (31.4%) in trial 3. Trial 1, 2, 4 and 5 of agitated pile composting of *Salvinia natans* showed maximum temperatures 42.3°C (8th day), 43.2°C (8th day), 49.8°C (7th day) and 32.2°C (5th day) with net VS reductions 14.7, 24.0, 29.7 and 9.6% respectively. Drum composting of *Salvinia natans* indicated highest temperature (54.2°C on 4th day) and highest net VS decrease (32.9%) also in trial 3. Trial 1, 2, 4 and 5 indicated maximum temperatures 40.2°C (5th day), 48.8°C (5th day), 50.9°C (4th day) and 39.1°C (7th day) with net VS reductions 24.8, 29.8, 30.8 and 15.7% respectively. The highest gain of earthworm biomass (2 folds) and maximum net VS reduction (38.6%) was indicated in trial 4 after the vermicomposting of *Salvinia natans*. Overall, trial 4 for phumdi and trial 3 for *Salvinia natans* were again found to be the best trials for pile or drum composting as shown by lowest oxygen uptake rates (phumdi: 4.2–2.4 mg/g VS/day; *Salvinia natans*: 2.9–2.3 mg/g VS/day) and CO_2 evolution rates (phumdi:1.2–1.1 mg/g VS/day; *Salvinia natans*:1.1–1.0 mg/g VS/day); and highest reductions of soluble biochemical oxygen demand (phumdi:77.5–81.3%; *Salvinia natans*:80.1–82.4%). In case of vermicomposting for both wastes, trial 4 combination was the best indicating that the growth of the earthworms was dependent on the proportion of cattle manure. The concentrations of total nutrients (nitrogen, phosphorous, sodium, potassium, calcium and magnesium) and total heavy metals (zinc, copper, manganese, iron, nickel, lead, cadmium and chromium) increased in all the processes for both wastes due to net loss of dry mass. The concentrations of the total heavy metals were relatively lower in vermicomposts indicating bio-accumulation of the heavy metals by the earthworms. The bioavailable forms of heavy metals represented by the water soluble, diethylene triamine penta-acetic acid and toxicity characteristic leaching procedure extracts decreased after the process. The vermicomposting with *Eisenia fetida* was very effective in reduction of the bioavailable forms of heavy metals as the gut action facilitated the process.

Therefore, drum composting and vermicomposting of phumdi biomass and *Salvinia natans* were found effective with appropriate proportion of cattle manure and rice husk or sawdust. However, the reduction of the bioavailable and leachable forms of heavy metals was totally dependent on the nature of the substrates.

Keywords: Phumdi, *Salvinia natans*, Composting, Rotary drum, Agitated pile, Vermicomposting, Heavy metals

TABLE OF CONTENTS

Contents	Page No.
Statement of Originality	i
Certificate	ii
Acknowledgements	iii–iv
Abstract	v–vi
Table of Contents	vii–x
List of Figures	xi–xiv
List of Tables	xv–xvii
Abbreviations	xix
Chapter 1 INTRODUCTION	1–7
1.1 Overview	1
1.2 Background of the problem	3
1.3 Objectives	4
1.4 Need of the study	5
1.5 Scope of the study	5
1.6 Thesis organisation	6
Chapter 2 LITERATURE REVIEW	9–47
2.1 General problem of aquatic weeds	9
2.2 Problem of phumdi and other aquatic weeds of Loktak Lake	11
2.3 Control of weeds through physical removal	14
2.4 Utilisation of harvested weeds	15
2.5 Composting	15
2.5.1 History of composting	15
2.5.2 Composting process	17
2.5.3 Composting techniques	18
2.5.4 Factors affecting composting process	23
2.5.5 Material amendments	27
2.6 Vermicomposting	28
2.6.1 History of vermicomposting	28

2.6.2 Vermicomposting process 28
2.6.3 Vermicomposting techniques 29
2.6.4 Factors affecting vermicomposting 32
2.7 Nutrients during composting 33
2.7.1 Transformation of primary nutrients 33
2.7.2 Transformation of secondary nutrients 34
2.8 Heavy metals during composting 34
2.8.1 Effects of heavy metals 35
2.8.2 Bioavailability of heavy metals 36
2.9 Compost stability/maturity 41
2.10 Studies on weed composting /vermicomposting 44
2.11 Inference from literature review 46
Chapter 3 MATERIALS AND METHODS 49–60
3.1 Experimental design 49
3.2 Feedstock materials and waste combinations 50
3.2.1 Phase 1: Phumdi biomass composting/vermicomposting 50
3.2.2 Phase 2: *Salvinia natans* composting/ vermicomposting 51
3.3 Composting methods 52
3.3.1 Agitated pile composting 52
3.3.2 Rotary drum composting 53
3.3.3 Vermicomposting 54
3.4 Sampling and analysis 55
3.4.1 Sampling 55
3.4.2 Physico-chemical analysis 57
3.4.3 Bio-chemical analysis 58
3.4.4 Nutrients and heavy metals analysis 58
3.4.5 Statistical analysis 59
3.4.6 Equipment used 60
Chapter 4 Composting and vermicomposting of phumdi biomass 61–112
4.1 Initial characterization of phumdi biomass and other 61

Contents			**Page No.**

feedstock materials

4.2 Agitated pile composting of phumdi biomass 64

4.2.1 Temperature profile 64

4.2.2 Physico-chemical and bio-chemical analysis 65

4.2.3 Nutrients 70

4.2.4 Total heavy metals 73

4.2.5 Bioavailability of heavy metals 75

4.3 Rotary drum composting of phumdi biomass 82

4.3.1 Temperature profile 82

4.3.2 Physico-chemical and bio-chemical analysis 83

4.3.3 Nutrients 86

4.3.4 Total heavy metals 89

4.3.5 Bioavailability of heavy metals 92

4.4 Vermicomposting of phumdi biomass 97

4.4.1 Earthworm biomass 97

4.4.2 Physico-chemical and bio-chemical analysis 98

4.4.3 Nutrients 102

4.4.4 Total heavy metals 105

4.4.5 Bioavailability of heavy metals 106

Chapter 5 Composting and vermicomposting of *Salvinia natans* 113–161

5.1 Initial characteristics *Salvinia natans* and other feedstock materials 113

5.2 Agitated pile composting of *Salvinia natans* 115

5.2.1 Temperature profile 115

5.2.2 Physico-chemical and bio-chemical analysis 116

5.2.3 Nutrients 120

5.2.4 Total heavy metals 123

5.2.5 Bioavailability of heavy metals 125

5.3 Rotary drum composting of *Salvinia natans* 131

5.3.1 Temperature profile 131

5.3.2 Physico-chemical and bio-chemical analysis 132

5.3.3 Nutrients 135

Contents **Page No.**

5.3.4 Total heavy metals 139
5.3.5 Bioavailability of heavy metals 139
5.4 Vermicomposting of *Salvinia natans* 147
5.4.1 Earthworm biomass 147
5.4.2 Physico-chemical and bio-chemical analysis 148
5.4.3 Nutrients 151
5.4.4 Total heavy metals 154
5.4.5 Bioavailability of heavy metals 157
Chapter 6 CONCLUSIONS AND RECOMENDATIONS 163
6.1 Conclusions 163
6.2 Recommendations 164
REFERENCES 165-186
PUBLICATIONS 187

LIST OF FIGURES

Figure No.	Figure caption	Page No.
2.1a	Location map of Manipur	10
2.1b	Location of Loktak Lake in Manipur, northeast India	11
2.2a	Formation of phumdi	12
2.2b	Phumdi obstructing waterways	12
2.5a	Representation of the composting process	18
2.5b	Arrangement of windrows	20
2.5c	Passive aerated pile	20
2.5d	Positive and negative pressure piles	21
2.5e	Schematic diagram of in-vessel vertical reactor	22
2.5f	Rotary drum composter	23
2.6	Commercial model vermireactor (ICRISAT)	31
3.1a	Design of research work for Phase 1	49
3.1b	Design of research work for Phase 2	50
3.2	Pictorial representation of collection, storage, cutting/shredding and mixing	52
3.3a	Schematic representation of compost pile	53
3.3b	Schematic diagram of rotary drum composter for batch operation	54
3.3c	Schematic diagram of a bamboo vermireactor	55
3.4	Plan for physico-chemical, bio-chemical and metal analysis of samples	56
4.2.1	Temperature profiles of phumdi piles during composting	64
4.2.2a	Variation of pH during pile composting of phumdi biomass	65
4.2.2b	Variation of EC during pile composting of phumdi biomass	66
4.2.2c	Variation of MC during pile composting of phumdi biomass	67
4.2.2d	Variation of VS during pile composting of phumdi biomass	68
4.2.2e	Variation of soluble BOD during pile composting of phumdi biomass	69
4.2.2f	Variation of CO_2 evolution rate during pile composting of phumdi biomass	69
4.2.2g	Variation of OUR during pile composting of phumdi biomass	70
4.2.3a	Variation of TKN and NH_4–N during pile composting of phumdi biomass	70

Figure No.	Figure caption	Page No.
4.2.3.b	Variation of TP and AP during pile composting of phumdi biomass	71
4.2.5	Variation of DTPA extractable “ŋ” of heavy metals during pile composting of phumdi biomass	80
4.3.1	Temperature profiles of drums during phumdi composting	83
4.3.2a	Variation of pH values during drum composting of phumdi biomass	83
4.3.2b	Variation of EC during drum composting of phumdi biomass	84
4.3.2c	Variation of MC during drum composting of phumdi biomass	84
4.3.2d	Variation of VS during drum composting of phumdi biomass	85
4.3.2e	Variation of soluble BOD during drum composting of phumdi biomass	86
4.3.2f	Variation of OUR during drum composting of phumdi biomass	86
4.3.2g	Variation of CO_2 evolution rate during drum composting of phumdi biomass	86
4.3.3a	Variation of TKN and NH_4–N during drum composting of phumdi biomass	87
4.3.3b	Variation of TP and AP during drum composting of phumdi biomass	87
4.3.5	Variation of DTPA extractable “ŋ” of heavy metals during drum composting of phumdi biomass	95
4.4.1	Variations in the no. of earthworms, cocoons, hatchings and earthworm biomass during vermicomposting of phumdi biomass	98
4.4.2a	Variation of pH during vermicomposting of phumdi biomass	100
4.4.2b	Variation of EC during vermicomposting of phumdi biomass	100
4.4.2c	Variation of VS during vermicomposting of phumdi biomass	100
4.4.2d	Variation of soluble BOD during vermicomposting of phumdi biomass	101
4.4.2e	Variation of soluble CO_2 evolution rate during vermicomposting of phumdi biomass	101
4.4.2f	Variation of OUR during vermicomposting of phumdi biomass	102
4.4.3a	Variation of TKN and NH_4–N during vermicomposting of phumdi biomass	103
4.4.3b	Variation of TP and AP during vermicomposting of phumdi biomass	103
4.4.5	Variation of DTPA extractable “ŋ” of heavy metals during vermicomposting of phumdi biomass	112
5.2.1	Temperature profiles of *Salvinia natans* piles during composting	116
5.2.2a	Variation of pH during pile composting of *Salvinia natans*	117

Figure No.	Figure caption	Page No.
5.2.2b	Variation of EC during pile composting of *Salvinia natans*	117
5.2.2c	Variation of MC during pile composting of *Salvinia natans*	118
5.2.2d	Variation of VS during pile composting of *Salvinia natans*	118
5.2.2e	Variation of soluble BOD during pile composting of *Salvinia natans*	119
5.2.2f	Variation of CO_2 evolution rate during pile composting of *Salvinia natans*	120
5.2.2g	Variation of OUR during pile composting of *Salvinia natans*	120
5.2.3a	Variation of TKN and NH_4–N during pile composting of *Salvinia natans*	121
5.2.3b	Variation of TP and AP during pile composting of *Salvinia natans*	121
5.2.5	Variation of DTPA extractable “ŋ” of heavy metals during pile composting of *Salvinia natans*	129
5.3.1	Temperature profiles of drums during *Salvinia natans* composting	132
5.3.2a	Variation of pH values during drum composting of *Salvinia natans*	132
5.3.2b	Variation of EC during drum composting of *Salvinia natans*	133
5.3.2c	Variation of MC during drum composting of *Salvinia natans*	133
5.3.2d	Variation of VS during drum composting of *Salvinia natans*	134
5.3.2e	Variation of soluble BOD during drum composting of *Salvinia natans*	134
5.3.2f	Variation of CO_2 evolution rate during drum composting of *Salvinia natans*	135
5.3.2g	Variation of OUR during drum composting of *Salvinia natans*	135
5.3.3a	Variation of TKN and NH_4–N during drum composting of *Salvinia natans*	136
5.3.3b	Variation of TP and AP during drum composting of *Salvinia natans*	136
5.3.5	Variation of DTPA extractable “ŋ” of heavy metals during drum composting of *Salvinia natans*	144
5.4.1	Variations in the no. of earthworms, cocoons, hatchings and earthworm biomass during vermicomposting of *Salvinia natans*	148
5.4.2a	Variation of pH during vermicomposting of *Salvinia natans*	149
5.4.2b	Variation of EC during vermicomposting of *Salvinia natans*	149
5.4.2c	Variation of VS during vermicomposting of *Salvinia natans*	150
5.4.2d	Variation of soluble BOD during vermicomposting of *Salvinia natans*	151
5.4.2e	Variation of soluble CO_2 evolution rate during vermicomposting of *Salvinia natans*	151

LIST OF TABLES

Table No.	Table caption	Page No.
3.1a	Proportion of feedstock mixtures during pile and rotary drum composting	51
3.1b	Proportion of feedstock mixtures during vermicomposting	51
3.4a	Instruments used for physico-chemical and bio-chemical analysis	60
3.4b	Accessories used for physico-chemical and bio-chemical analysis	60
4.1	Initial characterization of phumdi biomass and other feedstock materials	62
	a. Physico-chemical and bio-chemical parameters	62
	b. Total and WS nutrients	62
	c. Total, WS, DTPA extractable and TCLP extractable heavy metals	63
4.2.1	Variation of total Na, K, Ca and Mg during pile composting of phumdi	72
4.2.2	Variation of WS Na, K, Ca and Mg during pile composting of phumdi	73
4.2.3	Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi	74
4.2.4	Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi	76
4.2.5	Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi	79
4.2.6	Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi	81
4.3.1	Variation of total Na, K, Ca and Mg during drum composting of phumdi	88
4.3.2	Variation of WS Na, K, Ca and Mg during drum composting of phumdi	88
4.3.3	Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of phumdi	90

Table No.	Table caption	Page No.
4.3.4	Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of phumdi	91
4.3.5	Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during phumdi drum composting	93
4.3.6	Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of phumdi	96
4.4.1	Variation of total Na, K, Ca and Mg during vermicomposting of phumdi	104
4.4.2	Variation of WS Na, K, Ca and Mg during vermicomposting of phumdi	105
4.4.3	Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi	107
4.4.4	Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi	108
4.4.5	Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi	110
4.4.6	Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi	111
5.1	Initial characterization of *Salvinia natans* composting materials	
	a. Physico-chemical and bio-chemical parameters	114
	b. Total and WS nutrients	114
	c. Total, WS, DTPA extractable and TCLP extractable heavy metals	115
5.2.1	Variation of total Na, K, Ca and Mg during pile composting of *Salvinia natans*	122
5.2.2	Variation of WS Na, K, Ca and Mg during pile composting of *Salvinia natans*	123
5.2.3	Variation of total heavy Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of *Salvinia natans*	124
5.2.4	Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of *Salvinia natans*	126
5.2.5	Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of *Salvinia natans*	127

Table No.	Table caption	Page No.
5.2.6	Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of *Salvinia natans*	130
5.3.1	Variation of total Na, K, Ca and Mg during drum composting of *Salvinia natans*	137
5.3.2	Variation of WS Na, K, Ca and Mg during drum composting of *Salvinia natans*	138
5.3.3	Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *Salvinia natans*	140
5.3.4	Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *Salvinia natans*	141
5.3.5	Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *Salvinia natans*	143
5.3.6	Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *Salvinia natans*	145
5.4.1	Variation of total Na, K, Ca and Mg during vermicomposting of *Salvinia natans*	153
5.4.2	Variation of WS Na, K, Ca and Mg during vermicomposting *Salvinia natans*	154
5.4.3	Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting *Salvinia natans*	155
5.4.4	Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting *Salvinia natans*	156
5.4.5	Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting *Salvinia natans*	158
5.4.6	Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting *Salvinia natans*	160

ABBREVIATIONS

ANOVA	Analysis of variances
AP	Available phosphorous
APHA	American Public Health Association
BIS	Bureau of Indian Standards
BOD	Bio-chemical oxygen demand
C/N	Carbon-to-nitrogen ratio
C/P	Carbon-to-phosphorous ratio
COD	Chemical oxygen demand
DTPA	Diethylene triamine penta-acetic acid
EC	Electrical conductivity
h	Hour
L	Litre
MC	Moisture content
n	No. of measurements
ND	Not detected
NH_4-N	Ammonical nitrogen
OM	Organic matter
OUR	Oxygen uptake rate
P	Probability
rpm	Revolution per min
SD	Standard deviation
TCLP	Toxicity characteristics leaching procedure
TKN	Total Kjeldahl nitrogen
TP	Total phosphorous
USEPA	United States Environmental Protection Agency
VS	Volatile solids
WS	Water soluble
K_b	Biodegradability coefficient
ŋ	DTPA extraction efficiency

*All chemical symbols has their usual notation in the thesis

Chapter 1

INTRODUCTION

This chapter is about the importance of Loktak Lake and the impact of proliferation of phumdi and other aquatic weeds on the lake. The scope of composting of phumdi biomass and *Salvinia natans* of the lake, the need for use of bulking agents during composting, and the need for assessment of the quality including the undesirable contents of heavy metal of the product composts are also discussed. Finally, the chapter illustrates the objectives and the need of the study, and the organisation of the thesis.

1.1 OVERVIEW

Northeast India is one of the global hot spot regions for biodiversity as the associated natural wetlands[1] and forests support valuable bio-diversity or heterogeneity (Kalita et al., 2007). Loktak Lake (geographical location: 24° 25'-24° 42' N; 93° 46'-93° 55' E), situated in the southern part of the central Manipur valley, is the largest natural fresh water lake (area: 289 sq. km) of northeast India and is one of the 26 wetlands of India declared as Ramsar Sites[2]. The lake is also one of the two Ramsar Sites of India listed in the Montreux Record[3] (Ramsar Secretariat, 2015). This wetland plays an important role in the ecological and economic security of the region from ancient days. The lake buffers extreme conditions of flood and drought in the Manipur valley. A large population living in and around the lake depends upon the lake’s resources for its sustenance. The people of Manipur are culturally, socially and economically linked with the Loktak Lake and hence the lake has been referred to as a lifeline of the state (Trisal and Manihar, 2004). Wetlands have other ecological significances in terms of water purification, aquatic productivity, micro-climate regulations and rich flora and fauna (Lawn and Lam, 2012). The main characteristic of Loktak Lake is the presence of ‘phumdi’- a popularized Manipuri word meaning floating vegetation mass formed by the proliferation of weeds, other vegetation and organic debris at various stages of decomposition and occurring in different sizes and thickness. The phumdis play an important role in the ecological processes and functions of the lake and also act as a biological sink to the key nutrients and pollutants entering the lake (Trishal and Manihar, 2004). However, uncontrolled spread of phumdis poses a great threat to the ecosystem of the lake. Rapid proliferation of phumdis can choke the entire lake area and retard flow of water and natural aeration;

accelerate process of eutrophication; make water unfit for various uses; promote water logging; and reduce water holding capacity by accelerating sedimentation. This leads to decline in fish production, loss of open water area, disturbances in navigation, etc. (Santosh and Bidan, 2002; Singh, 2015).

There are also weeds in the clear water zone of the lake not associated with the phumdi biomass of which *Salvinia natans* (or simply Salvinia) is one of the invasive species (Trishal and Manihar, 2004). The weed is a dominant colonising aquatic fern species, which prevails over the aquatic ecosystem by its rapid growth and displacement of native plants that provide food and habitat for the native animals and waterfowl (Galka and Szmeja, 2012). The growth and spread of *Salvinia natans* may be enormous to the extent of 45% per day in nutrient rich water bodies (Blackman, 1960). The high viability of spores associated with rapid vegetative propagation is responsible for the spread of the weed producing vast thick mats and with global warming, the weed will create havoc to water bodies at the expense of submerged exotic plants in many parts of the world (Netten et al., 2010). The dense mats have a negative effect on the functioning and biodiversity of the freshwater ecosystems due to hampered photosynthesis of the underneath aquatic plants; reduced gas exchange at the air water interface; and increased consumption of oxygen by microbial decomposition of decayed weeds. The decayed dead weeds increase the nutrient level in the water leading to the problem of eutrophication (Gupta et al., 2007; Wang et al., 2012).

Phumdi proliferation of Loktak Lake is mainly controlled through harvesting. But, there has to be a definite answer to the problem of disposal of the huge harvested phumdi biomass. Some portion of the harvested phumdi biomass is reported to be transported either to the disposal sites or to the composting yards (LDA and WISA, 2011). The high organic matter contents of harvested phumdi and *Salvinia natans* biomass (Devi et al., 2002) indicate significant scope of bio-processing which in turn can control phumdi proliferation in the lake through purposive and enthusiastic harvesting of the weeds. The success of this option will depend upon the capability of conversion of the vegetative mass of phumdi and other aquatic weeds to quality compost and/or biogas which in turn could be effectively put into use by the surrounding inhabitants with minimal efforts. Composting and vermicomposting are two of the best known bio-treatment processes for the biological stabilization of green solid organic waste by transforming them into a safer and more stabilized reprocessed organic material i.e. compost or vermicompost (Manser and Keeling, 1996; Wong et al., 2001; Fernández-Gómez et al., 2015) that can be used as a soil conditioner in agricultural applications and minimizes the waste quantity left for disposal, thereby reducing the demand for landfill sites (Deka et al., 2011; Gabhane et al., 2012).

1.2 BACKGROUND OF THE PROBLEM

The scope for transforming of phumdi biomass of Loktak Lake into compost requires study on the application of different techniques in order to assess their performances and achieve process efficacy. For adopting composting as a viable option, the degradation characteristics of the biomass and the quality of the composts have to be minutely examined. In the evaluation of the composting techniques, the duration required to reach compost maturity is a key parameter for the proper design of solid waste composting facilities (Komillis, 2006) and the variability in design further affects the quality of the resulting compost. The initial solid organic carbon of the biomass maybe readily hydrolysable carbon, moderately hydrolysable carbon or slowly hydrolysable carbon (El-Fadel et al., 1989) and these different fractions of the biodegradable organic components eventually mineralize to CO_2 and H_2O at different rates. The investigation on the organic matter transformation during composting of the phumdi biomass is needed to fill the existing knowledge gap of performance assessment. Many tests are required to assess the biodegradation of phumdi as well as *Salvinia natans* biomass for assessing the stability and maturity of the resulting compost such as the soluble organic carbon content (Garcia et al., 1991; Inbar et al., 1993), oxygen and CO_2 respirometry (Iannotti et al., 1994; Kalamdhad et al., 2009), etc. Physico-chemical parameters viz. temperature, pH, moisture content, electrical conductivity (EC), volatile solids (VS), nitrogen and phosphorous content, other nutrients and trace elements are also required to be investigated to understand the dynamics involved in the bio-process and for successive utilization of the product composts (CCME, 2005; Tittarelli et al., 2007) .

Another important aspect is the likely presence of toxic heavy metals in the phumdi biomass. Rivers flowing through the capital city Imphal and/or other highly polluted stretches of the valley carry in large amounts of nutrients and pollutants into the lake. With rapid urbanization, industrialization and increasing population, the pollution load entering the lake increases day by day. The use of excessive amount of fertilizers, pesticides, insecticides and fungicides has aggravated the problem (Singh et al., 2013a). As stated before, the phumdis and the weeds of Loktak Lake act as a biological sink by absorbing most of the nutrients and the pollutants and accumulating them in the vegetative tissues. *Salvinia natans* is also highly effective in removing pollutants and heavy metals from water (Dhir and Srivastava, 2011; Kumari and Tripathi, 2014). Application of compost containing heavy metals has the potential to cause adverse effect on the environment as the heavy metals accumulate in the soil and bio-magnify in the food chain through uptake by plants (Wong and Selvam, 2006; Iwegbue et al., 2007; Chiroma et al., 2012).

Successful composting is associated with the blending of the composting materials with appropriate bulking agents and other easily degradable carbonaceous matter. Numerous bulking agents including wood chips, wheat straw, sawdust, rice husk, rice bran, chopped hay, wood shavings and peanut shells have been mixed with waste materials to adjust the moisture content (MC), carbon-to-nitrogen ratio (C/N) and void spaces between particles (Gea et al., 2007; Adhikari et al., 2009; Chang and Chen, 2010; Iqbal et al., 2010). The blending enhances the degradation process through provision of adequate energy and appropriate air movement for the microbes (Batham et al., 2013). Cattle manure is also widely used to blend industrial waste, sludge, food waste, water hyacinth, etc. during composting and vermicomposting as cattle manure controls moisture, bulk density, C/N and pH (Gajalakshmi et al., 2001; Pramanik, 2010; Sarkar et al., 2010). Several successful studies are available for agitated pile composting (Das and Kalamdhad, 2011) and vermicomposting (Gajalakshmi et al., 2001a; Mohee and Mudhoo, 2005; Gupta et al., 2007) of the obnoxious weed water hyacinth with the addition of bulking agents. Singh and Kalamdhad (2012; 2013 a, b) carried out study on the speciation of heavy metals during agitated pile composting, rotary drum composting and vermicomposting of water hyacinth. However, no scientific study has been reported on the physico-chemical and bio-chemical variations or the transformation of the form of nutrients and other heavy metals collectively during composting or vermicomposting for phumdi biomass and *Salvinia natans* weed. Therefore, the aim of the thesis was to investigate the physico-chemical and bio-chemical changes and assess the bioavailable and leachable forms of heavy metals during agitated pile composting, rotary drum composting and vermicomposting of phumdi biomass and *Salvinia natans* in two phases i.e. Phase 1 for phumdi biomass and Phase 2 for *Salvinia natans*.

1.3 OBJECTIVES

The objectives of the study were:

1. To investigate the organic matter transformation during agitated pile composting,

drum composting and vermicomposting of phumdi biomass as well as *Salvinia natans* by determining the physico-chemical and bio-chemical parameters at different stages of the process; and

2. To determine the fate of the heavy metals of the phumdi biomass and *Salvinia natans* during the aforesaid process by assessing the bioavailable and leachable forms of the metals at different stages of the process.

1.4 NEED OF THE STUDY

Agriculture is the mainstay of the people of northeast India as they mainly depend on agriculture for their sustenance and livelihoods (MOSPI, 2015). The indigenous people of this region have been managing their agricultural activities especially in the uplands with their traditional know-how since ages. The marginal farmers of the region often do not get access to chemical fertilizers and pesticides (Husain, 2003) and quality organic compost can be the basic requirement for motivating these farmers of the region. Therefore, effective composting of phumdi biomass will certainly reduce the demand for fertilisers in the state which are totally depended from imports. The Annual Administrative Report of Loktak Development Authority, Manipur for the year 2011-12 did not indicate significant headway in the effective composting of phumdi biomass undertaken by the authority. The said Report also indicated the expenditure incurred for phumdi clearance of Loktak Lake as Rs. 573 lakhs. The ultimate effect of phumdi proliferation has been impoverishment of livelihoods and enhancement of poverty within wetland communities of Loktak Lake as a result of ecosystem degradation. Effective composting followed by land application can also be one of the most economical ways for the treatment and final disposal of green phumdi and *Salvinia natans* weed because it combines material recycling and biomass disposal at the same time (Villasenor et al., 2011). The land application of the compost generated from the harvested biomass to the paddy fields and other intensive run-off crop lands returns the run-off nutrients to their land of origin (Kuo et al., 2004). Therefore, composting of phumdi promotes nutrient recycling which is beneficial for sustainable water and terrestrial eco-system (Larsen and Gujer, 1997).

1.5 SCOPE OF THE STUDY

The scope of the thesis is confined to the bio-processing of phumdi biomass and *Salvinia natans* weed using the following techniques:

- Agitated pile composting;

- Drum composting; and
- Vermicomposting.

The batch operations were run on 5 (five) trials both for phumdi or *Salvinia natans* biomass after blending with different proportions of bulking agents. The major portion of the work was on the collection of phumdi and *Salvinia natans* biomass with the help of local boatmen; collection of cattle manure, rice husk and sawdust from different places; cutting/chopping of vegetable waste in the desired size; observation/monitoring of the piles, drum and vermireactor during the process; and handling and analysis of data.

1.6 THESIS ORGANIZATION

The thesis is organized chapter wise as below:

- Chapter 1 is about Loktak Lake and its importance, the problem of phumdi and weed proliferation in the lake, the option for composting and vermicomposting of phumdi biomass and *Salvinia natans* weed, the objectives and need of the study, and the scope of the thesis.
- Chapter 2 gives a detailed literature review of the general weed problems, the problem of phumdi proliferation in Loktak Lake, the different techniques of composting, the quality of compost, the heavy metals problems, and the bioavailability and leachability of heavy metals during the composting process.
- Chapter 3 deals with the flow chart of phases of the research; collection of phumdi biomass, *Salvinia natans* weed and other feedstock materials; composting methods adopted in the study; and detailed procedures for physico-chemical, bio-chemical and heavy metal analysis (total heavy metal, water soluble, DTPA extractable and leachable forms).
- Chapter 4 is about results and discussion regarding the temperature profiles, the variation of physico-chemical and bio-chemical parameters, the bioavailability and leachability of heavy metals during agitated pile composting, rotary drum composting and vermicomposting of phumdi biomass.
- Chapter 5 is about results and discussion regarding the temperature profiles, the variation of physico-chemical and bio-chemical parameters, the bioavailability and leachability of heavy metals during agitated pile composting, rotary drum composting and vermicomposting of *Salvinia natans.*
- Chapter 6 lists the conclusions and recommendations of the thesis.

ENDNOTES

[1] Wetlands are areas where water is the primary factor controlling the environment and associated plants and animal life (Ramsar, 2006).There is no single, indisputable, ecologically sound definition for wetlands, primarily because of the diversity of wetlands and also because the demarcation between dry and wet environments lies along a continuum (Cowardin et al., 1985). Institutes and governments agencies dealing with wetlands have developed their own definitions for scientific and management purposes (Dugan, 1993). The broadest and most flexible definition is that of the 'Convention on Wetlands of International Importance', also popularly known as the 'Ramsar Convention'. Under the Article 1.1 of the Convention, wetlands are defined as: ''*areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters*'' (Ramsar, 2006, Page 7).

[2] Wetlands included in the Ramsar List acquire a new status at the national level and are recognized by the international community as being of significant value not only for the country, or the countries, in which they are located, but for humanity as a whole.

[3] A record of Ramsar Sites "where changes in ecological character have occurred, are occurring or are likely to occur" maintained by the Ramsar Secretariat (www.ramsar.org/montreux-record).

Chapter 2

LITERATURE REVIEW

This chapter is about the relevant available literature concerning the general problems of aquatic weeds, problems of proliferation of phumdi and other weeds of Loktak Lake, and option for control of phumdi and *Salvinia natans* proliferation through purposive harvesting and subsequent bioconversion to composts. The composting technologies, factors affecting composting and vermicomposting process, quality of the resulting composts, bio-accumulation of heavy metals in the vegetative tissues of phumdi and *Salvinia natans* biomass, and fate of the heavy metals during the bio-conversion process are also discussed.

2.1 GENERAL PROBLEM OF AQUATIC WEEDS

Aquatic weeds have been considered a menace for decades as they limit the optimum utilization of our water resources and are directly or indirectly responsible for huge economic losses. They are a threat to the ecosystem and invasive species such as water hyacinths have devastated a number of freshwater lakes and rivers in India (Mathur et al., 2005; Malik, 2007). Aquatic plants become aquatic weeds when they outgrow and take the form of noxious vegetation by outcompeting native species and reducing the biodiversity of the area (Varshney et al., 2007). Aquatic weeds blanket the water surface limiting sunlight and oxygen transfer. The limiting light availability reduces the temperature of the water bodies and interferes with photosynthesis of the submersed aquatic plant communities. Low dissolved oxygen levels in the water are detrimental to fishes and other aquatic organisms and make the water bodies unproductive (Kalita et al., 2006; Gorham, 2008; Madsen, 2014). Profuse growth of aquatic weeds creates dense mats obstructing waterways, impeding the flow of water in irrigation and drainage channels, and frequently damaging pumps and turbines in hydro-power stations. They assimilate large quantities of nutrients from water reducing the availability of the nutrients for planktonic algae. They increase flood frequency, duration and intensity; are the habitats for insect borne disease vectors; alter animal community interactions; reduce fish production and aesthetic value; interfere with navigation; promote habitat for mosquitoes; and cause water loss through evapo-transpiration (Lanker and Krake, 2002; Gunnarsson and Petersen, 2007; Sushilkumar, 2011; Dibble, 2014; Cuda, 2014). As the weeds decay, there is a sharp increase in the nutrient content of the water body creating problems of eutrophication and low dissolved oxygen (Gupta et al., 2007). Therefore, it is essential to keep aquatic weeds under control in water bodies.

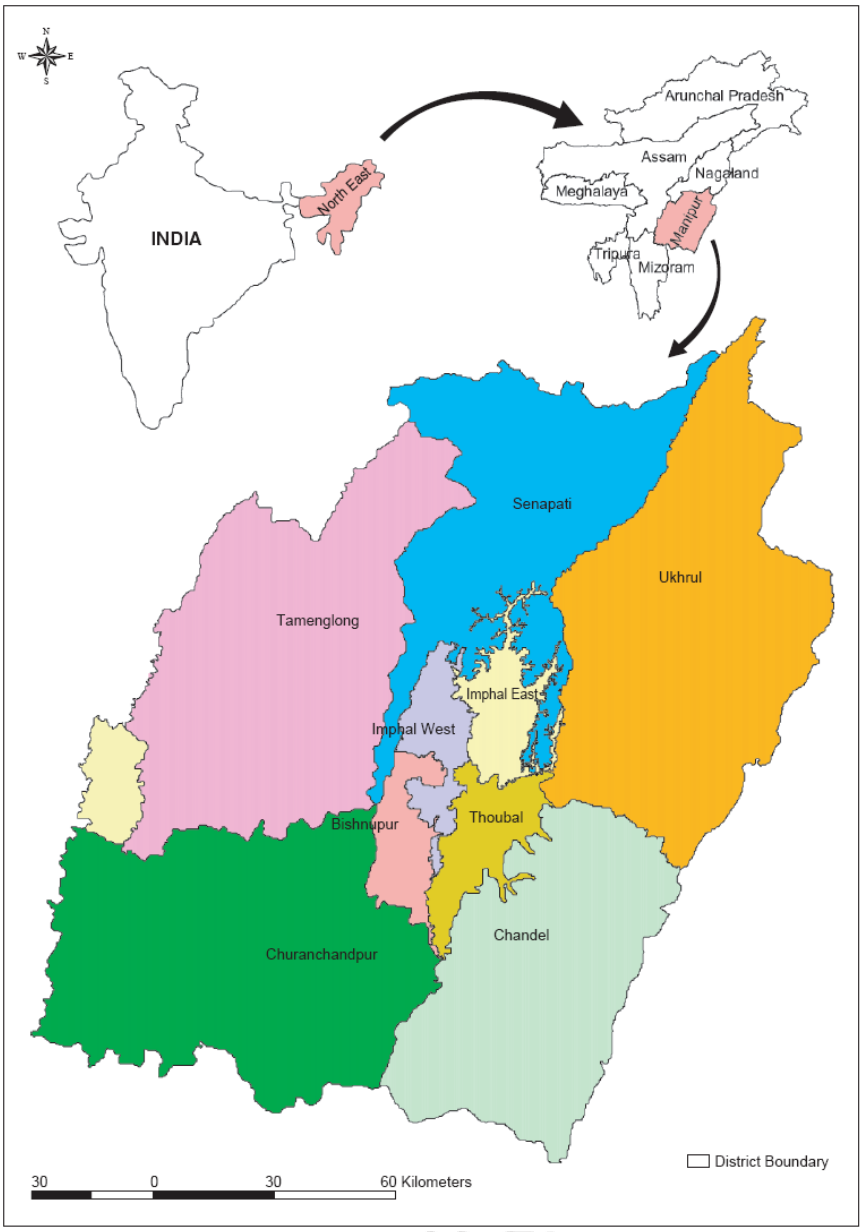

Fig. 2.1a. Location map of Manipur (source: LDA)

2.2 PROBLEM OF PHUMDI AND OTHER AQUATIC WEEDS OF LOKTAK LAKE

Loktak Lake of Manipur is the largest fresh water lake of northeast India (Fig. 2.1a and 2.1b) and is popular due to the presence of the unique ecosystem called ‘phumdi’- a Manipuri word for the floating vegetation mass formed by the proliferation of the weeds,

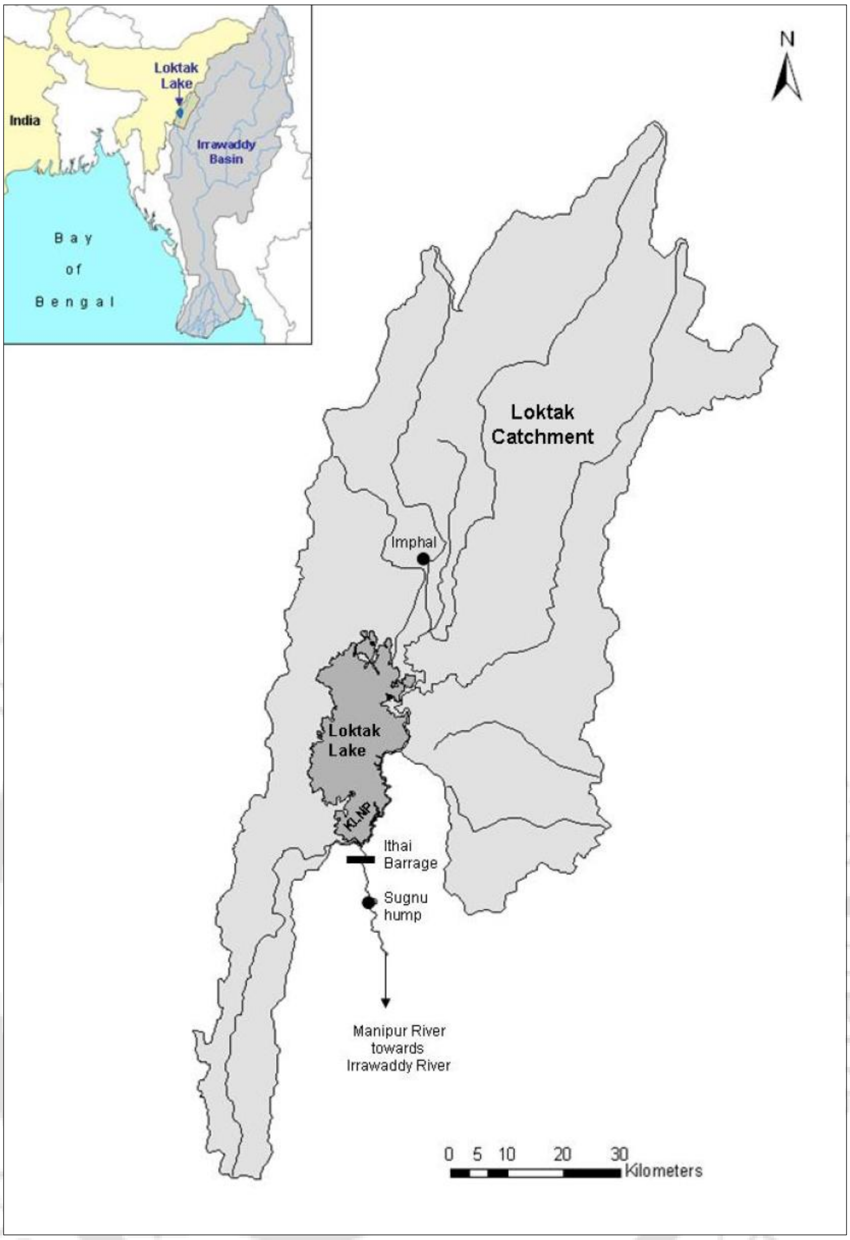

Fig. 2.1b. Location of Loktak Lake in Manipur, northeast India (Source: LDA)

vegetation and organic debris at various stages of decomposition and occurring in different size and thickness (Singh and Shyamananda, 1994; Trisal and Manihar, 2004). The core of a phumdi is composed of detritus material, which is black in colour and is highly spongy. The high proportion of vegetative matter gives the phumdi the specific gravity and buoyancy to keep it afloat on the lake with one-fifth of their thickness above and four-fifth below the water surface (Fig. 2.2a). The formation of phumdi is initiated when a small mass of un-decomposed organic matter (OM) or dense growth of aquatic weeds accumulates some suspended silt which is gradually colonized by grasses and other herbaceous plants (Singh and Khundrakpam, 2009).

Fig. 2.2a. Formation of phumdi

Fig. 2.2b. Phumdi obstructing waterways

Loktak Lake is listed as a wetland of international significance under the Ramsar Convention (Declaration no. 463 dated June 16, 1993). It was also included in the list of priority wetlands identified by Government of India for intensive conservation and management purposes (MoEF, 2000; Trisal and Manihar, 2004). Therefore, the management of the lake through proper planning is an obligation of the international treaty (DEC, 2012). Wetlands are vital for human survival. They are among the world's most productive environments; cradles of biological diversity that provide the water and productivity upon which countless species of plants and animals depend for survival. They act as nature's kidneys to purify water and regulate the micro-climate (Barbier et al., 1997; Anon, 1998). The phumdis play an important role in the ecological processes and functions of the lake (Trisal and Manihar, 2002). The floating biomass influence hydrological regimes, harbor several plant species of economic and ecological importance, support rich biodiversity and provide productive fisheries. Conservation of northern zone phumdis, which act as a biological sink to the pollutants brought in by the rivers from the urbanized areas, is extremely important for maintenance of water quality of the lake. Similarly, maintenance of thickness and overall health of phumdis in Keibul Lamjao National Park is crucial for the survival of the highly endangered ungulate species, *Cervus eldi eldi*, locally called Sangai deer and other wildlife fauna (Prasad and Chhabra, 2001; Dey, 2002; Trisal and Manihar, 2004; Angom, 2005).

The change in the hydrological regime of the lake caused by the commissioning of Ithai barrage across the lake's outlet in 1983 has led to profuse proliferation of phumdis due to the induced more or less constant water level. Traditionally, the local people managed the spread of phumdis through regular burning, cutting them into small pieces and flushing through the outlet channels down the Manipur River (LDA and WISA, 2008). The rapid spread of traditional aquaculture using enclosures of strips of phumdi in circular fashion has also contributed to phumdi proliferation. The process involves fragmentation of phumdi masses which ultimately spread in all parts of the lake. Fast growing aquatic plant species are introduced within the aquaculture enclosures to attract fish. These plant species are subsequently thrown out into open spaces, providing a means for further proliferation. Overall area of phumdis in the lake increased from 116.4 sq km in 1989 to 134.6 sq km in 2002. The situation improved from 2009 due to the removal intervention of aquaculture carried out by the local authorities in the central zone of the lake (Meitei et al., 2010). Phumdis, if not properly managed, pose a great threat to the lake ecosystem. Rapid proliferation of phumdis can choke the entire lake area and retard flow of water and natural aeration; accelerate process of eutrophication; make water unfit for various uses; promote water logging; and reduce water holding capacity by accelerating sedimentation. This leads to decline in fish production, loss of open water area, disturbances in navigation, etc. (Fig. 2.2b) (Santosh and Bidan, 2002; Meitei et al., 2010).

138 species of plants representing 88 genera are reported in the phumdis and in the clear water zones of the lake (Devi et al., 2002; LDA and WISA, 2002). The spread of water hyacinth is controlled through biological measures using weevil species. However, another invasive species, *Salvinia natans*, taking the advantage of the absence of competition and availability of free space has profusely grown in the lake and is a major threat to the natural vegetation (Trisal and Manihar, 2004). The floating water-moss

Salvinia natans is a dominant colonising aquatic fern species, which prevails over the aquatic ecosystem by its rapid growth and displacement of native plants that provide food and habitat for the native animals and waterfowl (Galka and Szmeja, 2012). The growth and spread of *Salvinia natans* may be enormous to the extent of 45% per day in nutrient rich water bodies (Blackman, 1960). The high viability of spores associated with rapid vegetative propagation is responsible for the spread of the weed producing vast thick mats and with the impending global warming, the weed will create havoc to water bodies at the expense of submerged exotic plants in many parts of the world (Netten et al., 2010).

2.3 CONTROL OF WEEDS THROUGH PHYSICAL REMOVAL

In spite of developments in the field of herbicidal or biological control of aquatic weeds, physical removal of the weeds either manually or mechanically is most widely practiced (Murphy, 1988). The following are the major advantages of weed harvesting (Haller, 2014):

- The water can be used immediately following removal. The plants removed during harvesting do not decompose in water as in the case of herbicide application. Other than the short term effect on water quality due to increase in turbidity, the oxygen content of the water is generally not affected by harvesting.
- The habitat remains intact because most harvesters do not remove submerged plants all the way to the lake bottom. Mechanical harvesting is site specific because plants are removed only where the harvester operates.
- Mechanical harvesting, despite few environmental concerns, is generally perceived to be environmental friendly.

An integrated approach, therefore, needs to be adopted for management of phumdis to control its proliferation and utilize it as a resource for economic development. Mechanical removal of phumdi on a large scale was initiated in 2010 along strategic locations in the lake shorelines. The controlled harvesting of biomass will also remove the inorganic nutrients entering the lake, which are assimilated by the aquatic plants (Devi et al., 2002). Keeping aside an area of 200 sq. km meant for reserved parks, biological sinks, regrowth, etc. in the northern and southern zones of the lake, plant materials from another about 100 sq. km mainly in the central zone will be available for annual harvest. Studies carried out by the Loktak Development Authority on experimental plots in the open water area indicated annual growth in phumdi coverage by more than 80% (Trisal and Manihar, 2004). Studies carried out for water hyacinth (Srivastava et al., 1984) indicated an annual biomass productivity of about 20 tonnes dry mass/ha (200 tonnes wet mass). Approximately, the annual biomass production of Loktak Lake is estimated to be about 2 million tonnes per annum on wet basis which is available for harvesting.

2.4 UTILISATION OF HARVESTED WEEDS

The final disposal of harvested weeds is still an unresolved problem everywhere (Gupta et al., 2007). Utilization of harvested biomass is thought by many to be a means of offsetting the relatively high costs and energy requirements associated with mechanical harvesting. No cost effective uses of harvested vegetation have been developed, despite much research examining the utility of harvested plant material as a biofuel, cattle feed, soil amendment, mulch or even as a papermaking substrate (Kalita et al., 2006; Haller, 2014). The total solids (TS), volatile solids (VS) and ash contents of phumdi and other aquatic plants range from 73–94%, 75–93% and 6–24%, respectively (Devi et al., 2002). The high OM content indicates significant scope for bio-processing of harvested phumdi and *Salvinia natans* biomass for the effective control of their proliferation in the Loktak Lake.

2.5 COMPOSTING

2.5.1 HISTORY OF COMPOSTING

"Biological decomposition is as ancient as the existence of OM on earth. With the division of the first cell and germination of the first seed, amino acids making up proteins and glucose links in cellulose chains initiated the first step towards chemical and biological breakdown, returning to the earth nutrients and energy for other life forms. This natural process of cleansing the surface of the earth enabled life, as we know it to exist today. It was the first step towards composting (Naylor, 1996)". Long back, composting was just something that happened in swamps, forests and meadows. The Romans, the Greeks and tribes of Israel knew about compost (Martin and Gershuny, 1992). There are also references of composting in the Medieval Church texts and Renaissance literature (Rynk, 1992).

Sir Albert Howard, a British government agronomist who came to British India in 1905, experimented with different ways to make compost during his 29 years stay in the country. While stationed at the Indore Institute of Plant Industry, he developed the

Indore Method where the waste and night soil were laid in alternate layers and turned at regular 4 to 5 days interval with intermittent watering to ensure optimum aerobic and moisture conditions. The recommendation by Sir Howard of carbon-to-nitrogen ratio (C/N) 33 for effective composting speaks volumes of his work (Howard, 1943; Brunt, 1949). The Indore method was a significant step towards modern era composting as it presented a recipe of the substrates, which gave better results than individual substrates, thus recognizing the importance of feed conditioning. Secondly, it also recognized the importance of the systematic and organized procedures to the overall success of the operation (Haug, 1993). In 1939, the Indian Council of Agricultural Research at Bangalore made some modification in the Indore Process such as frequent turning, heap protection, etc.

Golueke and his associates at the University of California at Berkeley demonstrated the effects of temperature, moisture content (MC), aeration by turning or other means, the C/N of the composting materials, the use of special biological inocula, and the impact of reducing the size of the composting material during the aerobic composting of mixed municipal refuse, food residues, and other biodegradable matter, both with and without the addition of biosolids (Golueke and Gotass, 1954; Golueke et al., 1954; McGauhey and Gotaas, 1955). Their findings are highly significant in the history modern day composting (Diaz and de Bertoldi, 2007).

An in-vessel composting system first developed in Denmark popularly known as the Dano Process used a large, slowly rotating drum with baffles incorporated inside it that carried the material forward during the digestion. Dano Process was mainly concerned with the segregation and size reduction of the waste and the outputs of the process were composted by any of the techniques that were available at that time. The Dano Corporation later developed a mechanical silo-type digester known as the Bio-stabilizer (Golueke, 1992). The materials are fed to the stabilizer and maintained in thermophilic conditions for most of the time. The outputs are passed through a 1 mm mesh screen and further composted using windrows system if necessary. In Netherlands, Mr. T. van Maanen started a company known as Vuilafvoer Maatschappij (VAM) to compost city refuse. The long and high refuse piles were sprinkled periodically with recirculated leachate (Diaz et al., 2007).

The trends and developments that will have a favourable fortune for composting are: drastic diminution of the economic imbalance between composting and its competitive options, compulsory source segregation of waste, and growing importance of yard and food waste disposal (Golueke and Diaz, 1996).

2.5.2. COMPOSTING PROCESS

Composting (Latin *compositum* meaning mixture) is the biodegradation process of a mixture of substrates by a microbial community of various populations in aerobic conditions and in the solid state (Fig. 2.5a). Biodegradation is the breakdown of a molecular structure into its elemental components, or segmentation of complex compounds into simpler compounds or even atoms. The segmentation often incorporates other atoms to form new compounds (Insam and de Bertoldi, 2007). Composting is an exothermic process that involves the accelerated degradation of OM by microorganisms under controlled conditions, in which the organic material undergoes a characteristic thermophilic stage preceded and followed by two mesophilic phases (Lung et al., 2001; Insam and de Bertoldi, 2007). During the process, the organic components undergo several important transformations producing metabolites which exhibit inhibiting or stimulating effects on plant growth before maturing into stable beneficial compost (Wong et al., 2001; Bhattia et al., 2013).

There are three phases in composting (i) starting mesophilic phase (25–40ºC) which is a period for adaptation of the microbes; (ii) an active thermophilic stage (35–65ºC), where decomposition takes place more intensively; (iii) a cooling mesophilic stage which is marked by the decrease of the temperature to the mesophilic range and where the remaining organic compounds are degraded at a slower rate; and (iv) maturation stage which is marked by increase in lignin-humus complexes. The duration of the active phase depends on the characteristics of the waste (amount of easily decomposable substances) and on the management of the controlling parameters (aeration and watering). The extent of the maturation phase is also variable and it is normally marked by the disappearance of the phytotoxic compounds. Approximately 50% of added OM becomes fully mineralized, mostly due to the degradation of easily degradable compounds such as proteins, cellulose and hemi-cellulose, which are utilized by microorganisms as carbon and nitrogen sources. The residual OM contains newly formed macromolecules along with non-degradable OM jointly forming humic-like substances, the most stable fraction of mature compost (Chefez et al., 1996).

The composting process leads to the final production of CO_2, water, minerals, and stabilized OM (compost). The process starts with the oxidation of easily degradable OM; this first phase is called decomposition. The second phase, stabilization, includes not only the mineralization of slowly degradable molecules, but also includes more complex processes such as the humification of ligno-cellulosic compounds (Toumela et al., 2000).

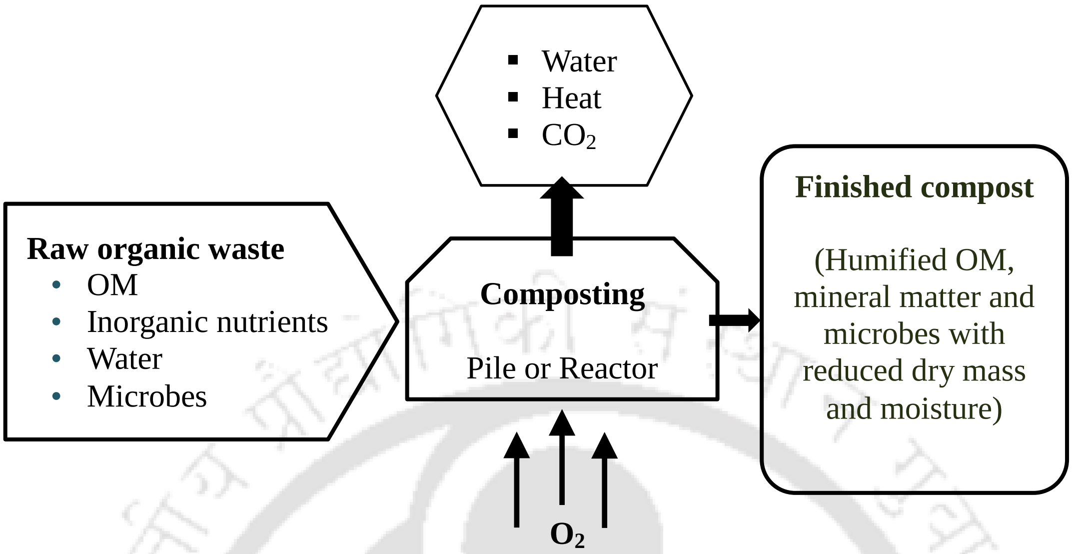

Fig. 2.5a. Representation of the composting process

2.5.3 COMPOSTING TECHNIQUES

Farmers in many parts of the world still find themselves at a disadvantage by not making the best use of organic recycling opportunities available to them due to various constraints which among others include absence of efficient expeditious technology, long time span, intense labor, land and investment requirements and economic aspects. Traditional methods adopted an approach of anaerobic or aerobic decomposition based on passive aeration through measures like little and infrequent turnings or through static aeration provisions like perforated poles/pipes or rapid composting methods like shredding, adjustment of C/N, etc.

2.5.3.1 Indore Method

All organic material wastes are collected and stocked in a pile. Hard woody material are first spread on the road and crushed under vehicles such as tractor or bullock carts and mixed with the other organic materials before being piled. These hard materials should not exceed 10% of the total plant residues. Green materials, which are soft and succulent, are allowed to wilt for two to three days to remove excess moisture before stacking. While stacking, each type of material is spread in layers about 15 cm thick until the heap is about one and a half meters high. The heap is then cut into vertical slices and about 20–25 kg each are placed overnight under the feet of the cattle as bedding. The next morning the beddings along with the cattle dung and urine earth are taken to the composting site. Pits or heaps were employed depending on the availability of water. A pit about 1m deep, 1.5–2 m wide and of suitable length is evacuated. The site is so selected that it should be near to the cattle shed and the water source and high enough so that no rainwater gets in during monsoon season. The material brought from the cattle shed is spread evenly inside the pit in layers 10–15 cm thick. On each layer is spread slurry made with 4.5 kg cattle dung, 3.5 kg urine-earth and 4.5 kg inoculum taken from a 15 day old composting pit. Sufficient quantity of water is sprinkled over the material in the pit to wet it. Care should be taken to avoid compaction of the material. The material is turned three times during the whole period of composting, the first time 2 to 3 weeks after charging the pit; the second after 5 weeks (Howard, 1943).

2.5.3.2 Turned windrow

A windrow is constructed by stacking the feedstock in the form of elongated pile (Fig. 2.5b). Three key factors determine the dimensions of a windrow namely aeration requirements, efficient utilisation of land area and structural strength and size of the feedstock particles. Structural strength is a key factor in the maintenance of the interstitial integrity needed to ensure a sufficient oxygen supply. In regions where rain is frequent or heavy and the windrows are not sheltered, the cross sectional configuration should be conical in order to shed water. On the other hand, a flattened top is suitable where rainfall is not a problem. With such a configuration, the heat loss is less and windrow volume per unit pad area is greatest. Windrows can be aerated by turning, by forced aeration or by a combination of two. Turning of windrow piles is accomplished by tearing down and then reconstructing the windrow either at its original position or immediately adjacent to it. Tearing down and reconstructing the windrow expose the composting materials to the ambient air and replenishes the interstitial oxygen supply. Turning every third day is sufficient to meet the oxygen uptake in actively composting MSW. If pile is water logged or compacted, frequency of turning should be increased (Rynk, 1992; Huag, 1993; Diaz et al., 2007).

Adequate frequency of turning in composting ensures proper mixing of the waste and equal exposure of the surface of the materials constituting OM to air facilitating bioconversion by the microorganisms. It releases heat, water vapour and gases; and restores the gap eliminated by decomposition (Haug, 1993). Turning affects MC, dry matter, pH, total carbon, total nitrogen, C/N and temperature of composting piles (Wong et al., 2001; Ogunwande et al., 2008; Getahuna et al., 2012).

Fig. 2.5b. Arrangement of windrows (Rynk, 1992)

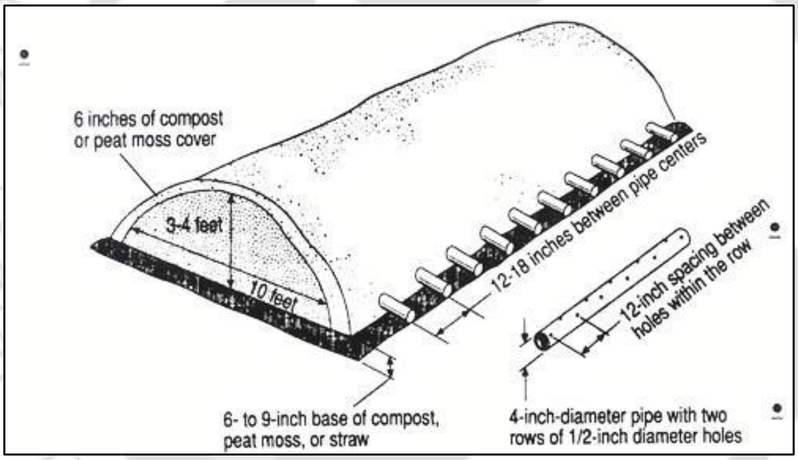

Fig. 2.5c. Passive aerated pile (Rynk, 1992)

2.5.3.3 Passive aeration windrow

Passively aerated windrow system eliminates the need for turning by facilitating air intake of the composting materials through perforated pipes embedded in each windrow (Fig. 2.5c). The pile is covered with a layer of finished compost or peat. Air flows through the pipes and to the windrows from the open ends, as a result of chimney effect created as the hot air rises upwards out of the windrow. The windrow should be built on top of a base of straw or finished compost to absorb moisture and insulate the windrow. Since the raw materials are not turn during the composting process, they must be thoroughly mixed before forming piles.

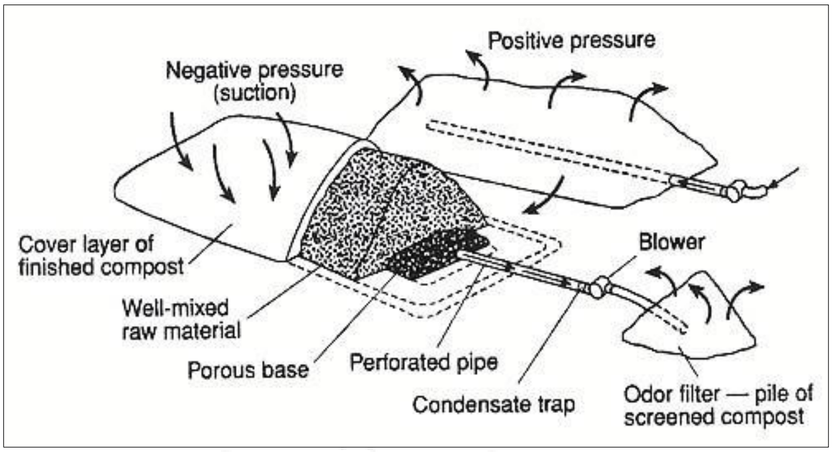

Fig. 2.5d. Positive and negative pressure piles (Rynk, 1992)

2.5.3.4 Forced aeration windrow

The construction of a windrow for forced aeration begins with the installation of a loop of perforated pipe on the compost pad. The perforations are evenly spaced in a long row slightly off centre at the top of the pipe. The pipe diameter is 12.2–12.7 cm. The loop is oriented longitudinally and is centered under what is to be the ridge of the windrow. After the pipe is placed, it is covered with a layer of bulking material or finished compost that extends over the area to be covered by windrows in order to serve as a means facilitating movement and uniform distribution of air (Fig. 2.5d). Additionally, the bed absorbs excess moisture and minimises seepage from the windrows. The completed windrow is entirely covered with a 30.5–47.7 cm layer of wood chips. An advance approach use aeration to maintain optimum temperatures (54.4–60°C). Electronic sensors such as thermocouples, thermistors provide a means to control airflow as well as monitor temperature. The direction of airflow through the windrow may or may not be reversed during the process. A common arrangement is to initially pull air through windrow (suction) and pass the discharged gaseous emissions through an emission-conditioning filter. The filter may consist of fully composted material, organically rich soil or other materials.

2.5.3.5 In-vessel systems

In-vessel composting systems enclose the feedstock in a chamber or vessel that provides adequate mixing, aeration and moisture, providing the perfect environmental conditions for the process. Obviously, this excellent control in composting is quite more expensive procedure than the first two ones. Reactors in in-vessel systems have one of the following configurations: vertical silo, horizontal silo, horizontal drum and horizontally oriented open tanks. They are appropriate for small institutions including schools, nursing homes, hospitals and commercial establishments (Bonhotal et al., 2011).

Vertical composting reactors are cylindrical containers or tanks of varying sizes made of steel or concrete mostly thermally insulated. Organic material is typically fed into the reactor at the top through a distribution mechanism, and flows by gravity to an unloading mechanism at the bottom. Process control is usually by pressure-induced aeration through aeration pipes, where the airflow is opposite to the downward materials flow (Fig. 2.5e). The material is removed from the bottom through a screw conveyor. The gas removed from the reactor is transported to a treatment system (Diaz et al., 2007). The latest version uses three completely enclosed vessels. One of the vessels serves as storage container for the carbonaceous materials intended for use as bulking agents or for correcting C/N. The composting process takes place in the second and third vessels i.e. the bioreactor and the curing reactor, respectively. Air is fed continuously to the reactors to maintain aerobic conditions and to remove moisture due to evaporative cooling. The retention period of the bioreactor is 14 days whereas the retention period of the cure reactor is 20 days. In cold climate, a pre-heater is incorporated to warm the air before introduction to the waste.

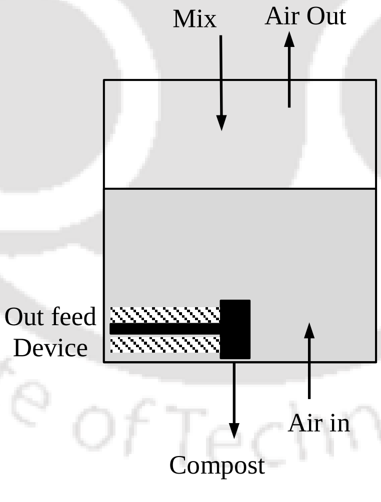

Fig. 2.5e. Schematic diagram of in-vessel vertical reactor (Diaz et al., 2007)

The rotating horizontal drum is a long slightly inclined drum, 2.7 m in diameter rotating at 2 rpm with retention time of 1–6 days depending on the composting material (Fig. 2.5f). The partially composted material is windrowed for periods ranging from 1–3 months to produce a matured product (Rynk, 1992). A recent technique in decentralized composting is the rotary drum composter, which provides agitation, aeration and mixing of the compost, to produce a consistent and homogeneous end product without any odor or leachate related problems (Kalamdhad et al., 2009). Warm and moist environments with the ample amount of oxygen and organic material available within the rotary drum, allow aerobic microbes to flourish and decompose the waste more rapidly; resulting the composting times significantly reduced to 2–3 weeks. The Rotary Drum Composter has been used to compost diverse organic wastes such as cattle manure, swine manure, municipal biosolids, brewery sludge, chicken litter, animal mortalities, olive mill waste, food residuals and even water hyacinths (Kalamdhad et al., 2009; Fernandez et al., 2010; Villasenor et al., 2011; Rodriguez et al., 2012; Singh and Kalamdhad, 2013 a, b).

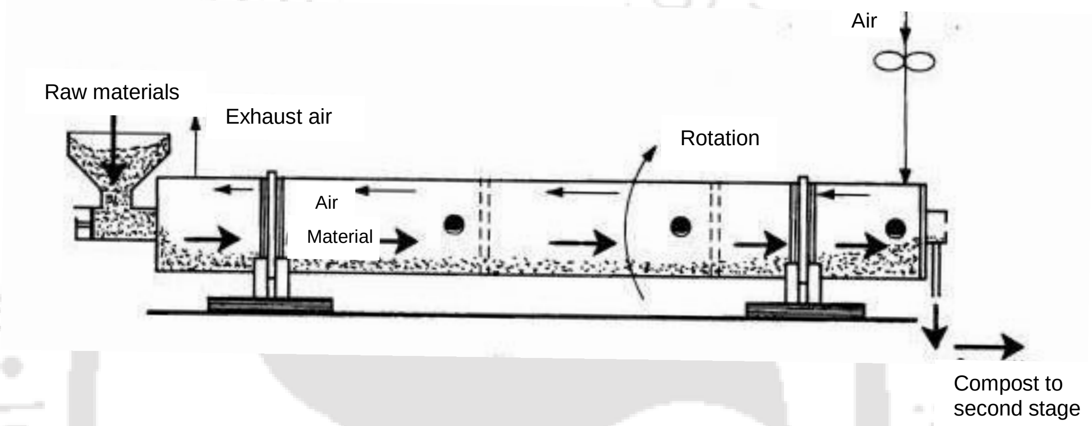

Fig. 2.5f. Rotary drum composter (Rynk, 1992)

2.5.4 FACTORS AFFECTING COMPOSTING PROCESS

2.5.4.1 Nutrients

Carbon (C), nitrogen (N), phosphorous (P) and potassium (K) are the primary nutrients required by the microorganisms involved in composting. Living organisms bring about the decomposition of OM by utilising the C as the source of energy and the N for building cell structure. An appropriate C/N usually ensures that the required nutrients are present in adequate amounts. Raw materials blended to provide a C/N of 25–35 are ideal for active composting, although initial C/N from 20–40 consistently gives good composting results (Gotaas, 1956; Rynk, 1992). With low C/N, ammonia is formed which, under favourable conditions, can be further oxidized to nitrite and nitrate. The average C/N in many bacteria is about 9–10. During active aerobic growth, living organisms use about 30 parts of C for each part of N. About 20 parts of C are oxidized to CO_2 and 10 parts are utilized to synthesize protoplasm. Hence, an initial C/N of 30 or less would seem most favourable for rapid composting (Golueke, 1977; Diaz and

Savage, 2007). If the C is in excess the microorganism die after using up the available N and their body nitrogen is used by other microorganisms to form new cell materials. More time is therefore required for the process. When the energy source C is less than that required for converting available N into protein, organisms make full use of the available C and get rid of the excess N as ammonia (Rynk, 1992). Kimberly et al. (1998) studied the influence of carbon-to-phosphorous ratio (C/P) on the biological degradation of municipal solid waste and observed that P is also an essential element in the composting of municipal solid waste. It was concluded that for optimal composting, a C/P between 120 and 240 is necessary when the C/N is 30. In a study on stability evaluation of compost during drum composting of vegetable waste with C/N 16, 22, 30 and 38, C/N 22 was able to produce stable compost with higher degradation of VS (Kalamdhad et al., 2008).

Even though nutrients may be present in sufficiently large concentrations in a substrate, they are unavailable to the microbes unless they are in a form that can be assimilated by the microbes. An important point to remember is that availability is a function of the enzymatic makeup of the individual microbe or the nature of organic molecules. Some organic molecules are very resistant, i.e. refractory to microbial attack, even to microbes that possess the required enzymatic complex. The consequence is that such materials are broken down slowly, even with all other environmental conditions maintained at an optimum level (Diaz and Savage, 2007).

2.5.4.2 Temperature

The exothermic bio-oxidative microbial degradation process of mixed OM produces a relatively large quantity of energy as heat, increasing the temperature in the mass even to the order of 70–90ºC. High temperatures inhibit microbial growth, slowing the biodegradation of OM. For high rate biodegradation and maximum microbial diversity, the temperature must range from 30–45ºC (de Bertoldi et al., 1983; Stentiford, 1993). Although the mesophilic temperature range allows effective composting, many authors suggest maintaining temperatures between 50 to 70ºC. Mc Gregor et al. (1981) found maximum decomposition of waste occurred at the range of 52–60ºC. Bhoyar and Bhide (1982) observed that maximum cellulose degradation and cellulase activity in MSW composting occurred in the temperature range of 40–50ºC. This temperature range is the optimum range for thermophilic fungi and is also the optimum for lignin degradation in compost (Toumela et al., 2000). The degradation is slowed at temperature beyond the range 20–70ºC (Liang et al., 2003).

2.5.4.3 Hydrogen ion level (pH)

The optimum pH range for the growth of most bacteria and fungi are 6.0–7.5 and 5.5–8.0 respectively. If the waste material has undergone putrefaction before being received for composting, the pH will be low. When the initial pH is between 6.0 and 7.0, the pH of the composting material will usually drop a little during the first two or three days of aerobic composting, due to degradation of simpler readily available carbohydrates (water soluble forms) at first thereby releasing hydrogen ions (Cheremisinoff, 1994). The benefit derived in addition of alkaline material for aerobic decomposition is out weighted by the loss of valuable N as ammonia gas due to high pH (Gotaas et al, 1953; Diaz and Savage, 2007). Composting being a batch-process operation, minor changes in the pH must be expected. After two to four days the pH usually begins to rise and will level off at between 8.0 and 9.0 towards the end of the process. This is attributed to the formation of ammonia during ammonification and also due to mineralization of organic N during microbial activity (Huang et al., 2004). Sundberg et al. (2004) observed low pH as an inhibiting factor during transition from mesophilic to thermophilic phase in composting of food waste. The mesophiles were inhibited by the high temperature whereas the thermophiles were inhibited by the low pH and organic acids. CO_2 released can escape as a gas or dissolve in the liquid, forming carbonic acid, bicarbonates and carbonates. This system has two dissociation constants (pKa), 6.35 and 10.33 at 25ºC, and thus it tends to neutralise the pH of the compost, increasing low pH and reducing high pH. During the initial phase of composting, most of the metabolised nitrogen is retained by growing microorganisms, but during the high rate phase ammonia is released. The ammonia system has a pKa of 9.24 at 25ºC and thus increases the pH towards this value (Sundberg, 2005).

2.5.4.4 Aeration and moisture content (MC)

Aerobic composting consumes large amount of oxygen, particularly during the initial stages. A minimum oxygen concentration of 5% within the pore spaces of the compost is necessary for aerobic composting (Pace, 1995). If the supply of oxygen is limited, the composting process may turn anaerobic, which is an odorous process. Interruption of oxygen supply may also lead to shunt metabolism. Highest organic degradation and temperature rise during composting of agricultural organic waste were obtained at the aeration rate of 0.4 L/min/Kg (Kulchu and Yaldiz, 2004). Guo et al. (2012) recommended 0.48 L/kg dry mass/min aeration rate during co-composting of pig feces and corn stalk having C/N 18 and MC 65–75%. Oxygen levels within the windrows or piles may be replenished by turning the materials over with a front-end loader, or by means of mechanical agitation with a special compost turner or through forced aeration. Frequency of aeration or turning and amount of aeration or total number of turns are governed primarily by MC and type of material. Moisture is important as it reduces the pore space available for air transport. Materials with a high C/N or containing large amounts of ash and other inert material may not have to be aerated as often as material which decomposes more actively and rapidly.

Moisture is necessary to support the metabolic processes of the microbes and MC can regulate the physical and biological reactions during composting process. MC will more likely affect degradation of soluble organics and hydrolysis of fibrous substrates, both having crucial impacts on the composting process (Wang et al., 2015). Composting process becomes inhibited when the MC is below 40%. Water displaces much of the air in the pore spaces of the composting materials when the MC is above 65%. This limits air movement and leads to anaerobic conditions (Pace, 1995). Examine by traditional physics, the MC at 50–55% was suitable for satisfying the degree of free air space (60–70%) of compost (Jolanum, 2005). Maximum MC for satisfactory aerobic composting varies with materials used. If it contains considerable amount of straw and strong fibrous material, the maximum MC can be much larger. But, if it contains considerable quantities of paper and garbage (low structural strengths when wet) or if it is granular like ash and soil, less water is better. In University of California studies, fibrous materials containing a considerable amount of straw were composted aerobically with MCs of 85–90%, but in other piles containing more papers, the process became anaerobic in one day when the MC was about 70% (Gotaas, 1956). Even for the same composting substrate, optimal moisture level may be affected by particle size, density, or structure of waste (Hamelers, 2001).

2.5.4.5 Particle Size and Shredding

The rate of aerobic decomposition increases with smaller particle size through exposing a greater surface area for microbial attack and destroying the natural resistance of vegetation in the process. In larger matter, sufficient oxygen is not available at the center of such objects to permit aerobic condition. Very small particles, however, may reduce the effectiveness of oxygen movement within the pile or windrow. Optimum composting conditions are usually obtained with particle sizes ranging from 1/8 to 2 inches average diameter (Farrell-Poe and Koenig, 1997). However, in the study by Lhadi et al. (2006) degradation was accelerated during co-composting of municipal solid waste and poultry manure with size 0.2 cm. The suitable size for composting of rigid or not easily compacted material such as fibrous waste, twigs and corn cover ranges from 13 mm to about 50 mm whereas for the greater part of green mash such as vegetable waste and fruits, the size should not be less than 50 mm (Diaz et al., 2002). Shredded materials are more homogenous, produce beneficial initial aeration, and provide a structure, which makes them more responsive to moisture control and aeration thereby, increasing the workability. Shredded refuse heats more uniformly, withstands excessive drying at the surface of the pile, is insulated against heat loss, and resists moisture penetration from rain better than unshredded refuse. Whether grinding or shredding should be practiced or not depends upon the nature of the raw material, the desired features of the final product, such as the appearance, size, quality and the economic requirements of the operation. When air permeability is guaranteed, the smaller the particle size the better is the composting efficiency (Ge et al., 2015).

2.5.5 MATERIAL AMENDMENTS

With a view to improve the quality of compost in terms of stabilized organic content and nutrient value and further to reduce the period of degradation, different studies are being carried out for proper amendments of the waste before composting. A bulking agent is the material that provides the optimum free air space and regulates the water contents of the waste to be composted. Bulking agents are commonly fibrous with carbonaceous material with low MCs to provide optimal free air space and adjust the C/N for optimal composting process (Adhikari et al., 2009; Iqbal et al., 2010). Sawdust, rice husk, rice straw, wheat straw, rice bran, etc. are used as bulking agents. Co-composting involves mixing one or more types of materials in order to improve the characteristics of the main residue and facilitate its stabilization. This strategy is being evaluated to improve the composting of waste that is difficult to degrade; one can add waste to decrease the C/N (Rashad et al., 2010; Liu et al., 2011) or straw to increase the C/N of animal waste (Qian et al., 2014). Cattle manure presents good composting performance (including a high degradation rate of OM) as well as a high nutrient concentration in the system, characteristics that are both environmentally and economically favorable (Orrico Junior et al., 2012; de Mendoca Costa et al., 2015). Co-composting of water hyacinth, sawdust and cattle manure was found very effective with the right proportions of the substrates (Singh and Kalamdhad, 2013a, b). Cattle manure is also considered an important and popular bulking agent used in composting and vermicomposting process of industrial waste, sludge, food waste, water hyacinth, etc. as it can control moisture, bulk density, C/N and pH (Gajalakshmi et al., 2001a; Pramanik, 2010; Sarkar et al., 2010).

2.6 VERMICOMPOSTING

2.6.1 HISTORY OF VERMICOMPOSTING

Darwin (1881) first drew attention to the great importance of earthworms in the decomposition of dead plants and the release of nutrients from them. However, it is only about two decades that the scientific community had started to take it seriously as a field of scientific knowledge or even a real technology (Mohee and Sobhany, 2014). The first vermicomposting experiment on a scientific basis on record was carried out in Holland in 1970 and thereafter in England and Canada (Sinha et al., 2002). The American Earthworm Company started a vermicomposting farm in 1978 producing about 5000 tons of vermicompost per month (Edwards, 2004). In early 1980, field scale vermicomposting methods were developed for disposing off poultry, pig and cattle waste at UK involving biologists, agricultural engineers and even economists (Edwards and Neuhauser, 1988). The University of Agricultural Sciences, Bangalore propagated vermicomposting to farmers in 1984 (Sharma, 2003). Several institutions, private companies, NGOs, etc. have now started promoting vermicomposting by setting up vermiculture units in different parts of India.

2.6.2 VERMICOMPOSTING PROCESS

Vermicomposting is a bio-oxidative process where the associated microorganisms, both in the gut of the earthworms and in the feedstock, are responsible for the bio-chemical degradation of the OM while the earthworms fragment the substrate thereby increasing the surface area exposed to the microorganisms. Hence, the role of the earthworms is to directly or indirectly modify the physical and chemical properties of the substrates (Fornes et al., 2012; Fernández-Gómez et al., 2015) and assist in aerating, conditioning, and fragmenting the substrate. Earthworms act as mechanical blenders and by comminuting the OM, they gradually reduce the C/N of the substrate and increase the surface area exposed to microorganisms (Domínguez et al., 1997).

Vermicomposting has three phases (i) an assimilation phase of the earthworms similar to the lag phase of composting; (ii) an active phase where the earthworms process the waste modifying its physical state and microbial composition; and (ii) an analogous maturation phase marked by the displacement of the earthworms towards fresher layers of undigested waste, where the microbes take over in the decomposition of the waste (Lores et al., 2006). The duration of the analogous active phase is not fixed, and depends on the species and density of earthworms, the main drivers of the process, and their ability to ingest the waste (ingestion rate). Apart from production of nutrient rich vermicompost, vermicomposting has also proved to be more efficient in removing pathogens as they are eliminated on entering the gut of earthworms (Canche et al., 2010). The earthworm gut is like a miniature composting tube that mixes and conditions the substrates. Moisture, temperature, pH, enzymes and microbial populations are maintained for a synergistic relationship resulting in the by-product vermicast that is rich in microbial activity, plant growth regulators and pest repellents (Indira and Lakhsmi, 2007).

Epigeic species of earthworms, with their natural ability to colonize organic wastes; high rates of consumption, digestion, and assimilation of OM; tolerance to a wide range of environmental factors; short life cycles; high reproductive rates; and endurance and tolerance of handling, show good potential for vermicomposting. Few earthworm species display all these characteristics, and in fact only five have been used extensively in vermicomposting: *Eisenia andrei* (Bouché), *Eisenia fetida* (Savigny), *Dendrobaena veneta* (Savigny), and, to a lesser extent, *Perionyx excavatus* (Perrier) and *Eudrilus eugeniae* (Kinberg) (Edwards, 2004). Several epigeic earthworms, e.g. *E. fetida*, *P. excavatus*, *Perionyx sansibaricus*, *E. eugeniae* and *E. andrei* have been identified as detritus feeders and can be used potentially to minimize the anthropogenic wastes from different sources (Suthar, 2008; Gupta and Garg, 2008). But *E. fetida* was, and still remains, the favoured earthworm species for laboratory trial experiments on vermicomposting due to its wide tolerance of environmental variables (pH, MC, temperature) (Mohee and Sobhany, 2014).

2.6.3 VERMICOMPOSTING TECHNIQUES

2.6.3.1 Windrow systems

Windrow vermicomposting is a traditional method for large scale vermicomposting operation and the cheapest option as minimal amount of capital expenditure is required.

In this method, organic materials are placed on the ground up to 50 cm in depth in long rows and worms are introduced to the material. Windrow vermicomposting systems are relatively inefficient and generally result in inferior vermicompost products because nutrients are lost through volatization and leaching (Edwards, 2004). Other drawbacks of windrow vermicomposting systems include: the requirement of large areas of land; they are labour intensive for feeding and harvesting (biomass and castings); they process organics relatively slowly; and they are usually exposed to a broad range of environmental conditions.

2.6.3.2 Continuous flow system

Continuous flow vermicomposting system was first developed and tested in 1981 at the Rothamstead Experimental Research Station, Silsoe, UK (Edwards, 2004). The vermicomposting container is raised on legs above the ground. The bottom of the container is a mesh floor and a beaker bar loosens the bottom layer of castings so that they can fall through for collection. This enables top feeding of feedstock. Continuous flow reactor, if managed effectively, can fully process 900 mm deep layers of suitable organics in less than 30 days (i.e. approximately 30 mm per day loading rate).

2.6.3.3 Tray or stacking system

A tray system involves stacking several trays (usually up to three 150 mm deep) on top of one another. Feedstock are applied to the bottom most tray and when the tray is full of vermicompost the next tray is added on top and feedstock are applied to encourage the worms to move out of the bottom tray and consume the fresh feed. When the next tray is full of vermicompost a third tray is added and the first tray should be relatively free of worms enabling the harvesting of castings. This tray is then emptied and ready to be placed on top again.

2.6.3.4 Batching system

Batching system or box system is a relatively popular and simple small scale vermicomposting unit. Batching system has been experimented with on all scales, but many of the disadvantages associated with the tray systems are also applicable for the batching system (ROU, 2007). As it requires labour intensive methods to harvest a by-product, tray and continuous flow systems are favoured. Batching systems are often applied in situations where there is very little start-up capital and by non-profit organizations such as schools and hospitals.

2.6.3.5 Wedge system

In a wedge system, the horizontal feeding method is used, where feed is applied to an ‘open face’ of the bedding, usually at 450º angle, in an even layer (Mitchell, 1997). It uses a wall to start a system and then move outwards, harvesting castings from behind. However, Mitchell (1997) found the horizontal method of feeding to be less successful than the vertical or furrow methods used in other system. Even though a spare wall may be allocated to use this method for on-site vermicomposting, the waste treatment process is not contained and would utilize too much space.

2.6.3.6 Commercial model

The commercial model for vermicomposting developed by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Andhra Pradesh, India consists of four chambers enclosed by walls (1.5 m width, 4.5 m length and 0.9 m height) (Fig. 2.6) (Nagavallemma et al., 2004). The walls can made up of locally available materials such as bricks, stones, asbestos sheets, etc. The partition walls are provided with small holes to facilitate easy movement of earthworms from one chamber to another. The excess water is collected at the outlet provided for each chamber, which is reused. The four components of the tank are filled with plant residues layer by layer along with cattle manure and then the earthworms are released. Once the contents in the first chamber are processed the earthworms move to chamber 2, which is already filled with substrates and ready for earthworms. This facilitates harvesting of decomposed material from the first chamber and also saves labour for harvesting and introducing earthworms.

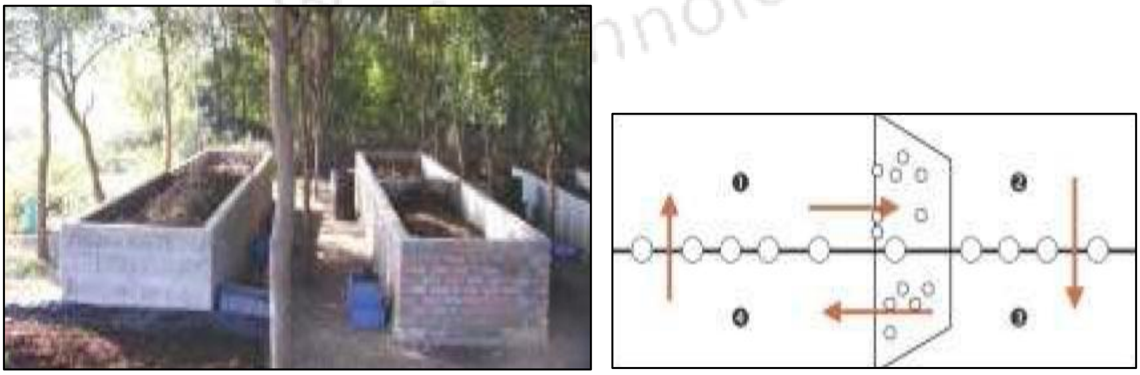

Fig. 2.6. Commercial model vermireactor (ICRISAT)

2.6.4 FACTORS AFFECTING VERMICOMPOSTING

The temperature, pH and C/N of the substrate are important factors influencing the growth and survival of earthworms (Qiao et al., 2003; Hou et al., 2004). Different authors suggest different temperature tolerance levels for different species of worms regarding laying of cocoon, hatching and growth. Temperature range of 15–20°C was found to be optimum for *Eisenia fetida* growth (Dominguez and Edwards, 2004). The optimum MC range is 75–90%, but could vary for substrate to substrate (Gunadi et al., 2003). Earthworms absorb water and breathe through their skin and are therefore sensitive to pH of the substrate. The appropriate range of pH value for vermicomposting is 6.0–8.0. If the temperature and moisture values are optimal, the growth of earthworms is determined by the quality of substrate materials. Ndewa and Thompson (2000) found that earthworms can grow better when C/N of material is 25 while some other researchers reported suitable C/N 20 (Liu et al., 2000). These factors differ from species to species of the earthworms. The optimum temperature, MC and pH for *Eisenia fetida* were 25ºC, 70% and 6.5, respectively. However, the optimum temperature, MC and pH for growth and development of *L. mauritii* were 30ºC, 60% and 7.5, respectively (Tripathi and Bhardwaj, 2004). As the earthworms are also aerobic organisms, oxygen consumption during vermicomposting is a function of both microbial and earthworm activity. Oxygen levels are also related to substrate temperatures and MC. In a vermicomposting system excessive MC can cause poor aeration and may affect the oxygen supply to the worms (Yadav and Garg, 2011a). To enable better aeration during adverse condition of vermicomposting, either mechanical means of aeration or manual turning is employed (Ismail, 1997). Commercial worm farming literature recommended “tossing the beds” a process of loosening the bedding substrate for aeration without inverting the materials.

Earthworms modify microbial communities and nutrient dynamics during vermicomposting (Edwards and Bohlen, 1996). Population of earthworms (stocking density) in vermicomposting system affects various physiological processes, such as respiration rate, reproduction rate, feeding rate and burrowing activity. The optimal density of *E. andrei* worms for sexual development was found to be eight earthworms per 43.61 g dry matter of pig manure (Dominguez and Edwards, 1997). Effects of population density on physiological processes may differ between various earthworm species. Dominguez and Edwards (1997) and Uvarov and Scheu (2004) reported increased mortality and reduced cocoon production and growth rate at higher population densities. High population densities of earthworms in vermicomposting systems result in a rapid turnover of fresh OM into earthworm casts (Aira et al., 2002). Ndegwa et al. (2000) reported an optimal worm stocking density of 1.60 kg/sq. m of substrates and an optimal feeding rate of 0.7 kg/kg worm/day for vermicomposting. Therefore, it is essential to maintain optimum earthworm density to obtain maximum population growth and reproduction in shortest possible time.

Researchers have explored variety of domestic, agriculture, and municipal waste as a feed stock for vermicomposting. The solids are partially decomposed to prevent overheating during the process. Vermicomposting has been successful in processing sewage sludge and other solids from wastewater (Neuhauser et al., 1988), paper wastes (Elvira et al., 1996), urban food, garden residues and animal wastes (Dominguez and Edwards, 1997). Vermicomposting of different livestock excreta including cattle dung (Gunadi et al., 2003), horse waste (Hartenstein et al., 1997), pig waste (Chan and Griffiths, 1988), goat waste (Loh et al., 2005) has been reported. Cattle manure remains the most popular amendment during vermicomposting. Other bulking agents used are sawdust, sugarcane trash, grass clippings, etc. during composting of crop residues, kitchen waste and sludges (Suthar, 2009).

2.7 NUTRIENTS DURING COMPOSTING

An adequate supply of N, P, K and other essential nutrients in soils is essential to sustain crop productivity. Without the availability of manufactured chemical fertilizers that typically contain high N, P and K several decades ago, composting was a technique utilized by some farmers to add stabilized OM to soil and to convert part of organic N in animal wastes and crop residues into a more readily available form for improving soil fertility and crop productivity. Composting is a biological process in which OM can be utilized by aerobic thermophilic and mesophilic microorganisms as substrate and mainly converted into mineralized products (CO_2, H_2O, NH_4^+, NO_3^-) or stabilized OM (mostly as humic substances) (Bernal et al., 2009; He et al., 2009; de Guardia et al., 2010 a, b).

2.7.1 TRANSFORMATION OF PRIMARY NUTRIENTS

C, N, P and K are the major nutrients for plants. Organic carbon (OC) is used by the microbes as an energy source and for biomass synthesis. The catabolic activity of OC generates CO_2, H_2O and energy. Organic nitrogen is utilized as an electron donor (oxidizing agent) and is converted into ammonical nitrogen (NH_4–N) (ammonification), an inorganic form of nitrogen. NH_4–N may be assimilated by the microbes and transformed back to the organic form or may be further oxidized into nitrates (nitrification). When C/N is near 40, assimilation will be dominating and when C/N is near 15, mineralization will be dominating the process (Davet, 2004). Humification is the process of conversion of more labile forms of OM into more recalcitrant forms called humic substances with more molecular weight, more complex and that are polymers with significant aromatic character. Humic acid are colloidal molecules comprising of humic acid, fulvic acid and humins (Jonathan, 2007).

P is another essential element for plant growth and its input has long been recognised as essential to maintain economically viable levels of crop production. In agricultural systems P is needed for the accumulation and release of energy associated with cellular metabolism, seed and root formation, maturation of crops (especially cereals), crop quality and strength of straw in cereals (Brogan et al., 2001). During composting, the soluble forms of P are transformed into more recalcitrant forms (Eneji et al., 2003). Many factors control the mineralization-immobilisation of minerals during decomposition of OM; pH, temperature, aeration, nitrogen and C availability. As most plants contain 0.05–0.5% P and 20–50% C on a dry weight basis, mineralization will be the net effect when the C/P is less than 200, while immobilisation predominates during the initial stages of decomposition when the C/P of the OM is greater than 300 (Alexander, 1977).

2.7.2 TRANSFORMATION OF SECONDARY NUTRIENTS

Mineralisation during composting also leads to generation of sulphates and carbonates of Ca, Mg and K, oxides of Fe and Mn, and phosphates. Some of these products get lost from the composting biomass as solutes with the drainage water (bicarbonates of K and Mg, NO_3^-, SO_4^{2-}) and some remain as precipitated or adsorbed compounds (NH_4^+, K^+, Ca^{2+}, Mg^{2+}, phosphates and sesquioxides) in the final compost product (Saad, 2001).

2.8 HEAVY METALS DURING COMPOSTING

Application of compost containing high concentration of heavy metals is dangerous for human health as the heavy metals can enter the human tissues through uptake by plants from the soil medium and bio-magnifications in the food chain (Sprynskyy et al., 2007; Jordao et al., 2006). Heavy metals are natural non-degradable inorganic materials in the environment. They are metallic elements with a density > 5000 kg/ m^3 (Talbot, 2006). Heavy metals especially Cu, Ni, Cd, Zn, Cr and Pb are considered one of the major sources of soil pollution (Karaca et al., 2010). Some heavy metals (Fe, Zn, Ca and Mg) have been reported to be of bio-importance to man and their daily medicinal and dietary allowances had been recommended. However, some others (As, Cd, Pb, and methylated forms of Hg) have been reported to have no known bio-importance in human biochemistry and physiology, and consumption even at very low concentrations is toxic (Duruibe et al., 2007).

2.8.1 EFFECTS OF HEAVY METALS

2.8.1.1 Plants

Heavy metal accumulation in plants depends upon plant species and the efficiency of different plants in absorbing metals (Khan et al., 2008). Some of the heavy metals i.e. As, Cd, Hg, Pb or Se are not essential for plants growth, since they do not perform any known physiological function in plants. Others i.e. Co, Cu, Fe, Mn, Mo, Ni and Zn are essential elements required minimally for normal growth and metabolism of plants, but are toxic at higher concentrations (Garrido et al., 2002; Rascio et al., 2011). For example, Pb may inhibit vital plant processes, such as photosynthesis, mitosis and water absorption with toxic symptoms of dark green leaves, wilting of older leaves, stunted foliage and brown short roots (Bhattacharyya et al., 2008). Heavy metals are phytotoxic for plants and result in chlorosis, stunted growth, low yield, and may even be accompanied by reduced nutrient uptake, disorders in plant metabolism and reduced ability to fix molecular nitrogen in leguminous plants (Guala et al., 2010).

2.8.1.2 Human health

Consumption of food crops contaminated with heavy metals is a major food chain route for human exposure to the heavy metals (Jordao et al., 2006). Heavy metals become toxic when they are not metabolized by the body and accumulate in the soft tissues (Sobha et al., 2007). Chronic level ingestion of toxic metals has undesirable impacts on humans and the associated harmful impacts become perceptible after several years of exposure (Khan et al., 2008). The target organs for Cd toxicity have been identified as liver, placenta, kidneys, lungs, brain and bones (Sobha et al., 2007). The Itai-itai disease in Japan brought the dangers of Cd contamination to world attention. Cd has been associated to a lesser or greater extent with many clinical conditions including anosmia, cardiac failure, cancers, cerebrovascular infarction, emphysema, osteoporosis, proteinuria cataract formation in the eyes (Lalor, 2008). Zn in low amount is relatively nontoxic but in excess can cause system dysfunctions that result in impairment of growth and reproduction. The clinical signs of zinc toxicosis have been reported as vomiting, diarrhea, bloody urine, icterus (yellow mucus membrane), liver failure, kidney failure and anemia (Duruibe et al., 2007). Cu is an essential element in mammalian nutrition as a component of metalloenzymes in which it acts as an electron donor or acceptor. Excessive human intake of Cu may lead to severe mucosal irritation and corrosion, widespread capillary damage, hepatic and renal damage, and central nervous system irritation followed by depression. The effects of Ni exposure vary from skin irritation to damage to the lungs, nervous system, and mucous membranes (Argun et al., 2007). Pb is physiological and neurological toxin to humans. Acute Pb poisoning may result in dysfunction of the kidney, reproduction system, liver and brain leading to sickness and death (Odum, 2000). Cr is a transition metal element and, as such, has several forms depending on its electronic configuration. Cr(III) is considered as being an essential micronutrient element for human, plant and animal metabolism (Anderson, 1981) and is relatively non-toxic. Cr(VI) is toxic to plants and animals, being a strong oxidizing agent, corrosive, soluble in alkaline and mildly acidic water and is a potential geno-toxic carcinogen (Kazemipour et al., 2008). Cr(VI) exists as chromates and dichromates depending on both pH and total Cr(VI) concentration (Ucun et al., 2002), High concentrations of Cr(VI) are considered as being most hazardous to animals and plants due to its high solubility, mobility, toxicity as well as having carcinogenic and mutagenic properties (Dixit et al., 2002; Oves et al., 2013).

2.8.2 BIOAVALABILITY OF HEAVY METALS

Although heavy metal concentrations in sewage sludge or compost are well within the regulation standard, long-term land application of compost with background heavy metal concentration can increase content and accumulation of the heavy metals in the soil (Chiang et al., 2007). Here, it is only the mobile bioavailable and leachable forms of the heavy metals rather than the total heavy metals concentrations that pose the risk of high toxicity and remobilization of the heavy metals in the environment (Liu et al., 2007; Nair et al., 2008). The bioavailability of metals in soil depends on combinations of chemical, biological and environmental parameters and include soil properties such as pH, OM content, redox potential, cation exchange capacity, soil texture, clay contents, etc. and also the formation of sulphates, carbonates and hydroxides (Prabpai et al., 2009; Guala et al., 2010). Metal in soils can be divided into two fractions: (i) inert fraction assumed as the non-toxic fraction and (ii) the labile fraction, assumed to be potentially toxic (Yobouet et al., 2010). The availability of metals for plants and micro-organisms in soil depends on the composition of the different component of soil such as carbonates, (oxy) metal hydroxides, OM and silica (Yobouet et al., 2010). The mobilization of pollutants depends on several factors: their mobility, their concentration in the soil and their solubility. The solubility depends on the chemical composition of leachate in equilibrium with the material; this chemical composition is influenced by the variation of pH that moves the redox equilibrium to predominant forms (Yobouet et al., 2010). At high pH, the predominant forms are hydroxides with low solubility whereas at low pH, the predominant forms are the free metallic ions which are highly soluble.

The labile form of Zn was found to increase when composted residuals or sewage sludge is applied to soil, particularly under acidic soil conditions (Smith, 2009). The mobile fraction of Zn increased during the composting process due to the oxidation of OM and its high oxidation-reduction potential (Nomeda et al., 2008). The formation of humic substances seems to transform Zn from sulfide fraction to organic fraction during the composting process.

The potential behavior, bioavailability and the transfer dynamics of Cu in soil-plant system cannot be predicted by the total concentration of Cu. The toxicity of excess Cu is determined by cupric ion activity and the mobile Cu is more toxic to plant growth than the strongly complex forms (Guan et al., 2011). Cu is strongly bound to the organic fraction forming metal-organic complexes (Gupta and Sinha, 2007). The OM is frequently reported to have a dominant role in controlling the behaviour of Cu in the soil, due to it potentially important binding site for this element in compost and amended soil. Cu dominates the organic bound fraction in both sludge and sludge compost (> 80%) by forming very stable complexes with organic ligands. The ion is directly bound to two or more organic functional groups mainly carboxylic, carbonyl and phenolic forming a rigid inner-sphere complex (Qiao and Ho, 1997; Nomeda et al., 2008; Hargreaves et al., 2008). However, at pH 9 the solubility of Cu increases due to the formation of soluble complexes (Yobouet et al., 2010).

Mn is reported to be found mostly as plant available carbonates and oxides (Venkateswaran et al., 2007) and the plant available forms increased after composting (Wong and Selvam, 2006). Ni cations also form complexes with organic ligands with stability a little lesser than Cu^{2+}. Therefore, the not readily available Ni dominated the sludge and compost mixture (Qiao and Ho, 1997). During composting, the stabilization of Ni in sewage sludge reduced the risks of the heavy metals in the compost (Zheng et al., 2007). The mobility of Ni increased with declining pH and OM content (Smith, 2009).

Pb has a stronger affinity to the adsorption sites on the clay materials such as silanol groups of silica and amorphous aluminium hydroxide. Pb also occurs mainly as carbonates and oxides (Ciba et al., 1999; Venkateswaran et al., 2007). Composting reduced the bioavailable fraction of lead during sewage sludge and swine manure composting (Qiao and Ho, 1997; He et al., 2009). Cd is regarded as a hard, high melting-point, unreactive substance, that exhibits a wide range of oxidation states and tends to form strong covalent bonds. The chemistry of Cd is similar to that of Zn (Whittle and Dyson, 2002). Cd occurs mainly in carbonates and sulphides (Ciba et al., 1999).

Cr is classed as a 'hard' metal, and as such, these metals are generally less mobile, quite stable, resisting attack from environmental processes (Whittle and Dyson, 2002). Cr is the 10th abundant element in the earth's mantle and persists in the environment as either Cr(III) or Cr(VI), which are characterized by distinctive chemical properties and toxicities (Garnier et al., 2006). Cr(III) has an electron configuration closest to a noble gas with a high spherical symmetry and its polarisability is low. It has a valency of three and therefore it has a stronger electrostatic affinity for the sorption sites than divalent cations (Qiao and Ho, 1997). Cr(VI) is a strong oxidizing agent and is highly toxic; it is 10 to 100 times more toxic than Cr(III). Whereas Cr(III) is a micronutrient, insoluble in water and a non-hazardous species (Shaffer et al., 2001) and less toxic to mammalian, aquatic organisms and plants due to its low solubility, mobility and bioavailability (Zhou et al., 2006). Cr(VI) exhibits more chemical activity (including amphotericity) as well as solubility and hence high potential mobility (Whittle and Dyson, 2002). Cr(III) on the contrary, showed a decrease in solubility/extractability during the stabilization process, i.e. with increasing degree of humification (Ciavatta et al., 1993). Gupta and Sinha (2007) reported that Cr mostly occurred as oxides in tannery sludge and composting changed the bioavailable fractions to forms that are unavailable for the plants (Zheng et al., 2007). Because of the high competitive nature of Cr for adsorption sites, any released Cr will displace other adsorbed metals. Therefore, leachable and plant available Cr were not detected in the sludge compost even though it contained 29 mg/kg total Cr (Qiao and Ho, 1997).

2.8.2.1 Water soluble heavy metals

The water soluble (WS) fraction of heavy metals is the most biologically active and the most bioavailable form of metals. WS metal fraction has highest potential of contamination of food chain, surface water and ground water (Iwegbue et al., 2007). The pH is the main parameter controlling ion exchange, reduction/oxidation, adsorption and complexation reactions ultimately affecting the mobility and bioavailability of metals. Cations are adsorbed on OM at high pH (Samuel et al., 2013). The effect of OM amendments on heavy metal solubility also depend greatly upon the degree of humification of their OM and their effect upon soil pH (Gupta and Sinha, 2007).

The oxidation process and the formation of organometallic complexes taking place during the composting reduced the soluble contents of Ni (Fang and Wong, 1999). WS fraction of Zn, Pb, Cu and Cd were found to decrease and stabilize after the thermophilic stage of composting. The pH of compost just before the thermophilic stage was found to be acidic causing higher available Pb and Zn (Hargreaves et al., 2008). The increase in total metal concentrations during composting was not accompanied with increase of the WS fraction of Cu, Mn and Zn. Sequential changes in the WS fraction of Cu, Mn and Zn were reflected by changes in WS organic carbon concentrations, which increased to a maximum at day 18 of composting and then declined (Hsu and Lo, 2001). Fang and Wong (1999) studied the changes in WS fraction of Cu, Mn, Ni and Zn contents in sewage sludge co-composted with lime and sawdust on day 0, 7, 21, 49 and 100 and reported that WS fraction of Pb, Cr and Cd content in all treatments were below the detection limits. Hsu and Lo (2001) carried out study on the variation of total concentration and water solubility of Cu, Mn and Zn during pile composting of swine manure for 122 days, and reported that the WS fraction of Cu (expressed as percent of the total concentration in the sample) increased from 3% in the raw separated swine manure to 5% on day 12, sharply increased to 16% on day 18 and gradually decreased to 3% in the final compost. The WS fraction of Mn and Zn increased from 1% in the raw material to 2% on day 18 and then gradually decreased to 0.5% at the end of the process. The metallic form of Cr is quite stable and can resist attacks from environmental processes. However, in either the trivalent or hexavalent forms, Cr exhibits higher chemical activity (including amphotericity, i.e., the ability to react chemically as an acid or a base), as well as solubility and hence potential mobility and subsequent removal from the solid fraction (Haroun et al., 2009). Ciavatta et al. (1993) reported that Cr released from OM in neutral or alkaline soils precipitates as insoluble forms; therefore it is not adsorbed by plants. Due to its low solubility, only a little amount of Cr is bioavailable, meaning that even when crops are grown in soils treated with sludge relatively high in Cr, phytotoxicity is rarely observed.

2.8.2.2 Diethylene triamine penta-acetic acid (DTPA) extractable heavy metals

DTPA is a chelating agent that mimics plant uptake and widely used for assessment of plant availability of the metals in soil at regular or even higher concentration (Guan et al., 2011). The DTPA extractable fraction of metals represents a supplemental approach to check the bioavailability of heavy metals in the soil and sludge amended soil for plant uptake (Fang and Wong, 1999; Fuentes et al., 2006). DTPA solution is assumed to extract both carbonate bound and organically bound metal fractions in calcareous soils, and indicates the amount of metals potentially available for plant uptake (Walter et al., 2006). The mobility of trace metals, their bioavailability and related eco-toxicity to plants, depend strongly on their specific chemical forms or ways of binding (Walter et al., 2006; Gupta and Sinha, 2007). The bioavailability of heavy metals in the soil also depends on their distribution between solid and solution phases, dependent on the soil processes like cation exchange, specific adsorption, precipitation and complexation. The process of metal uptake and accumulation by different plants depend on the concentration of available metals, solubility progressions and the plant species growing on these soils (Gupta and Sinha, 2007). The fate of toxic metals largely depends on their interactions with inorganic and organic soil surfaces (Bragato et al., 1998). During composting of water hyacinth with cattle manure and saw dust, DTPA extractable Zn, Cu, Mn, Ni and Cr could be reduced with appropriate proportion of cattle manure as the cattle manure provided the carboxyl (–COOH) and hydroxyl (–OH) binding sites for the metals during the composting process (Singh and Kalamdhad, 2013c).

2.8.2.3 Leachable heavy metals

The toxicity characteristic leaching procedure (TCLP) is designed to determine the mobility of both organic and inorganic analytes present in liquid, solid and multiphasic wastes. If an analysis of any one of the liquid fractions of the TCLP extract indicates that regulated heavy metals are present at such high concentrations that, even after accounting for dilution from the other fractions of the extract, the concentration would be above the regulatory level for those metals, then the waste is hazardous (USEPA, 1992). TCLP test is used to determine the suitability of compost for land application. The procedure is designed to simulate the leaching potential of the compost material when it is applied to soil. The regulatory limits for leached toxic heavy metals are based on avoiding groundwater contamination that would create a risk to human and environmental health (Chiroma et al., 2013).

The mobility, bioavailability and eco-toxicity of the metals depend on the specific chemical forms or bindings in which the metals exist in different waste materials. Therefore, it is necessary to examine leachability of heavy metals to determine the suitability of decontaminated sludge for land application (Pathak et al., 2009). Wang et al. (2010) studied leachability of Cu in chicken manure during 110 days of composting period and reported that the amount of leached Cu increased initially but at the end of composting process it was reduced significantly. The amount of Cu leached from manure throughout the composting process averaged 20% of the total Cu in the compost (Villasenor et al., 2011). The Ni was present at much higher WS levels in municipal solid waste (MSW) compost and considered as leachable (Hargreaves et al., 2008). Ciba et al. (1999) reported that Zn can be leached in significant amounts only at pH 2.5. Chiang et al. (2007) also found that the leached fraction of Cu, Zn and Ni decreased with increasing composting time during composting of sewage sludge.

2.9 COMPOST STABILITY/MATURITY

The changes in the material after composting can be grouped into three parts (Cheremisinoff, 1994) viz.-

Physical Changes

- Temperature of end product higher than that of raw material
- Colour changes to dark black
- Particle size is smaller than raw material
- Dry end product (no water comes out when squeezed)

Chemical Changes

- C/N of end product less than the raw material
- Organic substrate of the end product is stable

Biological Changes

- Activity of microbes is less, which can be detected by respiration rate
- Amount of pathogen decreases

Although composting has been widely practiced with its final products being utilized as fertilizers or soil amendments, there are still knowledge gaps in understanding it due to the high variety and heterogeneity of feedstock (Li et al., 2008; Himanen and Hänninen, 2011). Ability to tell whether or not the compost is stable or mature is important to compost makers, plant operators and end users. Application of unstable and immature compost to soil can sustain high microbial activities and immobilize the nitrogen content of the soil, thereby causing nitrogen deficiency in growing plants. Stable and mature compost implies stable OM content and absence of phytotoxic compounds. Stability is often related with the compost's microbial activity whereas maturity is associated with plant growth potential or phytotoxicity (Zucconi et al., 1985; Iannotti et al., 1993). There needs to be a consensus on the definition of stability and maturity of compost as many authors and different organisations have their own different stand.

- Haug (1993) defined stability as 'the point at which the rate of oxygen consumption is reduced so that anaerobic or odorous conditions are not produced to the extent that they cause problems with storage and end use of the product'.
- Stability is a stage in the decomposition of OM during composting and a function of biological activity. It is the level of biological activity in a moist, warm, and aerated biomass sample (Leege and Thompson, 1997).
- Stability is related to the level of microbial activity in the compost (Bernal et al., 1998; Butler et al., 2001) and hence the potential for unpleasant odour generation (Hue and Liu, 1995; Eggen and Vethe, 2001).
- Stability is the actual point reached in the biodegradation process. It is the degree of decomposition, that is, the extent to which the composting reaction has advanced (Stentiford and Lasaridi, 2000).
- McAdams and White (1996) proposed a theoretical stability definition as 'the point where readily degradable substrate is diminished so that its decomposition rate does not control the overall rate of decomposition'.
- The Californian Compost Quality Council (2001) defines stability as 'a stage or state of OM decomposition during composting which is related to the type of organic compounds remaining and the resultant biological activity in the material'.
- Stability is the degree to which composts have been decomposed (Iannotti et al., 1993; UK Composting Association, 2001) or the degree to which the biodegradable fraction in solid wastes has been diminished or consumed during composting (Iannotti et al., 1994; Lasaridi and Stentiford, 1999)

Maturity implies improved qualities resulting from 'ageing' or 'curing' of a product. An end product can be "mature" when it is ready for its particular intended use.

- Mature compost implies stable OM content and the absence of phytotoxic compounds (Iannotti et al., 1993; Bernal et al., 1998).

- Chen and Inbar (1992; 1993) stated that ‘compost maturity should be defined as the degree of decomposition of OM during composting’ but also stated that ‘any definition of maturity must be based on the potential utilisation of the compost and not posed adverse effects on plants’.
- Hue and Liu (1995) described maturity as associated with plant growth and phytotoxicity as distinguished from stability, which is related to microbial activity.
- Maturity is an organo-chemical condition of the compost, which indicates the presence or lack of organic phytotoxic chemicals in generally stable to very stable compost. It is the degree to which a biomass sample no longer consumes nitrogen or oxygen and is no longer highly active, and will not cause depletion of nitrogen in the soil with which it is mixed. It is any organic material which has undergone a biological decomposition process and will not act detrimentally when used as a soil amendment (Leege and Thompson, 1997).
- The UK Composting Association (2001) define maturity simply as ‘the degree to which a compost has matured’, but define mature compost as ‘compost that does not have a negative effect on seed germination or plant growth.’
- Butler et al. (2001) defined maturity as ‘the degree of humification of the material’, but also consider the effect of humification on nutrient availability and plant growth.
- The California Compost Quality Council (2001) defined maturity as ‘the degree or level of completeness of composting’ and further stated that ‘maturity is not described by a single property and therefore is best assessed by measuring two or more parameters describing stability and the impact on plant development’.

Physical characteristics such as colour, odour and temperature give a general idea of the decomposition stage reached, but give little information as regards to the degree of maturation. For this, chemical methods are widely used, including measurement of the VS, readily degradable OM, C/N, the cation exchange capacity (CEC), degree of OM humification, CO_2 evolution rate, oxygen uptake rate (OUR). A high level of NH_4–N indicates unstable and phyto-toxic material and a limit of 0.04% is prescribed for stable and mature compost (Zucconi and de Bertoldi, 1998). Since stabilization or maturation also implies the formation of some humic-like substances, the degree of OM humification is generally accepted as a criterion of maturity. Respirometric studies, which determine the O_2 consumption or CO_2 production caused by mineralization of compost's OM, have been carried out in pure composts and in compost mixed with soil in a proportion compatible with agricultural use (Iannotti et al., 1993). Insufficiently mature compost has a strong demand for O_2 and high CO_2 production rates due to intense development of microorganisms as a consequence of the abundance of easily biodegradable compounds in the raw material. For this reason, O_2 consumption or CO_2 production rate are the most reliable indicators of compost stability and maturity (Hue and Liu, 1995).

According to CCME (2005), compost must be cured for 21 days to be considered stable and mature and must meet one of the following three requirements:

- the respiration rate is less than or equal to 400 mg of O_2 per kg of VS (or OM) per h; or
- the CO_2 evolution rate is less than or equal to 4 mg of C in the form of CO_2 per g of OM per day; or
- the temperature rise of the compost above ambient temperature is less than 8°C.

2.10 STUDIES ON WEED COMPOSTING/VERMICOMPOSTING

Composting and land applications of water hyacinth which is one of the components of phumdi biomass have been reported in other parts of the world. Gajalakshmi et al. (2001a, b; 2002) subjected water hyacinth to high-rate composting and subsequent vermicomposting in reactors operatin with large densities of earthworm: 50, 62.5, 75, 87.5, 100, 112.5, 125, 137.5, and 150 adults of *Eudrilus eugeniae Kinberg* per liter of digester volume. The composting step was accomplished in 20 days and the composted weed was found to be vermicomposted three times faster compared with uncomposted water hyacinth. There was no earthworm mortality during the first four months in spite of the high animal densities in the reactors.

Fatmawati et al., (2001) investigated the influence of the composts prepared from *Azolla pinnata* and *Salvinia natans* on the growth of Beauty Hot chili. Growth parameters measured were plant height, number of branches, number of leaves, leaf weight, leaf size, flower number and number of perfect blooms. Beauty Hot chilli plants were treated either with 1 kg of *Azolla pinnata* compost or 1 kg *Salvinia natans* compost. The effects on the growth with the application of the mixtures of the two composts in different proportions were also studied. The results of the study indicated that administration of compost *Azolla pinnata* and *Salvinia natans* affect Beauty Hot pepper plant growth. Mixture 0.50 kg *Azolla pinnata* compost and 0.50 kg *Salvinia natans* compost gave the best effect for the growth of Beauty Hot chili.

The impact of the application of compost/vermicompost of water hyacinth (*Eichhornia crassipes*, Mart. Solms) on plants in terms of growth and flowering of the angiosperm crossandra (*Crossandra undulaefolia*) was also investigated (Gajalakshmi and Abbasi, 2002). Overall nine morphological, size, and yield attributes were considered in the study. Application of vermicompost led to statistically significant improvement in the growth and flowering of crossandra compared to the untreated plants. The impact of compost was also beneficial but comparatively lower than of the application of vermicompost. Qualitative studies were simultaneously conducted in five kitchen gardens owned by farmers near Pondicherry. In three of these locations except for the application of water hyacinth vermicompost no other fertilizer was applied for months to the vegetables. Water hyacinth compost was similarly applied in another two locations. No adverse effect on any of the plant species was observed in all the locations.

Gupta et al. (2007) investigated the potential of vermicomposting water hyacinth mixed with cowdung. Five vermireactors containing water hyacinth and cowdung in different ratios were run under laboratory conditions for 147 days. The maximum worm growth was recorded in cowdung alone. Worms grew and reproduced favorably in 25% water hyacinth and 75% cowdung feed mixture. Greater proportion of water hyacinth in feed mixture adversely affected the biomass gain, hatchling numbers and numbers of cocoons produced during the process. In all the vermireactors, there was significant decrease in pH, total organic carbon (TOC) and C/N, but increase in total Kjeldahl nitrogen (TKN), total K and total and available phosphorous (TP and AP) at the end. The heavy metals content in the vermicomposts was lower than initial feed mixtures.

Singh and Kalamdhad (2012, 2013a, b) successfully carried out composting and vermicomposting of water hyacinth with addition of saw dust and cattle manure in appropriate proportion and studied the fate of the heavy metals present in water hyacinth during the process by using metal speciation techniques. Composting of other closely related species of salvinia – *Salvinia molesta* and *Salvinia cucullata* are also found in literature. Salvinia and *Egeria densa* was composted effectively by blending with other materials such as leaves, grass clippings and woody prunings (Dorahy et al., 2009).

Suthar and Sharma (2013) vermicomposted the toxic weed– *Lantan camara* biomass spiked with cowdung and showed appreciable increase in exchangeable Ca, K, and AP. Ganeshkumar et al. (2014) demonstrated effective vermicomposting of *Salvinia molesta* weeds without addition of cattle manure in their pulse fed vermireactors. The available studies demonstrate composting as an effective method of reducing the viability of the aquatic weeds.

Mohee et al. (2013) carried out comparative study on the co-composting process of unwashed (Run A) and washed (Run B) seaweed *Ulva reticulata* with bagasse and broiler litter. Peak temperatures of 48.9ºC and 55.2ºC were recorded for Run A and B, respectively. VS reductions were 2.19 and 11.44% for Run A and B, respectively. Washing treatment lowered the chloride content by 3–5 times in Run B. Final compost from Run B had a better fertilising capacity with its higher N, P and K contents. Cole et al. (2015) composted seaweed (*Ulva ohnoi*) in varying C/N by mixing with different proportions of sugarcane bagasse and found that seaweed-bagasse mixes that had an initial C/N greater than 18 (up to 50) could be transformed into a mature compost within 16 weeks. However, only composts with a high seaweed content and therefore low initial C/N (18 and 22) supported a consistently high rate of plant growth, even at low application rates.

2.11 INFERENCE FROM LITERATURE REVIEW

Aquatic weeds cause deterioration of water bodies all over the world. Controlled harvesting of phumdi biomass and other invasive weeds of Loktak Lake remains the effective option for control of their proliferation and protect the water quality of the lake. Composting can be an effective option for economic utilization of the removed phumdi biomass and other weeds of Loktak Lake as it combines material recycling and appropriate biomass disposal. No scientific study has been reported on the composting or vermicomposting of phumdi biomass of Loktak Lake. There is also very limited scientific study on the composting of the invasive species *Salvinia natans*. There is the need to assess the quality of the composts by assessing their physico-chemical and bio-chemical parameters at different stages of the composting process to achieve process efficacy before agricultural applications. The phumdi also act as biological sink for the nutrients and pollutants brought in by the rivers after passing through the thickly populated urban areas. There is also possibility of toxic heavy metals entering the composting stream. Compost containing heavy metals changes the physical, chemical and biological properties of soil. Heavy metals uptake by plants and successive accumulation in human tissues through bio-magnifications are both health and environment concerns. The toxicity of heavy metals does not depend on the total concentration but depends on the different bioavailable fractions in which metals are present. Composting process can reduced toxicity of metals by reducing bioavailable fractions such as WS, DTPA extractable and leachable fractions by forming insoluble organometallic complexes with the OM of the composts. Vermicomposting is comparatively a new technology. During vermicomposting, earthworms can accumulate and convert the high concentration of heavy metals to nontoxic forms and are capable of utilizing the toxic heavy metals for physiological metabolism. Therefore, the aim of this thesis was to assess the physico-chemical and bio-chemical changes, and the bioavailability and leachability of the heavy metals during agitated pile composting, rotary drum composting and vermicomposting of phumdi biomass and *Salvinia natans* premixed with cattle manure, sawdust or rice husk.

Chapter 3

MATERIALS AND METHODS

This chapter describes the experimental design for composting and vermicomposting of phumdi and *Salvinia natans* biomass which were carried out in two phases with prior blending of cattle manure, rice husk or sawdust. The method of collection of phumdi and *Salvinia natans* biomass and the composting techniques employed for the study are elaborated. The procedures adopted for analysis of the physico-chemical and bio-chemical parameters and for determination of the concentrations of nutrients and heavy metals are also described.

3.1 EXPERIMENTAL DESIGN

In order to accomplish the objectives, the research was carried out in two phases i.e. Phase 1 for phumdi biomass composting/vermicomposting and Phase 2 for *Salvinia natans* composting/vermicomposting as indicated at Fig. 3.1a and 3.1b.

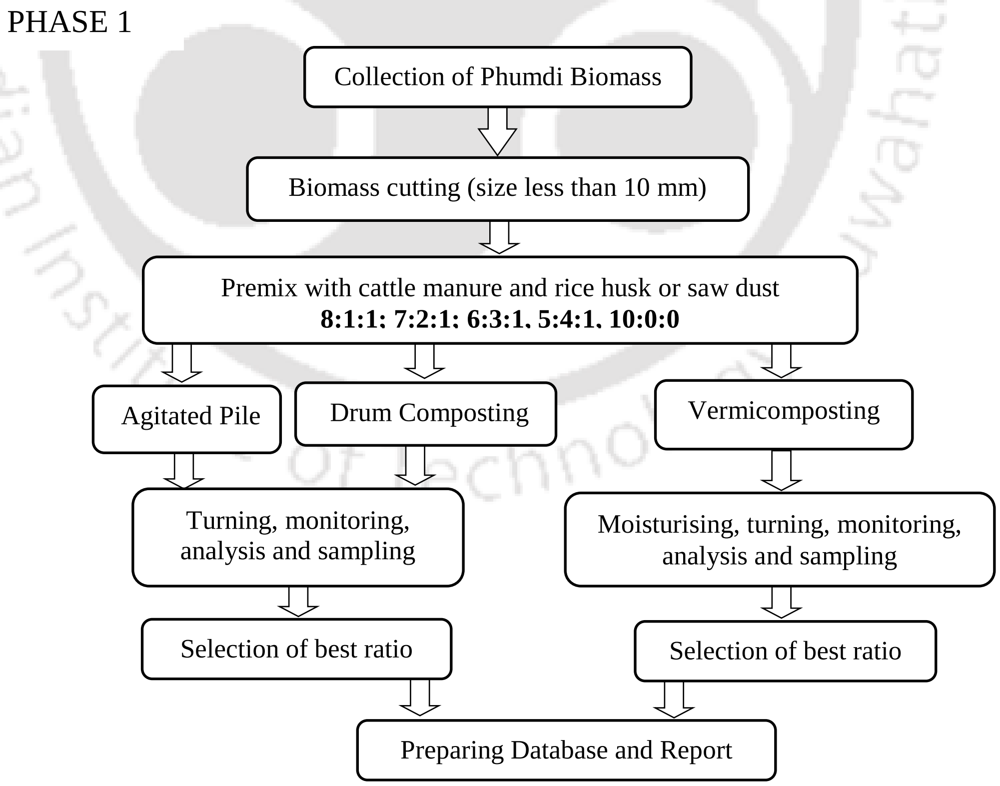

Fig. 3.1a. Design of research work for Phase 1

PHASE 2

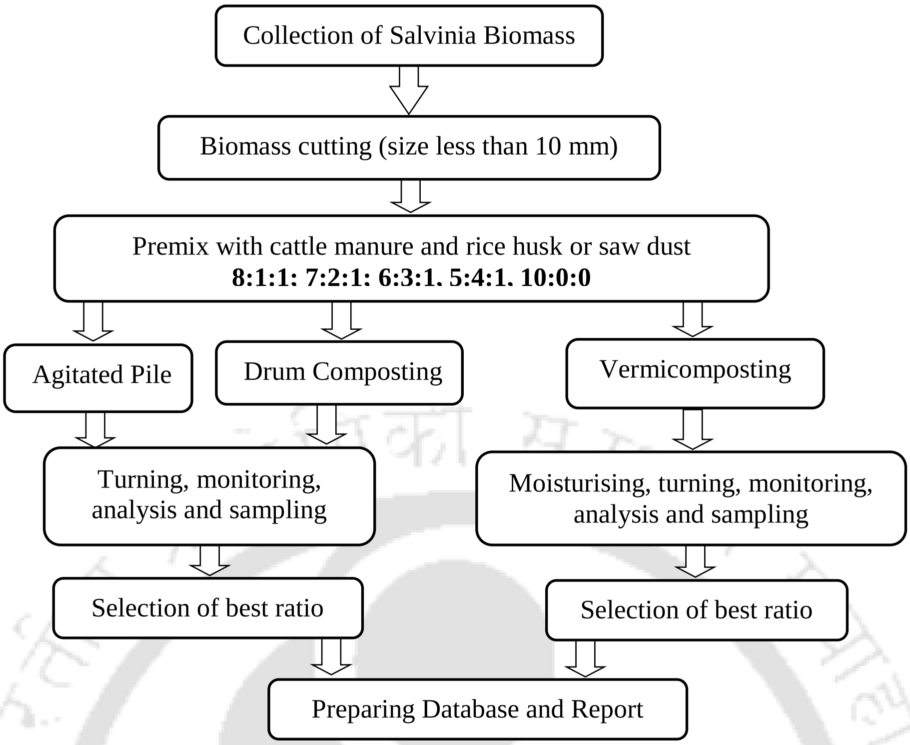

Fig. 3.1b. Design of research work for Phase 2

3.2 FEEDSTOCK MATERIALS AND WASTE COMBINATIONS

3.2.1 PHASE 1: PHUMDI BIOMASS COMPOSTING/VERMICOMPOSTING

The floating phumdi biomass was collected from the Loktak Lake near Thanga village, Bishnupur district, Manipur, India (Fig. 3.2). The large floating phumdis were cut into pieces weighing approximately 7–10 kg with long sickles, loaded on the local rowing boats and brought to the lakeside by the boatmen. Cattle manure and rice husks were obtained from Central Agriculture University, Imphal, India. The phumdi materials were prepared for composting through cutting/shredding (maximum size restricted to 10 mm to provide better aeration and moisture control) and uniform premixing with cattle manure and rice husk (total weight 150 kg) in five different proportions detailed at Table 3.1a.

The epigeic earthworm *Eisenia fetida* used for vermicomposting were brought from Central Plantation Crop Research Institute (CPCRI), Indian Council of Agricultural Research, Assam, India. Perspex bin size 450 mm × 300 mm × 450 mm was fabricated for culturing the earthworms in the laboratory. 16 holes (10 mm diameter) were drilled at equal spacing along the longer sides and at the bottom of the bin for aeration and drainage purpose. Before the addition of the culturing media and the earthworms, 10 cm thick bedding for the earthworms was prepared from partially degraded chopped hay (about 50 mm), cattle manure, banana pulp (chopped about 50 mm) and tree leaves. The bedding was then watered to keep it moist to facilitate breathing of the earthworms. The earthworm species were then added with partially degraded cattle manure as culturing media (Singh and Kalamdhad, 2013b). Sawdust for the experiment was purchased from Amingao village, near IIT Guwahati, Assam. The proportion of the cut phumdi biomass, cattle manure and sawdust (total weight 2.5 kg) for the vermicomposting trials are indicated in Table 3.1b.

Table 3.1a. Proportion of feedstock mixtures during pile and rotary drum composting

Trial	Feedstock materials (kg)		
	Phumdi /*Salvinia natans*	Cattle manure	Rice husk
Trial 1 (8:1:1)	120	15	15
Trial 2 (7:2:1)	105	30	15
Trial 3 (6:3:1)	90	45	15
Trial 4 (5:4:1)	75	60	15
Trial 5 (10:0:0)	150	0	0

Note: Total weight of feedstock in each trial was 150 kg

Table 3.1b. Proportion of feedstock mixtures during vermicomposting

Parameters	Feedstock materials (kg)			Earthworm
	Phumdi /*Salvinia natans*	Cattle manure	Sawdust	*Eisenia fetida* (kg)
Trial 1 (8:1:1)	2.00	0.25	0.25	0.10
Trial 2 (7:2:1)	1.75	0.50	0.25	0.10
Trial 3 (6:3:1)	1.50	1.25	0.25	0.10
Trial 4 (5:4:1)	1.25	1.00	0.25	0.10
Trial 5 (10:0:0)	2.50	0.00	0.00	0.10

Note: Total weight of feedstock in each trial was 2.5 kg

3.2.2 PHASE 2: *SALVINIA NATANS* COMPOSTING/VERMICOMPOSTING

Salvinia natans was also collected from Loktak Lake near the same Thanga village, Bishnupur district, Manipur, India by the local boatmen. Cattle manure and rice husks for *Salvinia natans* composting were also obtained from the Central Agriculture University, Imphal, India. The process for preparation of feedstock was similar to phumdi biomass composting/vermicomposting and the proportions of the mix for composting and vermicomposting of *Salvinia natans* are also shown respectively in Table 3.1a and 3.1b. The earthworm *Eisenia fetida* employed for vermicomposting of *Salvinia natans* was also cultured in perpex bin in the same way as was carried out for phumdi biomass vermicomposting.

Fig. 3.2a. Picture showing collection of phumdi and *Salvinia natans*

Fig. 3.2b. Picture showing storage of phumdi and *Salvinia natans* at composting shed

Fig. 3.2c. Picture showing cutting/shredding and mixing of feedstock materials

3.3 COMPOSTING METHODS

3.3.1 AGITATED PILE COMPOSTING

The prepared five different waste combinations of composting materials were formed into five trapezoidal piles with minimum length (*L*), minimum base width (*W*), minimum height (*H*) and top width (*T*) of the piles shown at Fig. 3.3a (Singh and Kalamdhad, 2012; Prasad et al., 2013). The five piles containing 150 kg of composting materials were manually turned once on 3rd, 6th, 9th, 12th, 15th, 18th, 21st, 24th, 27th and 30th days. The composting piles were monitored for only 30 days.

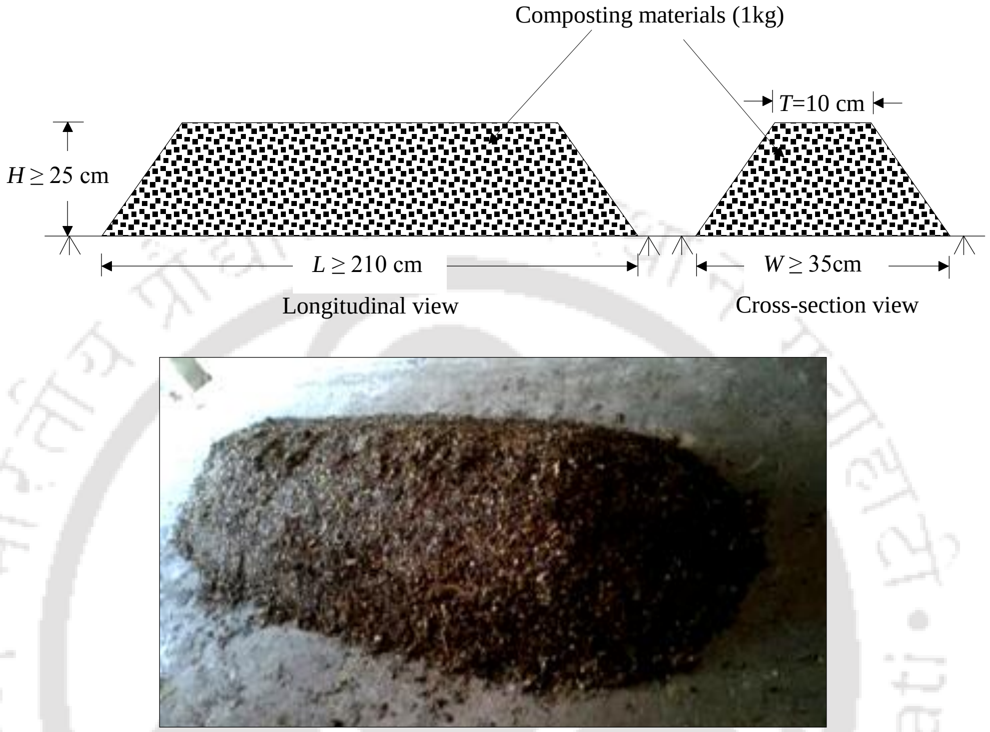

Fig. 3.3 a. Schematic representation of compost pile

3.3.2 ROTARY DRUM COMPOSTING

Fig. 3.3b shows the schematic diagram of a pilot scale rotary drum composter of 550 L capacity. The main unit of the composter i.e. the drum (length: 1.22 m; diameter: 0.76 m) was fabricated with 4 mm thick metal sheet. The inner side of the drum was coated with anticorrosive paints. The drum was mounted on four rubber rollers attached to a metal stand and rotated manually with the handle. In order to ensure appropriate mixing, agitation and aeration of the wastes during rotation, 8 nos. of 40 mm × 40 mm angles were welded longitudinally inside the drum at equal spacing. In addition, two adjacent holes of 10 cm each were drilled on top of the drum to drain out the excess water. The pilot scale rotary drum composter was fabricated in such a way that it could be rotated manually by a single person. Manual turning was done after every 24 h through one complete rotation of the rotary drum to ensure that the material on the top portion moved to the central portion, where it was subjected to higher temperature. After that, aerobic condition was provided by opening the top half side doors of the two circular faces. Rotary drum composting was carried out for 20 days as proper degradation and stabilization was found to be achieved by day 20 during rotary drum composting of water hyacinth as well as vegetable wastes (Kalamdhad et al., 2009; Singh and Kalamdhad, 2013a).

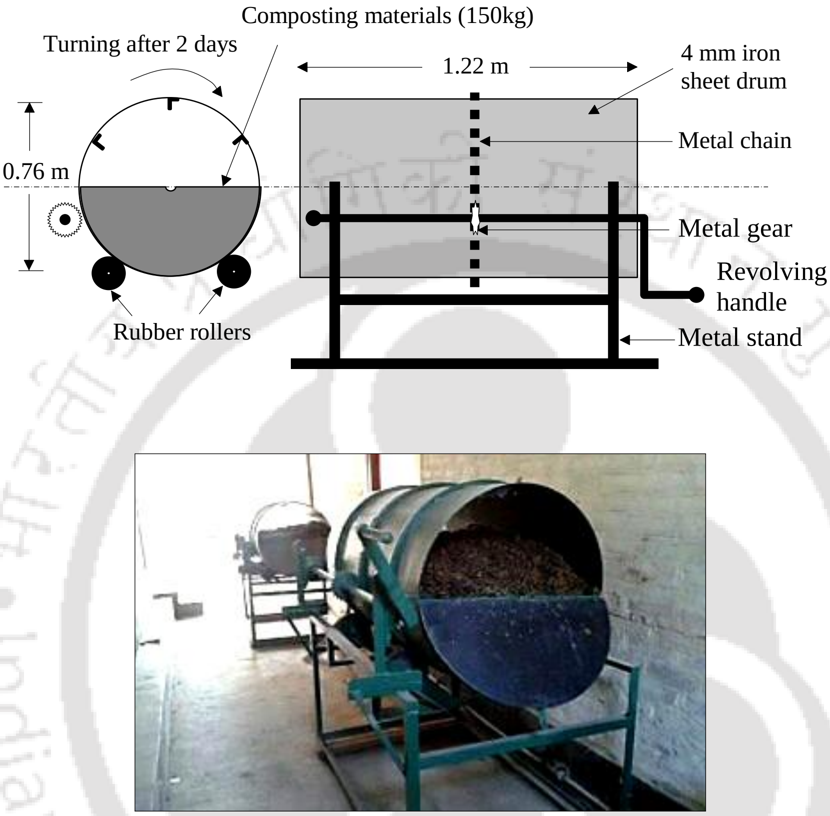

Fig. 3.3b. Schematic diagram of a rotary drum composter for batch operation

3.3.3 VERMICOMPOSTING

Vermicomposting experiments were conducted in triplicate at room temperature in locally made curved shaped bamboo containers (reactors) (top radius: 150 mm and depth: 100 mm) to facilitate better ventilation for the earthworms (Fig. 3.3c). The reactors were designed for 2.5 kg of the substrates and approximately 100 g live weight of earthworms (approximately 180–200 nos. of clitellated and young non-clitellated *Eisenia fetida*) were randomly picked from the perspex bin culture and introduced gently into the substrates from the top. The earthworm biomass weight was decided on the basis that earthworms consumed materials approximately half their body weights per day under favourable conditions (Haimi and Huhta, 1986).

All the containers were kept in the dark under identical ambient conditions (room temperature 25±3ºC). The optimum moisture content is one of the most important requirements for the earthworms throughout the vermicomposting process. Excess moisture content may create anaerobic conditions which may be fatal to the earthworms (Garg and Gupta, 2011). The moisture level was maintained at about 50–60% throughout the study period by periodic sprinkling of adequate quantity of tap (potable) water whenever required. To prevent moisture loss, the reactors were covered with gunny bags. The mixtures were manually remixed on every 15th day after separation of the earthworm biomass in order to provide suitable aeration to the earthworms.

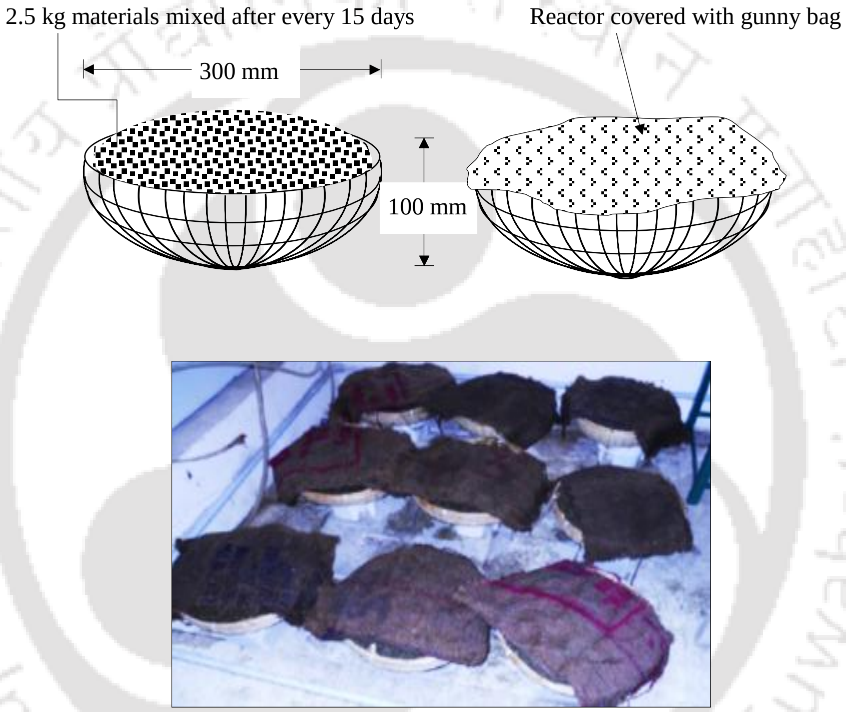

Fig. 3.3c. Schematic diagram of a bamboo vermireactor

3.4 SAMPLING AND ANALYSIS

3.4.1 SAMPLING

Samplings for analysis were carried out by a compost sampler on 0 day and after every turning (manual rotation) i.e. every 3rd day for agitated pile composting and every 2nd day for rotary drum composting. Grab samples were collected from five different locations mainly from the mid and end portions of the piles or the rotary drums and thoroughly mixed to form a homogenous sample and divided into three equal portions. Samples in triplicates were stored immediately at 4ºC for a maximum of 2 days for bio-chemical analysis. After bio-chemical analysis, remaining subsamples were immediately air dried at 105ºC in oven, ground to pass through 0.2 mm sieve and stored for analysis of the physico-chemical parameters. Samples of the individual materials (Table 3.1a and b) were also stored in the same way for initial characterisation.

For the vermicompost reactors, the earthworms and hatchings were separated by light separation and hand sorting method and the earthworm biomass was recorded. The cocoons were sorted manually. Wet substrate (free of earthworms, hatchlings and cocoons) were collected from the reactors on day zero (before inoculation of earthworms) and on the 15th, 30th and 45th day of the vermicomposting period after earthworm separation and complete mixing. The samples in triplicates were also stored immediately at 4ºC for bio-chemical analysis. The remaining sub-samples were oven dried and ground to pass through a 0.2 mm sieve as was carried out for physico-chemical and metal analysis of the compost samples.

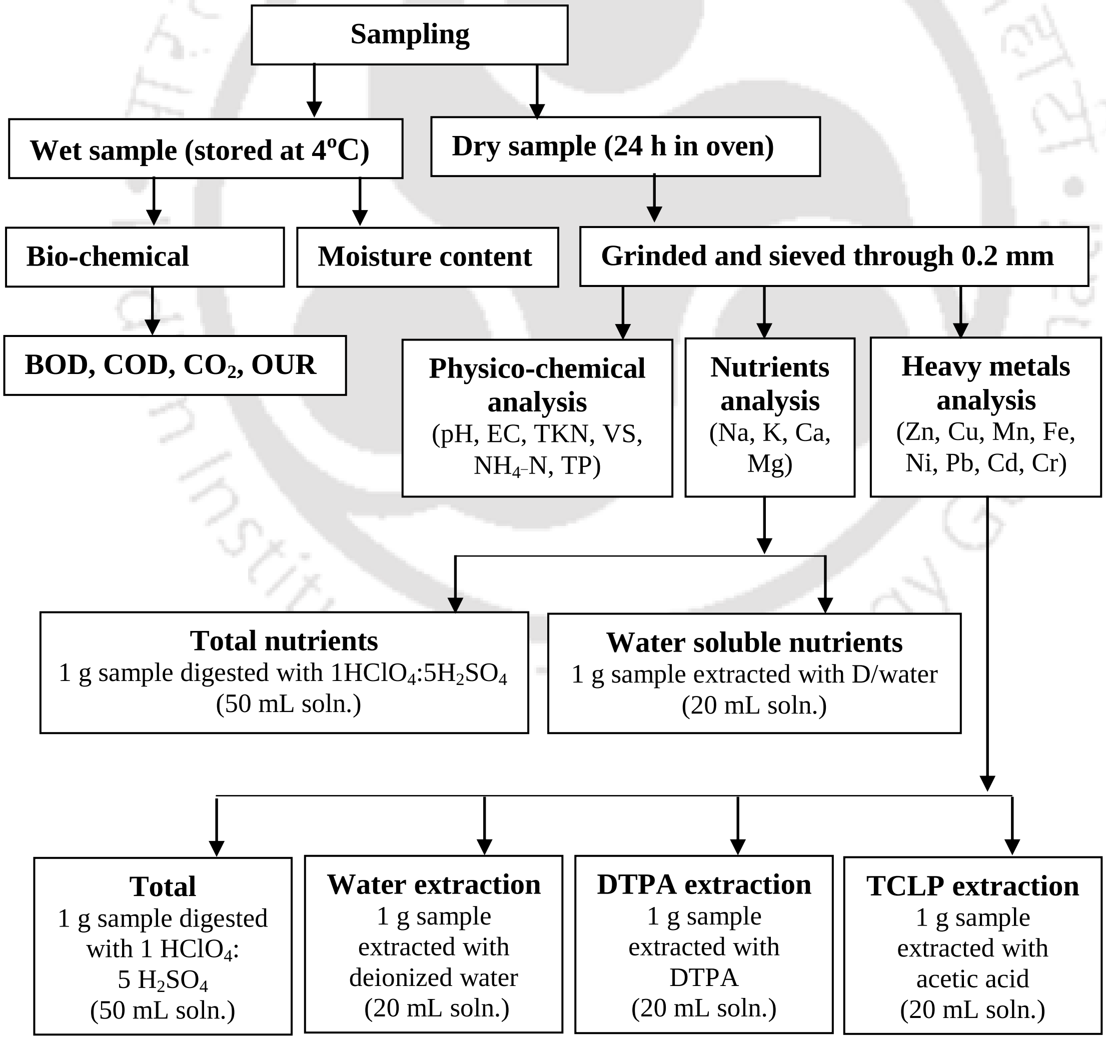

Fig. 3.4. Plan for physico-chemical, bio-chemical and metal analysis of samples

3.4.2 PHYSICO-CHEMICAL ANALYSIS

Temperature was monitored every 6 h using a digital thermometer throughout the composting period within the pile and rotary drum composter. The analysis plan is shown at Fig. 3.4. Moisture content (MC) was determined by weight loss of the wet compost sample (105ºC for 24 h in oven) using the gravimetric method (BIS: 10158–1982). 10 g of the sub-sample was shaken with 100 mL distilled water in a horizontal shaker for 2 h and kept for half an hour for settling down the solids. The pH of the supernatant was measured using a pH meter after calibration and correction for temperature (BIS: 10158–1982). Electrical Conductivity (EC) of the filtrate of the above mixture (using Watman filter paper No. 42) was measured using a conductivity meter. Volatile solids (VS) were determined by the weight loss of 10±0.1 g sub-sample from ignition (550ºC for 2 h in muffle furnace) (BIS: 10158–1982). Biodegradability is a parameter that relates initial and final content of the organic matter during composting. Biodegradability coefficient (K_b) was calculated for all trials using the following equation (Yadav and Garg, 2009):

$$K_b = \frac{(OM_i - OM_f)\,100}{OM_i\,(100 - OM_f)} \qquad \text{Eq. (1)}$$

where OM_f is the organic matter content at the end of process and OM_i is the organic matter content at the beginning of the process.

Total Kjeldahl nitrogen (TKN) was analyzed using the Kjeldahl method and NH_4–N using KCl extraction (Tiquia and Tam, 2000). For TKN analysis 0.2 g of dried sub-sample mixed with 3 g catalyst mixture of potassium sulphate and cupric sulphate (5:1) was digested with 10 mL conc. H_2SO_4 using block digestion equipment at 400ºC for 2 h (until end color of digested sample was green). After digestion, the digested sample was allowed to cool and made up to 100 mL with distilled water. 10 mL of diluted sample was taken in the distillation unit (Pelican Equipments Chennai, India) and about 10 mL of 40% NaOH was passed into the diluted solution. The distillate from the unit was collected in 25 mL boric acid mixed with indicator till the boric acid turned green. The collected distillate was titrated with 0.02N H_2SO_4 till purple colour developed.

For the analysis of NH_4–N, 5 g sub-sample with 50 mL of 2M KCl was taken in a reagent bottle and kept in a horizontal shaker for 2 h. After shaking, sample was filtered and supernatant was taken for NH_4–N analysis using Phenate method (APHA, 2005). 25 mL of the supernatant was taken in a 50 mL Erlenmeyer flask and 1 mL phenol solution, 1 mL sodium nitroprusside solution and 2.5 mL oxidizing solution were added with thorough mixing after each addition. The sample was wrapped with paraffin wrapper film and kept at room temperature (22–27ºC) in subdued light for at least 1 h till a stable color (stable for 24 h) developed. A blank and two other standards solution was prepared by diluting stock ammonia solution in the range of concentration of the sample for plotting standard curve. The absorbance was recorded at 640 nm.

3.4.3 BIO-CHEMICAL ANALYSIS

The biodegradable organic matter was measured as soluble biochemical oxygen demand (BOD) (by the dilution method, APHA, 1995) and soluble chemical oxygen demand (COD) (by the dichromate method, APHA, 1995) of supernatant of the blended mixture of 10 g sample in 100 mL deionized water. For the measurement of oxygen uptake rate (OUR), a dissolved oxygen (DO) probe was inserted below 5–7 cm of the surface of a liquid suspension of compost (8 g of wet sample in 500 mL of distilled water added with $CaCl_2$, $MgSO_4$, $FeCl_3$ and phosphate buffer at pH 7.2 made up according to the standard methods for BOD test procedures (APHA, 2005) and incubated at room temperature (24±2ºC)) contained in an airtight flask. The suspension was continuously stirred by means of a magnetic stirrer and the decrease in DO concentration was measured continuously till it reaches zero to determine OUR in mg O_2/g VS/day. For determination of CO_2 evolution rate, 20 g of wet sample was kept with 10 g oven dried soda lime in separate beakers inside an airtight 500 mL container for 24 h. The CO_2 evolution rate is determined from the difference in the initial weight and final weight of soda lime.

3.4.4 NUTRIENTS AND HEAVY METALS

For determination of nutrients and heavy metals, 0.2 g sub-sample was digested with 10 mL mixture of H_2SO_4 and $HClO_4$ (5:1) in block digestion system (Pelican equipments, Chennai, India) for 2 h at 300ºC and made up to 100 mL after allowing it to cool. The Flame Photometer (Systronic 128) was used for analysis of Na, K and Ca whereas Mg concentration was measured by atomic absorption spectrometer (AAS) (Varian Spectra 55B). For determination of total phosphorous (TP), 50 mL of diluted solution was taken in Nessler's tube and 1 mL of ammonium molybdate solution followed by 5 drops of freshly prepared stannous chloride solution were added. The absorbance of the developed blue colour was recorded at 690 nm for the determination of TP against standard calibration curve. The available phosphorous (AP) was extracted from 0.2 g sub-sample with bray solution (ammonium fluoride (NH_4F) dissolved with 17 mL concentrated hydrochloric acid and made up to 2 L with deionised water) made up to 50 mL.

The total concentration of Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr was measured using AAS. The water soluble heavy metals were determined after extraction of 2.5 g sample with 50 mL distilled water (sample: solution ratio = 1:20) at room temperature for 2 h in a shaker at 100 rpm (Ciavatta et al., 1993). The diethylene triamine penta-acetic acid (DTPA) extractable metals were obtained by mechanically shaking 4 g ground sample (screened through 0.22 mm sieve) with 40 mL of 0.005M DTPA, 0.01M $CaCl_2$ and 0.1M triethanolamine buffered to pH 7.3 at 100 rpm (Guan et al., 2011). The extractable efficiency (ŋ) of DTPA extractable heavy metals was calculated using following equation (Chen et al., 2010).

$$ŋ\ (\%) = \frac{(C_{DTPA})\ 100}{(C_{Total})} \qquad \text{Eq. (2)}$$

where C_{DTPA} is concentration of DTPA extractable heavy metal and C_{Total} is concentration of total heavy metals.

The leachable heavy metals of the solid samples were determined by the standard Method 13111–Toxicity characteristic leaching procedure (TCLP) (USEPA, 1992). According to this method, 5 g solid sample (size less than 9.5 mm) with 100 mL of acetic acid at pH 4.93±0.05 (pH adjusted with 1N NaOH) (sample: solution ratio = 1:20) was taken in 125 mL reagent bottle and kept at room temperature for 18 h in a shaker at 30±2 rpm. The suspensions of water, DTPA and TCLP extraction were centrifuged for five minutes at 10,000 rpm and filtered through Whatman no. 42 filter paper. The TCLP extracted solution was stored in a plastic reagent bottle at 4ºC for analysis of the selected heavy metals.

3.4.5 STATISTICAL ANALYSIS

All the results reported are the means of three replicates. One-way, two-way analysis and repeated measures treated with ANOVA (Analysis of variances) were made using Statistica software and SPSS package. The objective of statistical analysis is to determine any significant differences among the parameters analyzed during the composting process.

3.4.6 EQUIPMENT USED

The instruments and accessories for compost analysis are given at Table 3.4a and 3.4b respectively.

Table 3.4a. Instruments used for physico-chemical and bio-chemical analysis

Sl. No.	Parameters	Equipment/Instrument	Model and manufacturer
1	Temperature	Digital thermometer	Mextech multithermometer
2	MC	Hot air oven	International commercial traders
3	pH	pH meter	µ pH system 36, Systronics
4	EC	Conductivity meter VSI-04 Deluxe	VSI Electronics Pvt. Ltd.
5	VS	Muffle furnace	International Commercial Traders
6	TKN	Kjeldahl distillation unit	Distyl M, Pelican Equipments
7	NH_4–N	UV visible spectrophotometer	Varian Cary 50 Bio
8	Na, K, Ca and Mg	Flame photometer	Systronic 128
9	BOD	BOD Incubator	International Commercial Traders
10	COD	COD Digester	HACH
11	CO_2 evolution rate		
12	OUR	DO meter	Eutech Instrumets Pvt. Ltd.
13	Heavy metal	Atomic absorption spectrophotometer	Varian Spectra 55B

Table 3.4b. Accessories used for physico-chemical and bio-chemical analysis

Sl. No.	Purpose	Equipment/Instrument	Model and manufacturer
1	Grinding of sample	Grinder	USHA
2	Sieving of grinded sample	Sieve (0.22 mm)	Unique Drawing & Survey Emporium
3	Acid digestion of sample	Block digestion system	Pelican Equipments Chennai, India
4	Centrifuge	Centrifuge	R- 24, REMI instruments Limited
5	Weighing	Electronic balance	WENSAR, Weighing scale Ltd.

Chapter 4

COMPOSTING AND VERMICOMPOSTING OF PHUMDI BIOMASS

This chapter deals with the study on the agitated pile composting, rotary drum composting and vermicomposting of phumdi biomass blended with cattle manure and rice husk/sawdust carried out as Phase 1 of the research. The chapter starts with a discussion on the initial characteristics of phumdi biomass and other feedstock used in the process and further discusses the variation of physico-chemical and bio-chemical parameters, as well as the bioavailability of nutrients and heavy metals during the process.

4.1 INITIAL CHARACTERISATION OF PHUMDI BIOMASS AND OTHER FEEDSTOCK MATERIALS

The initial characteristics of the composting/vermicomposting materials used in phase 1 are shown at Table 4.1. The initial moisture content (MC) of phumdi biomass was high (88.9%) and so the use of either rice husk or sawdust to adjust the moisture was required (Table 4.1a). Phumdi biomass also contained 70.4±0.56% volatile solids (VS), 2.01±0.04% of total Kjeldahl nitrogen (TKN) and 0.29±0.003% of total phosphorous (TP) which were higher than water hyacinth (Singh and Kalamdhad, 2012). The available phosphorous (AP) of the biomass and feedstock were significantly lower than the TP. The initial pH of the phumdi biomass, cattle manure, rice husk and sawdust (i.e. 6.01±0.01, 7.11±0.04, 6.51±0.02 and 6.32±0.04, respectively) were within the optimal range required for the development of bacteria (6.0–7.5) and fungi (5.5–8.0) (Amir et al., 2005) or for the survival of earthworms (5.5–8.5) (Yadav and Garg, 2011a) during composting or vermicomposting. The soluble BOD and COD of cattle manure were higher than phumdi biomass indicating more degradable carbonaceous matter. The higher oxygen uptake rate (OUR) and the CO_2 evolution rate in cattle manure were indicative of the rich microbial activity in the substrate. The electrical conductivity (EC) reflects the salinity of the materials due to the presence of exchangeable sodium, chloride, potassium, nitrate, sulphate and ammonia salts (Wong et al., 2001) or due to the presence of the highly conductive metal ions (Singh and Kalamdhad, 2012). The concentrations of Na, K, Ca and Mg of phumdi biomass were in the order K > Na > Mg >

Ca. The concentration of the water soluble (WS) nutrients were significantly lower than the concentration of the total nutrients of the phumdi biomass (Table 4.1b).

Table 4.1. Initial characterization of phumdi biomass and feedstock
a. Physico-chemical and bio-chemical parameters

Parameters	Feed stock materials			
	Phumdi	Cattle manure	Rice husk	Sawdust
MC (%)	88.9 ± 1.2	85.9 ± 0.9	9.1 ± 0.15	9.7 ±0.14
pH	6.01 ± 0.01	7.11 ± 0.04	6.51 ± 0.02	6.32 ± 0.04
EC (dS/m)	3.1 ± 0.03	3.5 ± 0.05	1.8 ± 0.01	0.7 ± 0.02
VS (%)	70.4 ± 0.56	72.4 ± 0.21	78.7 ± 0.21	81.9 ± 0.22
TKN (%)	2.10 ± 0.04	1.50 ± 0.02	0.70 ± 0.01	0.40 ± 0.06
Ammonical nitrogen (NH_4-N) (mg/kg)	350 ± 2.0	660 ± 1.5	39 ± 0.5	40 ± 0.5
TP (mg/kg dry mass)	2940 ± 30	3200 ± 26	1001 ± 16	200 ± 4
AP (mg/kg dry mass)	1960 ± 12	1805 ± 10	700 ± 2	81 ± 0.4
Soluble BOD (mg/kg wet mass)	3830 ± 30	4564 ± 20	1254 ± 25	1553 ± 11
Soluble COD (mg/kg wet mass)	7040 ± 40	9250 ± 40	4509 ± 30	4020 ± 14
OUR (mg/g VS/day)	10.8 ± 0.15	12.9 ± 0.16	1.8 ± 0.04	1.3 ± 0.06
CO_2 evolution rate (mg/g VS/day)	4.3 ± 0.05	5.6 ± 0.02	0.7 ± 0.01	0.6 ± 0.01

Note: (Mean ± SD, n = 9), SD −standard deviation, n −no. of observations

Table 4.1. Initial characterization of phumdi biomass and feedstock
b. Total and WS nutrients

Parameters	Feedstock materials (mg/kg dry mass)			
	Phumdi	Cattle manure	Rice husk	Sawdust
Total nutrients				
Na	5562 ± 36	2809 ± 7	2109 ± 12	1102 ± 13
K	12252 ± 94	991 ± 9	8259 ± 21	701 ± 8
Ca	3901 ± 12	5885 ± 17	3890 ± 11	2415 ± 10
Mg	4678 ± 53	6961 ± 23	1001 ± 19	3031 ± 13
WS nutrients				
Na	914 ± 7	689 ± 7	542 ± 7	301 ± 4
K	5580 ± 32	291 ± 6	392 ± 7	199 ± 4
Ca	1349 ± 17	2485 ± 21	1402 ± 31	418 ± 11
Mg	852 ± 12	965 ± 11	584 ± 13	816 ± 2

Note: (Mean ± SD, n = 9), SD −standard deviation, n −no. of observations

Phumdi biomass indicated presence of heavy metals in the order Fe > Pb > Mn > Ni > Zn > Cr > Cd > Cu (Table 4.1c). The total concentrations of heavy metals indicate the extent of contamination, but provide little information about their potential for mobility and bioavailability in the environment (Cai et al., 2007). The WS, diethylene triamine penta-acetic acid (DTPA) extractable and toxicity characteristic leaching procedure

(TCLP) extractable forms of heavy metals represent the bioavailable forms. Cd and Ni were not present in the highly bioavailable WS form.

Table 4.1. Initial characterization of phumdi biomass and feedstock
c. Total, WS, DTPA extractable and TCLP extractable heavy metals

Parameters	Feed stock materials (mg/kg dry mass)			
	Phumdi	Cattle manure	Rice husk	Sawdust
Total heavy metals				
Zn	182 ± 1.5	160 ± 2.0	117 ± 2.5	107 ± 2.3
Cu	58.5 ± 1.0	47.8 ± 0.8	29.5 ± 1.0	20.5 ± 1.0
Mn	733 ± 7.0	527 ± 1.5	189 ± 8.5	143 ± 3.5
Fe	14554 ± 32.5	1869 ± 14.2	3645 ± 16.3	2751 ± 12.1
Ni	247 ± 2.6	237 ± 2.4	146 ± 2.4	281 ± 1.8
Cd	70.5 ± 0.9	47.9 ± 1.1	41.0 ± 1.0	58.1 ± 0.5
Pb	786 ± 1.2	747 ± 2.5	60.4 ± 0.8	770.0 ± 2.1
Cr	97.5 ± 1.8	122 ± 4.2	9.4 ± 0.10	79.6 ± 0.21
WS heavy metals				
Zn	12.5 ± 0.5	6.3 ± 0.04	4.6 ± 0.07	2.2 ± 0.04
Cu	9.0 ± 0.1	3.7 ± 0.8	2.5 ± 1.0	0.9 ± 0.02
Mn	89.9 ± 2.4	22.4 ± 0.9	21.9 ± 0.8	5.2 ± 0.22
Fe	104 ± 5.5	139 ± 11.8	74 ± 1.7	122 ± 2.5
Ni	ND	ND	ND	ND
Cd	ND	ND	ND	ND
Pb	11.5 ± 1.0	ND	ND	ND
Cr	12.7 ± 1.1	6.5 ± 0.04	1.2 ± 0.04	2.2 ± 0.12
DTPA extractable heavy metals				
Zn	107.0 ± 5.5	46.4 ± 1.5	34.7 ± 1.1	10.8 ± 0.70
Cu	12.5 ± 0.5	6.8 ± 0.6	5.5 ± 0.5	1.7 ± 0.20
Mn	290 ± 2.1	230 ± 2.5	76 ± 2.5	40.4 ± 0.90
Fe	123 ± 2.2	374 ± 11.5	192 ± 3.1	8.1 ± 0.20
Ni	1.4 ± 0.15	0.1 ± 0.01	ND	0.08 ± 0.03
Cd	0.9 ± 0.05	ND	ND	ND
Pb	20.4 ± 0.7	ND	ND	ND
Cr	7.4 ± 0.4	12.4 ± 0.2	1.8 ± 0.05	0.6 ± 0.02
TCLP extractable heavy metals				
Zn	110.5 ± 5.5	32.3 ± 1.4	28.6 ± 1.2	15.4 ± 1.40
Cu	14.5 ± 0.5	8.8 ± 0.6	7.5 ± 0.5	2.1 ± 0.10
Mn	390 ± 5.1	451 ± 4.5	85 ± 2.5	43.9 ± 1.30
Fe	229 ± 32.5	320 ± 12.5	144 ± 11.5	13.0 ± 0.20
Ni	7.4 ± 0.5	1.9 ± 0.04	0.8 ± 0.02	0.9 ± 0.05
Cd	2.8 ± 0.02	1.4 ± 0.05	3.1 ± 0.05	7.9 ± 0.10
Pb	34.8 ± 1.4	2.81 ± 0.14	7.85 ± 0.12	0.94 ± 0.04
Cr	69.8 ± 1.5	14.54 ± 0.15	5.43 ± 0.08	4.01 ± 0.15

Note: (mean ± SD, n = 9), ND −not detected, SD −standard deviation, n −no. of observation

4.2 AGITATED PILE COMPOSTING OF PHUMDI BIOMASS

4.2.1 TEMPERATURE PROFILE

The temperature variations during the composting of the five piles are shown at Fig. 4.2.1. The temperature profiles of the figure show rapid increase from the 5th day of the composting process in trial 1, 2, 3 and 4 due to the release of heat in the piles caused by microbial catabolism. Trial 4 containing maximum proportion of cattle manure (Table 3.1a) recorded the highest peak temperature (46.8ºC) on the 8th day of composting process. Trial 3 also recorded the second highest peak temperature of 45.8ºC on the same day. However, the control trial 5 attained a maximum temperature of 31.7ºC only on the 10th day of the process showing that effective pile composting of phumdi biomass was not feasible without addition of readily degradable carbonaceous matter and appropriate bulking agents. In terms of the temperature profiles, trial 3 and 4 more or less gave the best combination for composting of phumdi biomass. The thermophilic phases in the phumdi compost piles were achieved only after 6 days in trial 4 and 3 as compared to 3 days in case of water hyacinth compost piles (Singh and Kalamdhad, 2012) indicating slower degradation of phumdi biomass compared with water hyacinth. Some early research indicates that high microbial activity can be possible even at low temperatures (Suler and Finstein, 1977; McKinley and Vestal, 1984). Low ambient temperature (17.1–21ºC), heat retention properties of the composting materials, etc. might be the reason for the lower temperature profile (Koivula et al., 2004; Margesin et al., 2005). The temperatures started to decrease prominently from 11th day of the composting process and there was little variation after day 27.

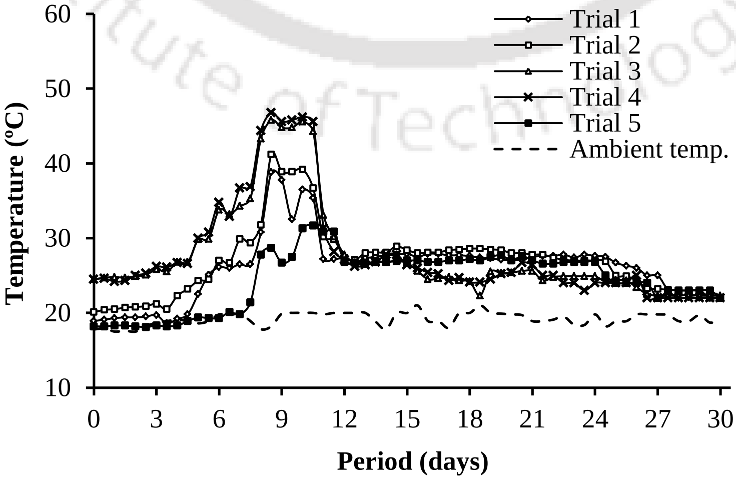

Fig. 4.2.1. Temperature profiles of phumdi piles during composting

4.2.2 PHYSICO-CHEMICAL AND BIO-CHEMICAL ANALYSIS

The pH of trial 1, 2 and 5 increased during the composting process (trial 1 from 6.1 to 7.2; trial 2 from 6.1 to 7.3; and trial 5 from 5.9 to 7.1). In case of trial 3 and 4, the pH values after an initial downward trend increased from 6.5 to 7.7 and 7.0 to 7.8 before decreasing to 7.6 and 7.7, respectively (Fig. 4.2.2). The decomposition of organic matter (OM) forming intermittent organic and inorganic acids, the release of CO_2, the possible volatilization of ammonia (at pH > 7) or the nitrification of ammonical nitrogen or assimilating back of the ammonical nitrogen (NH_4–N) by the microbes lower the pH values (Wong et al., 2001; Beck-Friis et al., 2003) while ammonification or mineralization of organic nitrogen (Wong et al., 2001), release of basic salts or degradation (decarboxylation) of organic acids (Cayuela et al., 2008) due to the microbial activity raises the pH values. The variation of pH was similar with the results of pile composting of water hyacinth (Prasad et al., 2013).

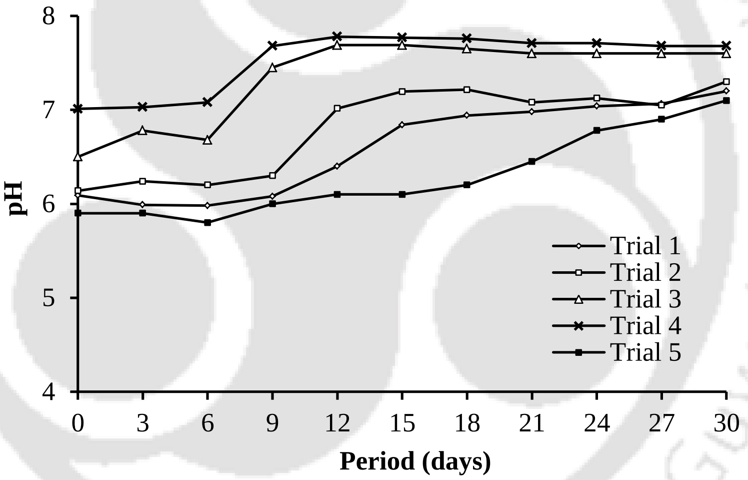

Fig. 4.2.2a. Variation of pH during pile composting of phumdi

The pH in composts is influenced by three acid-base systems. One is the carbonic system, with CO_2, which is formed during decomposition and can escape as a gas or dissolve in the liquid forming carbonic acids, bicarbonates and carbonates. This system has two dissociation constants (pKa) 6.35 and 10.33 at 25ºC, and thus it tends to neutralise the pH of the compost, increasing low and reducing high pH values. The second system is the NH_4–N, which is formed when protein is decomposed. During the initial phase of composting, most of the metabolised nitrogen is retained by growing microorganisms, but during the high rate phase of composting NH_4–N is released. The ammonia system has a pKa of 9.24 at 25ºC and thus increases the pH towards this value.

The third system is composed of several organic acids of which acetic and lactic acid dominate. This system can reduce pH down to 4.14, which is the pKa of lactic acid at 25ºC (Sundberg, 2005) and is relevant at the beginning of composting. ANOVA analysis shows significant difference in the variation of pH among all trials ($P < 0.05$). The pH is an important parameter which strongly influences the dissolution of heavy metals at the biomass surface and also the solution chemistry of heavy metals: hydrolysis, precipitation, complexation of organic and/or inorganic ligands, redox reaction that controls the bioavailability of the heavy metals (Wang et al., 2009).

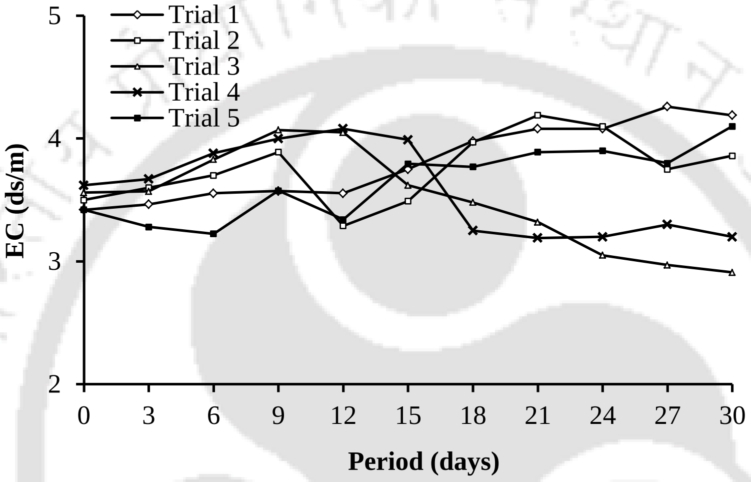

Fig. 4.2.2b. Variation of EC during pile composting of phumdi

The EC is measured because high salinity is not desirable for plant growth (Huang et al., 2004; Lin, 2008). A common disadvantage of compost as fertilizer is weakening of the water intake ability of plants due to osmotic effect from high salt concentrations (Koivula et al., 2004). EC about 4 dS/m or higher in composts will adversely influence plant growth, e.g. low germination rate, withering, etc. (Gao et al., 2010). Some soluble salts may be required in composts as plants take up nutrients in soluble forms. There was an initial increase in the EC of the compost materials of all trials which might be due to the release of mineral salts such as phosphates and ammonium ions during the decomposition of OM (Fang and Wong, 1999). The precipitation of mineral salts could be the reasons for the decrease of EC in trial 3 and 4 after 15 days (Wong et al., 2001). The release of humic substances that interact with the highly conductive exchangeable metal ions to form insoluble complexes at the later phase of composting might have also decreased the EC of the composts (Amir et al., 2005). After 30 days, the EC of trial 4 and 3 were only 2.9 and 3.0 dS/m, respectively (Fig. 4.2.2b). There was no reduction of

EC in trial 1, 2 and 5 after the end of the composting period indicating that the phumdi composts of these trials might be phyto-toxic. ANOVA analysis shows significant difference in the EC variation among all trials ($P < 0.05$).

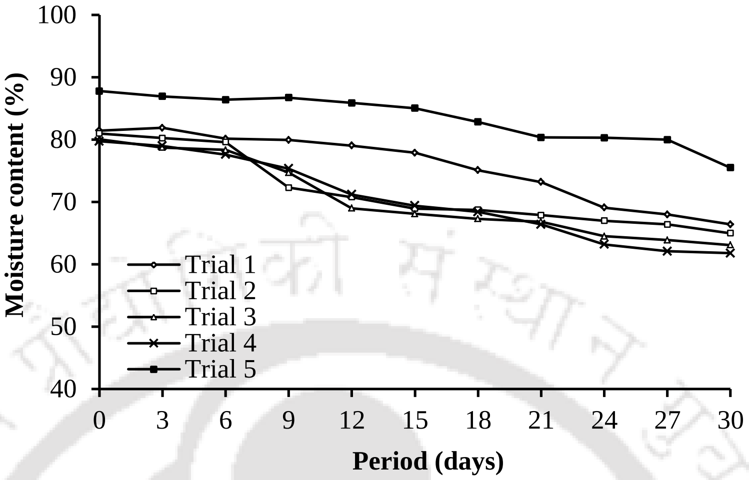

Fig. 4.2.2c. Variation of MC during pile composting of phumdi

Moisture is liberated as water vapor during the composting process and the loss of moisture can be viewed as an index of decomposition rate (Liao et al., 1996). The net loss of H_2O could also occur due to the convective transport of moisture during turning. The composting material should have bare minimum moisture content for the survival of microorganisms. On the other hand the rate of oxygen diffusion of the pores decreases when moisture content is high. A maximum limit of 60–80% moisture depending on the composting materials is prescribed by the US Composting Council (TMECC, 2002). The highest moisture lost was in trial 4 (22.5%) followed by trial 3 (21.2%) indicating that trial 4 and 3 had the highest decomposition rate and the result was in agreement with the temperature profile of the piles (Fig. 4.2.2c). Least moisture loss is seen in trial 5 (14%). The MCs in all the piles were mostly above 60% during the active phase and addition of water in the piles was not required. ANOVA test indicates significant variation of MC among the trials ($P < 0.05$).

The VS concentration is an indicator of OM content and decreases during the composting process due to degradation of the organic components by the microorganisms and loss of carbon in the form of CO_2. There were no significant changes in the concentration of the VS in all the five trials during the first 6 days of the composting process (Fig. 4.2.2d). After 6 days, there was remarkable reduction of VS concentration in all the trials and the trend was in agreement with temperature profile of the compost piles where the temperature started rising only on the 6th day of the composting process. The highest reduction of VS was observed in trial 4 (20.4%) due to the presence of more degradable cattle manure. Trial 5 achieved a reduction of only 6.4% indicating that amendment of phumdi biomass was necessary for effective composting. There was no further significant VS reduction in trial 4 and 3 after 21 days indicating decrease in microbial activity. In case of water hyacinth composting, maximum reduction (31%) was observed in the pile having 40% cattle manure (Prasad et al., 2013). This again shows that the phumdi biomass is difficult to degrade as compared to water hyacinth. ANOVA test shows significant difference in the reduction of VS among all trials ($P < 0.05$). The biodegradability coefficient (K_b) is highest in trial 4 (0.48) followed by trial 3 (0.45), trial 2 (0.41), trial 1 (0.37) and trial 5 (0.19).

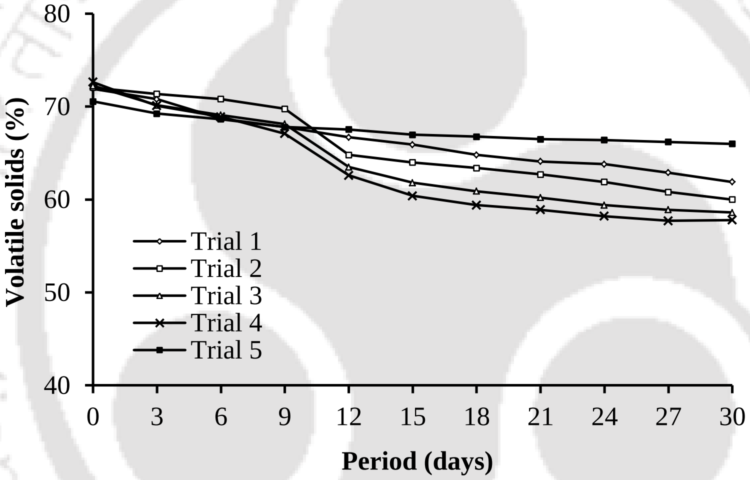

Fig. 4.2.2d. Variation of VS during pile composting of phumdi

Low soluble BOD concentration indicates stable compost due to the aerobic microbial degradation of the readily bioavailable compounds. Oxygen consumption will continue if soluble BOD is high indicating unstable compost. During land applications of such composts for crops, the bio-chemical processes can continue and strip the nutrients from soil (Wang et al., 2004). The soluble BOD decreased during the composting process in all trials (Fig. 4.2.2e) due to degradation of easily degradable WS compounds. Trial 4 recorded highest reduction of soluble BOD (77.5%) followed by trial 3 (73.3%) after 30 days of composting. There were no significant changes in soluble BOD concentrations of the phumdi composts of trial 3 and 4 after 24 days. ANOVA test indicates significant difference in the reduction of soluble BOD in all trials during the composting process ($P < 0.05$).

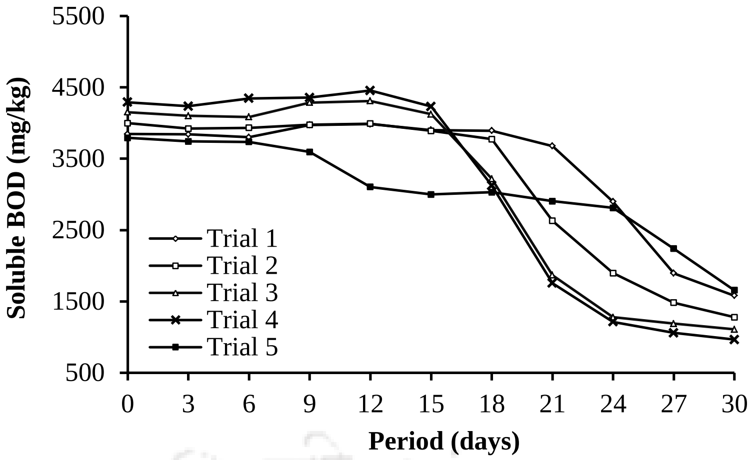

Fig. 4.2.2e. Variation of soluble BOD during pile composting of phumdi

The CO_2 evolution rate and the OUR are direct indicators for microbiological activity in the compost piles. OUR and CO_2 evolution rate are measures for stability of compost as unstable compost has high demand of oxygen and high evolution of CO_2 (Bernal et al., 2009). The CO_2 evolution rate of trial 1, 2, 3 and 4 initially increased and then decreased after 9 days during the composting process (Fig. 4.2.2f). The CO_2 evolution rate of trial 4 and 3 after 30 days decreased from 6.4 and 6.1 mg/g VS/day to 1.3 and 1.4 mg/g VS/day, respectively. The results show that phumdi biomass composting can be achieved with cattle manure and rice husk in appropriate proportions and obtained stable compost. The OUR of trial 1, 2, 3 and 4 also showed temporal decrease after 9 days and the result is in agreement with CO_2 evolution rate. The OUR of trial 3 and 4 reduced to 4.8 and 4.2 mg/g VS/day. From the results of CO_2 evolution rate and OUR, the phumdi compost of trial 4 and 3 can be considered stable (TMECC, 2002).

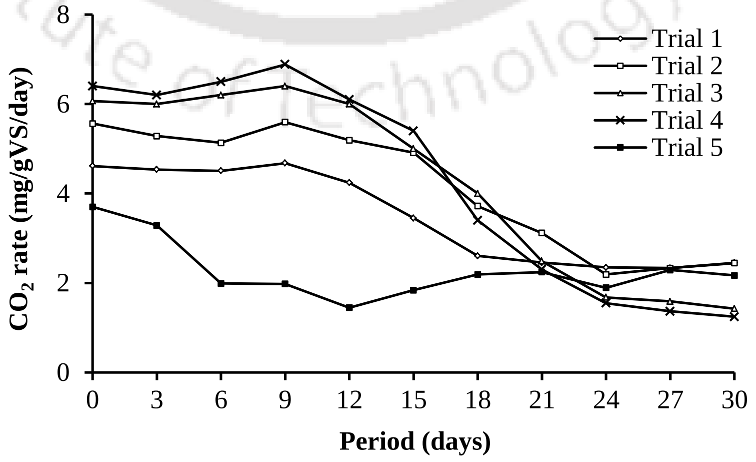

Fig. 4.2.2f. Variation of CO_2 evolution rate during pile composting of phumdi

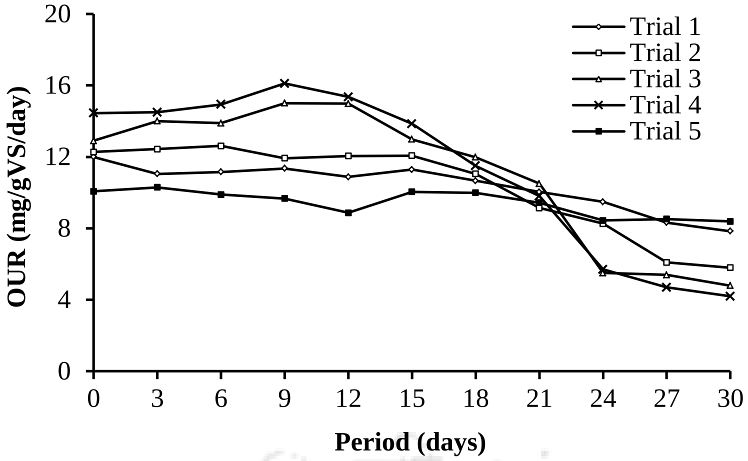

Fig. 4.2.2g. Variation of OUR during pile composting of phumdi

4.2.3 NUTRIENTS

The nitrogen content depends on the rate of ammonia volatilization and OM degradation (Bernal et al., 1998). If the ammonia volatilization is more, there will be decrease in the total nitrogen concentration. On the other hand, if the OM degradation is higher, there will be increase in the total nitrogen content due to the net loss in dry mass from the release of CO_2 (Huang et al., 2004). The TKN concentration was highest in trial 5 containing only green phumdi biomass. Trial 4 showed the highest increase in the concentration of TKN (32.4%) followed by trial 3 (24.4%) due to the higher loss of dry mass (Fig. 4.2.3a). ANOVA analysis shows significant difference of the variation of TKN concentration among all the phumdi trials during the composting ($P < 0.05$).

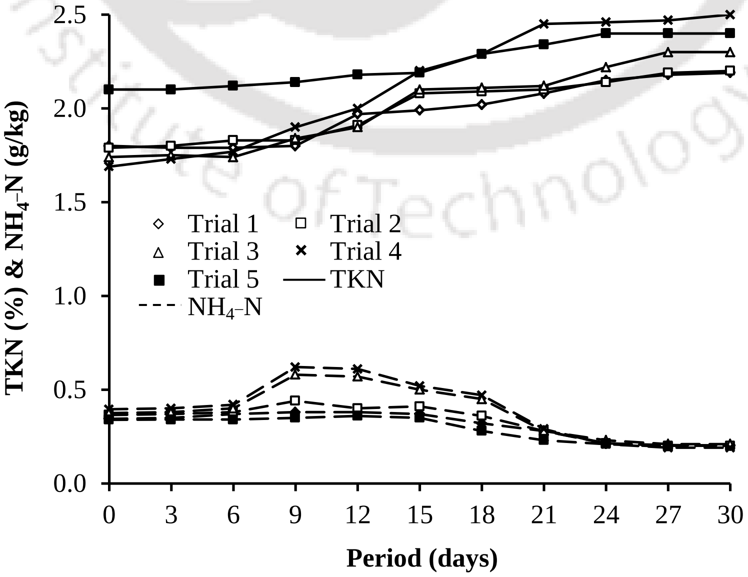

Fig. 4.2.3a. Variation of TKN and NH_4–N during pile composting of phumdi

Due to mineralization or ammonification, organic forms of nitrogen (i.e. protein, amino sugar and nucleic acid) are converted to ammonical nitrogen (NH_4–N) resulting in initial increase of NH_4–N content in trial 3 and 4 (He et al., 2003). The gradual decrease in NH_4–N concentration in all the piles during the composting process could be for many reasons such as volatilization of ammonia ($pH > 7$) (Beck-Friis et al., 2003); immobilization or assimilation of NH_4–N by the microorganisms; and nitrification or denitrification (Sundberg, 2005). Trial 4 recorded lowest NH_4–N concentration (190±4 mg/kg) after the process. The NH_4–N contents of phumdi composts of all trials after 30 days were within the limits (≤ 400 mg/kg) and there was no risk of phytotoxicity (Bernal et al., 1998). ANOVA analysis also indicates significant difference in the variation of NH_4–N concentration amongst all trials during the composting ($P < 0.05$).

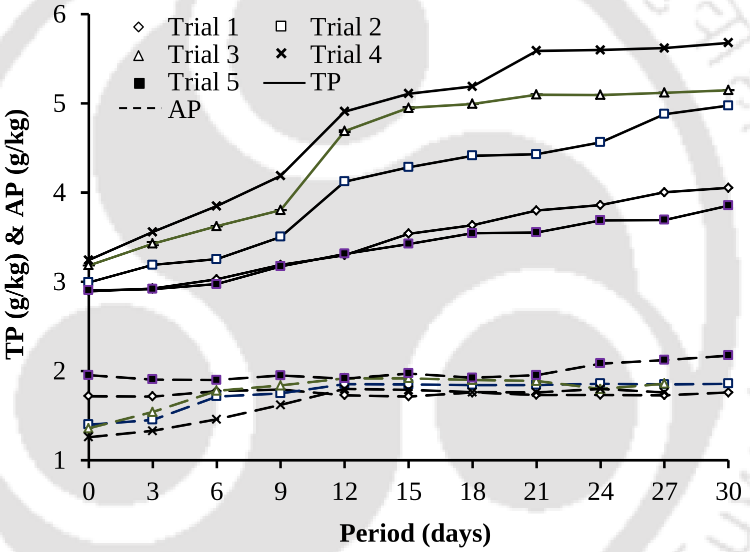

Fig. 4.2.3b. Variation of TP and AP during pile composting of phumdi

Similar to TKN, the concentration of TP during phumdi pile composting gradually increased also due to net loss in dry mass (Fig. 4.2.3b). Phosphorous (P) in OM is not only utilized by the micro-organisms for their body metabolism but is also an essential element for plant growth. It is believed that plants take up P in the plant available forms i.e. soluble form as HPO_4^{2-}; portions of less soluble forms such as Ca, Al and Fe phosphates that would solubilize via dissolution or desorption; and organic P that would undergo mineralization (Rivin, 2007). The AP increased prominently in trial 2, 3 and 4. The change in AP is dependent on the type of the initial feedstock and increases due to OM loss but decreases due to formation of complexes and/or phosphates with Ca and Mg ions (Chanyasak et al., 1983; Traore et al., 1999).

Table 4.2.1. Variation of total Na, K, Ca and Mg during pile composting of phumdi

Days	Total nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	5503 ± 30	5395 ± 42	5300 ± 61	4915 ± 34	5607 ± 36
6	5527 ± 42	6123 ± 43	6105 ± 55	6075 ± 50	5623 ± 53
12	5628 ± 31	6364 ± 54	6935 ± 56	6722 ± 38	5982 ± 43
18	6056 ± 26	6704 ± 44	7316 ± 70	7151 ± 35	6178 ± 47
24	6308 ± 47	6846 ± 62	7536 ± 60	7698 ± 46	6308 ± 37
30	6423 ± 52	7081 ± 60	7759 ± 98	8260 ± 32	6447 ± 33
	K				
0	9729 ± 108	9545 ± 58	9344 ± 54	9226 ± 46	12307 ± 94
6	10230 ± 115	9701 ± 89	10818 ± 104	9890 ± 99	12354 ± 104
12	10680 ± 125	9891 ± 61	12391 ± 108	11327 ± 104	13955 ± 110
18	11557 ± 124	10417 ± 65	12900 ± 100	12998 ± 106	14249 ± 103
24	11847 ± 103	10761 ± 99	12479 ± 119	13079 ± 106	14616 ± 102
30	12108 ± 105	11993 ± 91	12992 ± 105	13143 ± 102	14628 ± 108
	Ca				
0	4230 ± 51	4991 ± 43	5081 ± 47	5245 ± 61	3951 ± 72
6	4529 ± 63	5225 ± 48	5318 ± 54	5334 ± 21	3984 ± 32
12	4845 ± 47	5657 ± 60	5588 ± 32	6415 ± 54	4499 ± 44
18	4998 ± 43	5829 ± 43	5765 ± 12	6693 ± 93	4875 ± 69
24	5136 ± 37	5970 ± 39	5929 ± 13	6787 ± 13	4951 ± 55
30	5246 ± 38	6191 ± 38	6435 ± 47	7746 ± 62	4835 ± 47
	Mg				
0	4723 ± 23	4861 ± 39	5060 ± 74	5126 ± 36	4599 ± 53
6	4718 ± 27	4623 ± 55	5197 ± 60	5280 ± 47	4817 ± 20
12	4722 ± 30	4924 ± 59	5790 ± 55	6039 ± 64	4821 ± 45
18	4924 ± 49	4746 ± 61	5881 ± 43	6190 ± 65	4863 ± 51
24	5038 ± 59	4904 ± 77	5950 ± 33	6350 ± 55	5000 ± 34
30	5180 ± 47	5355 ± 45	6087 ± 42	6350 ± 45	5035 ± 56

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

The changes in the concentrations of total Na, K, Ca and Mg are shown at Table 4.2.1. The concentrations of these nutrients increased due to loss of dry mass of the materials caused by the decomposition of the OM resulting in release of CO_2 and subsequent mineralization during the process (Singh and Kalamdhad, 2013a). The argument was enforced by the highest increase of the concentration of the nutrients of trial 4 compost, which indicated the highest reduction of VS. The total concentration of these nutrients increased in the range 15–68% for Na, 19–42.5% for K, 22.4–34.3% for Ca and 9.5–23.9% for Mg. The final concentrations of K (1.2–1.5%), Ca (0.5–0.8%), Mg (0.5–0.6%) and Na (0.6–0.8%) of the composts obtained from all trials were near the prescribed limits (Barker, 1997; Bord na Mona, 2003; ALCL, 2004) and in the decreasing order K > Na > Mg > Ca.

Table 4.2.2. Variation of WS Na, K, Ca and Mg during pile composting of phumdi

Days	WS nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	703 ± 2	688 ± 2	669 ± 4	649 ± 2	717 ± 2
6	708 ± 2	672 ± 3	651 ± 3	627 ± 4	716 ± 4
12	844 ± 4	932 ± 2	1012 ± 2	908 ± 2	736 ± 4
18	874 ± 6	959 ± 4	1187 ± 4	1183 ± 3	750 ± 6
24	887 ± 7	1005 ± 3	1204 ± 5	1129 ± 2	758 ± 4
30	917 ± 2	997 ± 2	1237 ± 2	1178 ± 4	772 ± 5
	K				
0	4250 ± 12	4155 ± 10	4028 ± 11	3825 ± 12	5680 ± 22
6	4445 ± 14	4354 ± 12	4626 ± 12	4106 ± 14	5652 ± 21
12	5363 ± 15	4925 ± 14	5991 ± 14	5399 ± 15	6208 ± 20
18	5470 ± 16	5091 ± 12	5987 ± 21	5811 ± 16	6309 ± 24
24	5530 ± 17	5288 ± 15	6098 ± 15	5712 ± 17	6374 ± 21
30	5466 ± 18	5428 ± 16	6178 ± 16	5706 ± 21	6661 ± 18
	Ca				
0	1472 ± 11	1559 ± 12	1679 ± 16	1733 ± 14	1389 ± 17
6	1560 ± 15	1767 ± 12	1836 ± 21	1540 ± 12	1391 ± 16
12	1782 ± 21	2139 ± 15	2267 ± 12	2309 ± 11	1449 ± 18
18	1809 ± 17	2138 ± 17	2307 ± 11	2354 ± 11	1475 ± 10
24	1857 ± 12	2118 ± 14	2292 ± 12	2323 ± 19	1491 ± 15
30	1854 ± 22	2229 ± 20	2295 ± 10	2378 ± 14	1511 ± 15
	Mg				
0	838 ± 5	875 ± 2	906 ± 5	941 ± 7	872 ± 2
6	863 ± 6	867 ± 2	896 ± 7	823 ± 5	899 ± 8
12	1010 ± 5	1020 ± 5	1130 ± 6	1118 ± 4	897 ± 7
18	1020 ± 6	1021 ± 4	1173 ± 6	1186 ± 4	917 ± 4
24	978 ± 4	1043 ± 4	1212 ± 4	1174 ± 4	922 ± 5
30	1041 ± 5	1060 ± 2	1240 ± 9	1176 ± 6	928 ± 6

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

The concentrations of the WS nutrients the final composts increased in the range 7.8–84.9% for Na, 17.3–53.4% for K, 8.8–42.9% for Ca and 6.4–36.8% for Mg (Table 4.2.2). The concentrations of these WS alkaline earth metals increased after the process also due to concentration effect caused by the net the loss of dry mass (Faridullah et al., 2014). The concentrations did not follow a particular trend during the process and there was possibility of the formation of insoluble mineral precipitates and complexes (Rivin, 2007). The variation in concentration of WS nutrients among all trials was significant ($P < 0.05$).

4.2.4 TOTAL HEAVY METALS

The changes in concentrations of Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr of phumdi compost are shown at Table 4.2.3. The total concentrations of the heavy metals of the composts increased due to weight loss of the dry matter from the decomposition of the

Table 4.2.3. Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi

Days	Total heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	172 ± 2.9	165 ± 2.6	163 ± 2.4	161 ± 0.8	181 ± 2.8	206 ± 1.5	197 ± 2.3	186 ± 2.3	182 ± 2.8	242 ± 3.0
6	175 ± 2.4	171 ± 1.4	168 ± 3.3	166 ± 2.4	183 ± 2.5	210 ± 2.7	205 ± 3.3	200 ± 2.2	186 ± 2.3	246 ± 2.5
12	188 ± 2.5	179 ± 2.7	200 ± 1.8	183 ± 2.8	190 ± 2.6	216 ± 2.9	211 ± 2.5	212 ± 2.3	194 ± 2.1	247 ± 2.1
18	193 ± 2.7	182 ± 1.6	205 ± 1.9	188 ± 1.7	197 ± 0.9	220 ± 1.3	213 ± 2.1	215 ± 1.9	212 ± 3.1	240 ± 2.8
24	198 ± 0.5	193 ± 2.1	207 ± 2.0	206 ± 1.8	204 ± 1.8	226 ± 1.5	220 ± 2.1	222 ± 1.6	225 ± 1.5	242 ± 1.3
30	202 ± 3.3	196 ± 2.8	211 ± 1.5	220 ± 1.5	209 ± 1.1	230 ± 1.5	230 ± 2.5	229 ± 1.9	232 ± 1.5	253 ± 1.5
	Cu					**Pb**				
0	51.7 ± 0.5	42.6 ± 0.5	39.5 ± 0.4	39.6 ± 0.6	55.0 ± 0.6	718 ± 7.5	671 ± 3.3	628 ± 2.6	653 ± 6.5	755 ± 2.0
6	55,0 ± 0.3	44.1 ± 0.5	40.3 ± 0.3	36.3 ± 0.9	55.3 ± 0.4	708 ± 7.5	707 ± 5.0	649 ± 2.1	705 ± 2.6	764 ± 4.5
12	55.5 ± 0.3	49.5 ± 0.9	41.8 ± 0.3	42.9 ± 0.8	59.0 ± 0.3	806 ± 3.5	749 ± 3.5	650 ± 2.5	688 ± 3.5	805 ± 3.1
18	59.8 ± 0.8	51.9 ± 0.5	46.9 ± 0.9	47.5 ± 1.0	61.8 ± 0.8	815 ± 4.2	781 ± 4.5	690 ± 3.5	703 ± 2.1	815 ± 2.3
24	62.5 ± 0.5	54.1 ± 0.7	50.6 ± 0.6	49.5 ± 1.1	65.2 ± 0.4	838 ± 3.0	794 ± 4.5	723 ± 6.5	785 ± 3.5	821 ± 3.3
30	66.7 ± 0.7	56.3 ± 0.4	52.6 ± 0.4	53.4 ± 0.7	66.8 ± 0.2	858 ± 3.5	807 ± 4.5	804 ± 4.0	848 ± 1.5	828 ± 4.3
	Mn					**Cd**				
0	697 ± 2.2	592 ± 3.8	569 ± 1.1	545 ± 1.7	713 ± 2.3	68.5 ± 1.10	54.9 ± 1.07	63.0 ± 1.12	51.8 ± 0.82	71.0 ± 0.86
6	704 ± 3.5	597 ± 3.5	602 ± 2.4	570 ± 1.3	722 ± 2.3	72.1 ± 0.55	57.1 ± 0.51	62.9 ± 0.67	52.9 ± 0.71	72.5 ± 0.50
12	748 ± 4.5	647 ± 2.3	606 ± 1.8	586 ± 1.4	733 ± 1.5	73.7 ± 0.45	59.4 ± 0.82	63.3 ± 0.91	54.7 ± 1.02	73.7 ± 0.45
18	720 ± 2.8	653 ± 3.4	632 ± 3.9	626 ± 1.5	717 ± 1.5	75.9 ± 0.50	61.6 ± 0.77	78.4 ± 0.69	63.3 ± 0.49	74.2 ± 0.75
24	740 ± 3.4	685 ± 4.2	641 ± 3.4	630 ± 1.5	733 ± 3.2	77.8 ± 0.60	64.3 ± 1.01	80.1 ± 0.74	65.1 ± 0.65	75.5 ± 0.50
30	737 ± 2.6	699 ± 2.1	677 ± 1.1	659 ± 1.0	744 ± 3.1	80.0 ± 0.25	66.7 ± 0.97	80.7 ± 0.65	67.2 ± 0.56	78.0 ± 0.95
	Fe					**Cr**				
0	13957 ± 092	13730 ± 080	13263 ± 107	12795 ± 102	14490 ± 105	98 ± 1.5	103 ± 1.5	111 ± 1.5	122 ± 2.3	102 ± 1.7
6	14051 ± 089	14192 ± 102	13621 ± 111	13263 ± 099	14526 ± 092	106 ± 2.8	127 ± 1.9	105 ± 2.4	131 ± 2.4	108 ± 1.7
12	14594 ± 092	15301 ± 080	15102 ± 091	15939 ± 096	15352 ± 109	108 ± 3.4	123 ± 1.8	124 ± 2.7	137 ± 1.8	109 ± 1.3
18	14774 ± 103	16978 ± 091	17078 ± 092	16097 ± 129	15644 ± 118	110 ± 1.7	135 ± 1.6	136 ± 2.5	154 ± 1.2	113 ± 1.1
24	14987 ± 101	17484 ± 096	17134 ± 096	16557 ± 110	15967 ± 116	116 ± 1.8	126 ± 1.5	137 ± 2.5	152 ± 1.5	114 ± 1.8
30	15784 ± 108	17236 ± 089	16728 ± 110	16349 ± 107	16158 ± 109	114 ± 1.6	128 ± 2.8	141 ± 2.5	163 ± 1.5	116 ± 1.1

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

OM resulting in release of CO_2 and the subsequent mineralization during the composting process (Singh and Kalamdhad, 2013a). The orders of the range of total heavy metals concentrations of phumdi biomass compost was Fe > Pb > Mn > Ni > Zn > Cr > Cd > Cu. ANOVA analysis indicates significant differences amongst the trials ($P < 0.05$).

4.2.5 BIOAVAILABILITY OF HEAVY METALS

4.2.5.1 WS heavy metals

WS fraction of heavy metals are the most easily bioavailable fraction and belongs to the most toxic constituents of composts (Singh and Kalamdhad, 2013c). The variation of WS concentration of Zn, Cu, Mn, Fe, Pb and Cr during the phumdi pile composting is shown at Table 4.2.4. The concentration of the WS forms of the heavy metals of the phumdi biomass composts decreased significantly in all trials ($P < 0.05$) after the agitated pile composting process. The order of reduction of WS forms of heavy metals for the trials was as below:

Zn: T4 (38.5%) > T3 (35.0%) > T2 (21.5%) > T1 (19.3%) > T5 (02.2%)
Cu: T4 (55.7%) > T3 (48.8%) > T2 (20.5%) > T1 (16.8%) > T5 (01.6%)
Mn: T4 (58.3%) > T3 (49.0%) > T2 (31.1%) > T1 (27.3%) > T5 (11.2%)
Fe: T4 (28.3%) > T3 (25.4%) > T2 (20.2%) > T1 (14.2%) > $T5^*(-3.7\%^*)$
Pb: T4 (47.8%) > T3 (39.8%) > T2 (32.6%) > T1 (30.5%) > T5 (11.7%)
Cr: T4 (46.8%) > T3 (45.3%) > T2 (43.0%) > T1 (37.5%) > T5 (31.7%)

(Note: T–trial, *–increase)

The order of WS heavy metals concentration of the final phumdi biomass composts was Fe > Mn > Zn > Pb = Cu = Cr. WS Ni and Cd were not detected in the phumdi biomass composts. Reduction of WS forms of Zn, Cu, Mn, Fe, Pb and Cr during the process may be attributed to the binding of the metals with the phenolic hydroxyl (−OH) and carboxyl (−COOH) groups enriched by cattle manure. These groups and the newly formed humus increased the binding sites and combined with metals (released during mineralization of organic biomass) to form insoluble and immobile complexes (Guan et al., 2011; Singh and Kalamdhad, 2013c). The increase of WS fraction of Fe in trial 5 (without cattle manure) might be to the incomplete degradation of phumdi biomass. The reduction of WS fraction of heavy metals was also reported by other researchers during solid waste composting (Castaldi et al., 2006; Cai et al., 2007; Singh and Kalamdhad, 2013c). The solubility of the nutrients and heavy metals depend on the initial concentration of the

Table 4.2.4. Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi

Days	WS heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	12.2 ± 0.05	11.8 ± 0.07	9.2 ± 0.08	8.5 ± 0.06	13.6 ± 0.10	–	–	–	–	–
6	12.2 ± 0.05	11.8 ± 0.10	8.8 ± 0.02	8.3 ± 0.02	13.7 ± 0.05	–	–	–	–	–
12	11.3 ± 0.07	9.7 ± 0.08	8.7 ± 0.08	8.4 ± 0.10	14.2 ± 0.05	–	–	–	–	–
18	10.6 ± 0.03	9.7 ± 0.06	6.7 ± 0.03	6.1 ± 0.07	14.2 ± 0.10	–	–	–	–	–
24	10.4 ± 0.10	9.4 ± 0.15	7.3 ± 0.03	5.5 ± 0.04	13.9 ± 0.05	–	–	–	–	–
30	9.9 ± 0.04	9.3 ± 0.04	6.0 ± 0.10	5.3 ± 0.05	13.3 ± 0.10	–	–	–	–	–
	Cu					**Pb**				
0	8.8 ± 0.01	8.3 ± 0.02	9.6 ± 0.02	9.5 ± 0.02	10.1 ± 0.02	10.19 ± 0.04	9.85 ± 0.07	9.75 ± 0.05	9.80 ± 0.10	11.40 ± 0.08
6	8.6 ± 0.03	8.2 ± 0.02	8.9 ± 0.01	9.0 ± 0.01	10.0 ± 0.01	10.19 ± 0.07	9.74 ± 0.08	7.54 ± 0.08	10.99 ± 0.09	10.89 ± 0.08
12	8.8 ± 0.04	7.9 ± 0.01	9.1 ± 0.02	9.2 ± 0.01	9.9 ± 0.01	8.18 ± 0.02	7.35 ± 0.09	6.07 ± 0.09	7.50 ± 0.12	11.05 ± 0.07
18	7.3 ± 0.01	6.6 ± 0.01	5.2 ± 0.01	4.6 ± 0.01	10.0 ± 0.02	8.18 ± 0.04	7.73 ± 0.09	6.16 ± 0.10	7.54 ± 0.08	10.83 ± 0.05
24	7.4 ± 0.03	6.7 ± 0.04	5.0 ± 0.01	4.6 ± 0.02	9.9 ± 0.01	7.29 ± 0.10	7.35 ± 0.12	5.80 ± 0.12	7.24 ± 0.12	9.97 ± 0.12
30	7.3 ± 0.01	6.6 ± 0.01	4.9 ± 0.01	4.2 ± 0.02	9.9 ± 0.01	7.08 ± 0.06	6.64 ± 0.11	5.87 ± 0.14	5.12 ± 0.08	10.07 ± 0.04
	Mn					**Cd**				
0	73.9 ± 0.10	59.3 ± 0.20	70.0 ± 0.40	63.9 ± 0.40	88.3 ± 0.70	–	–	–	–	–
6	71.6 ± 0.20	57.6 ± 0.50	68.1 ± 0.60	58.4 ± 0.40	84.5 ± 0.50	–	–	–	–	–
12	61.5 ± 0.40	45.4 ± 0.40	69.8 ± 0.41	60.2 ± 0.60	82.8 ± 0.16	–	–	–	–	–
18	60.1 ± 0.21	44.4 ± 0.91	45.4 ± 0.32	36.1 ± 0.50	81.7 ± 0.44	–	–	–	–	–
24	55.9 ± 0.45	42.5 ± 0.90	36.7 ± 0.34	30.2 ± 0.40	80.3 ± 0.40	–	–	–	–	–
30	53.7 ± 0.60	40.9 ± 0.60	35.7 ± 0.24	26.7 ± 0.25	78.4 ± 0.63	–	–	–	–	–
	Fe					**Cr**				
0	105 ± 1.2	108 ± 0.7	112 ± 1.1	115 ± 1.1	104 ± 0.8	8.80 ± 0.01	10.00 ± 0.04	9.88 ± 0.02	9.30 ± 0.04	13.15 ± 0.02
6	96 ± 1.1	107 ± 0.9	108 ± 0.9	109 ± 1.1	98 ± 1.1	7.40 ± 0.02	9.80 ± 0.02	9.95 ± 0.03	7.51 ± 0.03	13.09 ± 0.03
12	91 ± 1.4	93 ± 1.1	95 ± 0.8	92 ± 1.0	96 ± 1.4	6.90 ± 0.01	7.50 ± 0.04	7.80 ± 0.03	6.30 ± 0.03	10.35 ± 0.05
18	95 ± 1.5	92 ± 1.0	96 ± 0.7	90 ± 1.2	97 ± 1.3	7.40 ± 0.02	7.15 ± 0.03	7.12 ± 0.04	6.00 ± 0.04	9.30 ± 0.03
24	91 ± 1.6	92 ± 1.1	91 ± 0.8	85 ± 1.0	99 ± 1.7	5.90 ± 0.01	5.90 ± 0.02	6.16 ± 0.02	5.12 ± 0.02	9.00 ± 0.04
30	90 ± 0.9	86 ± 0.8	83 ± 0.6	83 ± 0.9	108 ± 1.8	5.50 ± 0.03	5.70 ± 0.01	5.4 ± 0.03	4.94 ± 0.04	8.98 ± 0.05

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

ions, pH, complex formations, etc. (Larson et al., 1973; Benefield et al., 1982; Wang et al., 2009). The pH of the phumdi composts were in the range where the alkali or alkaline earth metals (i.e. Na^+, K^+, Ca^{2+}, Mg^{2+}, etc.) were soluble. The possible reason for the decreased in WS trace metals was the formation of complexes with the heavy metal ions. Composting results in humification of the OM with the formation of humus substances rich in humic acid like organic carbons having increased aromatic characteristics, oxygen and nitrogen concentrations, functional groups, etc. depending on the nature and composition of the initial OM. The humic substances are low in fulvic acid like and WS organic carbon (Roletto et al., 1985; Senesi, 1989). Structurally, 20% of hydrogen is bound to oxygen as −COOH and −OH groups and the rest bound directly to carbon (Young, 2010). The interaction of the alkali or alkaline earth metals (i.e. Na, K, Mg and Ca) and heavy metals with the humic substances is a complex phenomenon. The alkali or alkaline earth metals are held weakly by exchangeable hydrated ions, or by electrostatic forces on charge humus carboxyl groups. In case of heavy metals, a chelate complex is formed and two or more coordinate positions of the metal ion are occupied by donor groups of a single ligand to form an internal ring structure (Stevenson, 1994; Tan, 2010). The divalent and trivalent metals formed highly insoluble complexes i.e. multidentate or multinuclear chealate sites with the functional groups of humus and are dominated by double or triple bonds to the mix of −COOH and −OH groups (Young, 2010). Cations with two positive charges such as Cu^{2+} can only be replaced by another transitional metal ion that has two positive charges. Chealation of toxic heavy metals such as Hg, Pb and Cd forms organo-metallic complexes which are less available for plant uptake (Chen et al., 2006). Therefore, the stability of a metal-chelate complex is determined by such factors as the number of atoms that form a bond with the metal ion, the number of rings that are formed, the nature and concentrations of the metal ions, and pH. The order of decreasing ability of metal ions to form chelating complexes with humic acids is $Fe^{3+} > Cu^{2+} > Ni^{2+} > Co^{2+} > Zn^{2+} > Fe^{2+} > Mn^{2+}$ (Stevenson, 1994). Whereas, Tipping and Hurley (1993) evaluated the binding strength of the metals with humus in the increasing order $VO^{2+} > Cu^{2+} > Pb^{2+} > Zn^{2+} = Ni^{2+} > Co^{2+} > Cd^{2+} > Mn^{2+} > Ca^{2+} > Mg^{2+}$.

4.2.5.2 Diethylenetriamine penta-acetic acid (DTPA) extractable heavy metals

The variation of the plant available DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during the composting process is shown at Table 4.2.5. The DTPA extractable forms of heavy metals were reduced significantly ($P < 0.05$) among all trials during the composting process. The order of DTPA reduction for all trials was as below:

Zn: T4 (66.7%) > T3 (52.1%) > T2 (44.7%) > T1 (33.1%) > T5 (24.8%)
Cu: T4 (48.8%) > T3 (46.3%) > T2 (43.5%) > T1 (36.0%) > T5 (28.9%)
Mn: T4 (45.1%) > T3 (31.9%) > T2 (29.4%) > T1 (24.9%) > T5 (22.1%)
Fe: T4 (50.7%) > T3 (42.5%) > T2 (38.8%) > T1 (34.3%) > T5 (30.4%)
Ni: T3 (52.9%) > T4 (47.5%) > T2 (47.0%) > T1 (43.4%) > T5 (42.4%)
Pb: T4 (50.1%) > T2 (46.3%) > T3 (43.5%) > T1 (43.1%) > T5 (32.3%)
Cd: T4 (37.4%) > T3 (31.8%) > T2 (26.5%) > T1 (22.6%) > T5 (4.3%)
Cr: T4 (52.5%) > T3 (39.0%) > T2 (29.6%) > T1 (23.1%) > T5 (17.2%)

(Note: T–trial)

The order of DTPA extractable heavy metal concentration of the final phumdi biomass composts was Mn > Fe > Zn > Pb > Cu > Cr > Ni = Cd. The DTPA solution is assumed to extract both carbonate-bound and organically-bound metal fractions in calcareous soils, and indicates the amount of metals potentially available for plant uptake (Walter et al., 2006). The precipitation of heavy metals with the anions (hydroxides, carbonates, phosphates, sulfides, etc.), as well as the formation of complexes with the organic ligands, is the main mobility controlling mechanisms for heavy metals (Kumpiene et al., 2008). The reduction of DTPA extractable heavy metals was attributed to the degraded OM forming complex compounds with heavy metals (Fang and Wong, 1999; Singh and Kalamdhad, 2013a, b). The bioavailable heavy metals renovated into a more stable form during composting process (Castaldi et al., 2005; Singh et al., 2013a) due to the increase in pH, metal biosorption by the microbial biomass or metal complexation with the newly formed humic substances (Castaldi et al., 2006; Cai et al., 2007). The pH is considered as one major factor controlling ion exchange, reduction/oxidation, adsorption and complexation reactions (Walter et al., 2006). Cations are adsorbed on OM at high pH. The effect of OM amendments on heavy metal solubility also depend greatly upon the degree of humification of the OM and subsequent effect upon soil pH (Gupta and Sinha, 2007). The extractable efficiency of DTPA extractable heavy metals (ŋ) reduced in all trials after the process (Fig. 4.2.5). The intermediate increase of "ŋ" indicated during the thermophilic phase of the composting process was due to the release of soluble OM coupled with initial low pH (Ahmed et al., 2007; Singh and Kalamdhad, 2013a). The concentration of DTPA extractable metals of the composts is important for the end users whereas "ŋ" gives a clearer picture of the fate of heavy metals since "ŋ" is independent on the net loss in dry mass of the composts.

Table 4.2.5. Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi

Days	DTPA extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	93.8 ± 0.1	87.7 ± 0.1	81.6 ± 0.1	75.6 ± 0.1	107 ± 0.4	1.06 ± 0.01	0.76 ± 0.01	0.79 ± 0.00	0.92 ± 0.01	1.33 ± 0.01
6	90.8 ± 0.2	79.2 ± 0.2	80.1 ± 0.2	75.1 ± 0.1	102.4 ± 0.2	0.99 ± 0.12	0.70 ± 0.01	0.70 ± 0.01	0.90 ± 0.01	1.24 ± 0.01
12	95.3 ± 0.4	75.7 ± 0.2	71.6 ± 0.2	70.6 ± 0.1	113.5 ± 0.3	0.98 ± 0.01	0.68 ± 0.01	0.72 ± 0.01	0.88 ± 0.01	1.25 ± 0.01
18	68.3 ± 0.2	48.2 ± 0.3	41.1 ± 0.2	24.6 ± 0.1	88.7 ± 0.2	0.88 ± 0.01	0.65 ± 0.01	0.62 ± 0.01	0.68 ± 0.01	1.14 ± 0.01
24	69.3 ± 0.3	46.5 ± 0.2	38.1 ± 0.2	26.7 ± 0.1	88.7 ± 0.2	0.78 ± 0.01	0.50 ± 0.01	0.41 ± 0.01	0.58 ± 0.01	0.92 ± 0.01
30	62.8 ± 0.2	48.5 ± 0.2	39.1 ± 0.2	25.2 ± 0.1	80.5 ± 0.3	0.60 ± 0	0.40 ± 0.00	0.38 ± 0.01	0.48 ± 0.01	0.76 ± 0.01
	Cu					**Pb**				
0	11.3 ± 0.05	10.7 ± 0.03	10.1 ± 0.08	9.6 ± 0.05	12.5 ± 0.05	19.9 ± 0.15	19.2 ± 0.12	19.1 ± 0.1	19.0 ± 0.11	20.3 ± 0.08
6	11.1 ± 0.05	10.6 ± 0.15	10.8 ± 0.14	9.3 ± 0.10	12.3 ± 0.05	18.4 ± 0.12	14.8 ± 0.09	16.7 ± 0.12	17.4 ± 0.11	16.7 ± 0.09
12	7.9 ± 0.05	8.5 ± 0.12	9.1 ± 0.06	8.1 ± 0.10	9.3 ± 0.05	14.5 ± 0.11	12.9 ± 0.08	14.6 ± 0.12	13.5 ± 0.09	15.6 ± 0.09
18	7.9 ± 0.46	6.5 ± 0.20	6 ± 0.12	6.9 ± 0.05	9.1 ± 0.02	13.8 ± 0.11	12.7 ± 0.09	12.1 ± 0.11	12.1 ± 0.15	14.9 ± 0.12
24	7.9 ± 0.05	6.2 ± 0.05	5.8 ± 0.1	5.2 ± 0.05	9.2 ± 0.05	12.1 ± 0.09	10.5 ± 0.09	10.2 ± 0.09	10.0 ± 0.12	14.1 ± 0.09
30	7.2 ± 0.2	6.0 ± 0.18	5.4 ± 0.12	4.9 ± 0.05	8.9 ± 0.05	11.3 ± 0.1	10.9 ± 0.11	10.3 ± 0.08	9.5 ± 0.11	13.7 ± 0.08
	Mn					**Cd**				
0	262 ± 1.1	255 ± 1.1	249 ± 1.2	243 ± 0.7	291 ± 1.2	0.8 ± 0.01	0.51 ± 0.01	0.44 ± 0.02	0.60 ± 0.03	0.94 ± 0.04
6	259 ± 0.9	256 ± 1.2	245 ± 1.1	236 ± 0.9	286 ± 1.4	0.72 ± 0.01	0.46 ± 0.01	0.45 ± 0.02	0.54 ± 0.02	0.91 ± 0.05
12	269 ± 1.2	225 ± 1.1	255 ± 1.2	232 ± 0.9	264 ± 1.2	0.80 ± 0	0.40 ± 0.03	0.31 ± 0.02	0.49 ± 0.02	0.94 ± 0.04
18	216 ± 0.9	188 ± 1.1	201 ± 1.3	160 ± 1.2	239 ± 1.1	0.73 ± 0.01	0.39 ± 0.05	0.35 ± 0.01	0.42 ± 0.02	0.94 ± 0.03
24	206 ± 0.8	190 ± 0.8	176 ± 0.6	148 ± 1.1	228 ± 1.1	0.71 ± 0.01	0.42 ± 0	0.31 ± 0.01	0.40 ± 0.04	0.91 ± 0.04
30	197 ± 0.9	180 ± 1.1	170 ± 0.9	133 ± 0.9	227 ± 1.2	0.62 ± 0.01	0.38 ± 0.01	0.30 ± 0.01	0.37 ± 0.01	0.90 ± 0
	Fe					**Cr**				
0	137 ± 1.2	133 ± 0.9	148 ± 0.6	148 ± 0.9	133 ± 0.8	13.3 ± 0.08	12 ± 0.04	10.2 ± 0.07	10.6 ± 0.12	17.5 ± 0.08
6	133 ± 1.1	130 ± 0.8	145 ± 0.7	145 ± 1.1	135 ± 0.9	12.8 ± 0.07	11.2 ± 0.12	9.6 ± 0.08	9.8 ± 0.10	16.5 ± 0.08
12	127 ± 1.4	118 ± 1.1	133 ± 0.8	125 ± 1.1	130 ± 1.1	12.7 ± 0.06	9.3 ± 0.11	7.3 ± 0.08	8.3 ± 0.14	16.6 ± 0.12
18	122 ± 1.2	113 ± 0.9	128 ± 1.1	89 ± 0.8	106 ± 1.0	11.6 ± 0.12	9.7 ± 0.10	7.6 ± 0.08	6.5 ± 0.11	16.0 ± 0.10
24	117 ± 1.1	108 ± 0.9	105 ± 0.8	78 ± 0.9	100 ± 1.1	11.0 ± 0.07	8.5 ± 0.09	6.8 ± 0.06	5.0 ± 0.12	15.0 ± 0.08
30	90 ± 1.1	81 ± 1.1	85 ± 1.0	73 ± 1.1	92 ± 0.9	10.2 ± 0.09	8.4 ± 0.07	6.2 ± 0.12	5.1 ± 0.15	14.5 ± 0.15

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

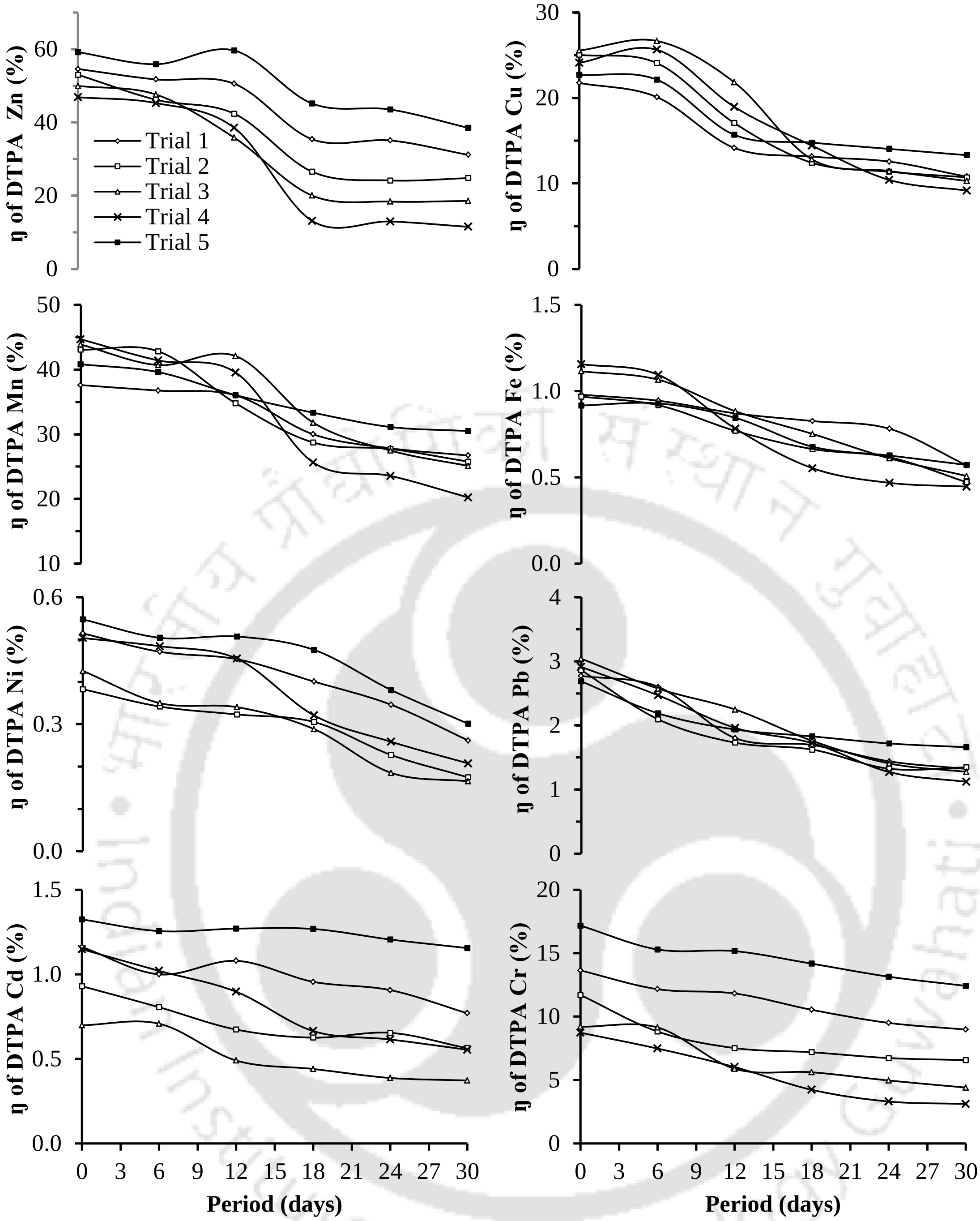

Fig. 4.2.5. Variation of DTPA extractable "ŋ" of heavy metals during pile composting of phumdi biomass

4.2.5.3 Toxicity characteristic leaching procedure (TCLP) test for heavy metals

The changes in leachability of Zn, Cu, Mn, Fe, Ni, Cd, Pb and Cr during the composting process are given in Table 4.2.6. The table indicates reduction of the leachable heavy metals in all process except Pb in trial 5. The reduction of leachable fraction of heavy metals was consistent with the findings of other researchers (Chiang et al., 2007; Singh and Kalamdhad, 2013c). The reduction of leachability of all selected

Table 4.2.6. Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of phumdi

Days	TCLP extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	94.3 ± 0.9	86.2 ± 0.9	78.5 ± 0.8	70.6 ± 0.8	106.4 ± 1.0	6.76 ± 0.01	6.00 ± 0.04	5.50 ± 0.09	5.05 ± 0.05	7.19 ± 0.20
6	93.0 ± 1.1	85.0 ± 0.8	78.5 ± 0.9	69.8 ± 0.9	113.5 ± 1.0	6.22 ± 0.02	5.52 ± 0.04	5.69 ± 0.07	5.01 ± 0.02	6.75 ± 0.07
12	67.1 ± 1.2	65.6 ± 0.9	54.2 ± 0.9	36.4 ± 0.8	92.8 ± 0.9	5.86 ± 0.05	7.86 ± 0.12	7.55 ± 0.03	6.60 ± 0.16	5.69 ± 0.11
18	66.1 ± 1.0	60.2 ± 1.1	52.1 ± 1.0	35.8 ± 0.8	86.7 ± 0.9	5.06 ± 0.07	5.98 ± 0.02	5.7 ± 0.08	5.33 ± 0.05	5.49 ± 0.08
24	66.0 ± 0.9	59.1 ± 1.0	51.2 ± 0.9	34.4 ± 0.8	85.4 ± 0.8	4.89 ± 0.08	4.64 ± 0.03	5.12 ± 0.04	3.41 ± 0.05	5.11 ± 0.10
30	65.0 ± 1.1	56.0 ± 1.0	47.0 ± 1.0	32.4 ± 0.8	84.0 ± 0.9	4.61 ± 0.09	3.76 ± 0.02	3.34 ± 0.06	2.46 ± 0.06	4.95 ± 0.19
	Cu					**Pb**				
0	13.2 ± 0.02	12.7 ± 0.02	12.1 ± 0.04	11.5 ± 0.04	14.5 ± 0.07	29.9 ± 0.05	28.3 ± 0.09	25.0 ± 0.09	24.8 ± 0.09	34.1 ± 0.08
6	12.8 ± 0.05	11.9 ± 0.09	11.5 ± 0.15	11.6 ± 0.02	14.3 ± 0.09	25.9 ± 0.06	25.0 ± 0.10	23.6 ± 0.08	22.0 ± 0.08	33.1 ± 0.09
12	9.3 ± 0.11	9.1 ± 0.17	9.5 ± 0.11	7.1 ± 0.11	10.3 ± 0.10	23.5 ± 0.02	21.4 ± 0.09	16.7 ± 0.14	15.5 ± 0.16	29.0 ± 0.06
18	9.2 ± 0.11	8.8 ± 0.09	8.9 ± 0.14	6.5 ± 0.11	10.2 ± 0.14	23.2 ± 0.10	22.8 ± 0.12	19.8 ± 0.15	18.2 ± 0.17	30.4 ± 0.10
24	8.8 ± 0.11	8.5 ± 0.07	8.4 ± 0.07	6.0 ± 0.17	10.1 ± 0.14	22.4 ± 0.05	21.5 ± 0.14	18.4 ± 0.15	17.7 ± 0.14	28.5 ± 0.12
30	8.5 ± 0.16	8.0 ± 0.07	7.2 ± 0.09	5.6 ± 0.17	10.0 ± 0.12	21.9 ± 0.05	20.5 ± 0.15	18.2 ± 0.16	17.7 ± 0.12	27.6 ± 0.14
	Mn					**Cd**				
0	406 ± 1.1	436 ± 1.1	447 ± 1.2	412 ± 1.2	386 ± 0.9	2.70 ± 0.10	2.60 ± 0.17	2.40 ± 0.14	2.30 ± 0.18	2.78 ± 0.12
6	394 ± 1.4	444 ± 1.4	434 ± 1.5	392 ± 1.1	373 ± 0.9	2.20 ± 0.09	1.12 ± 0.17	1.24 ± 0.14	1.98 ± 0.09	2.41 ± 0.11
12	386 ± 1.2	338 ± 1.2	305 ± 1.3	301 ± 1.4	354 ± 1.9	1.27 ± 0.06	1.20 ± 0.17	1.00 ± 0.04	1.18 ± 0.07	1.45 ± 0.08
18	376 ± 1.3	336 ± 1.1	292 ± 1.2	312 ± 1.6	359 ± 1.8	1.14 ± 0.06	1.07 ± 0.07	0.74 ± 0.15	0.89 ± 0.06	1.34 ± 0.06
24	390 ± 1.4	309 ± 1.0	276 ± 1.4	281 ± 1.4	367 ± 1.3	1.16 ± 0.07	0.88 ± 0.08	0.61 ± 0.14	0.67 ± 0.09	1.24 ± 0.02
30	387 ± 1.5	326 ± 1.1	252 ± 1.4	273 ± 1.4	378 ± 1.4	0.98 ± 0.09	0.66 ± 0.17	0.31 ± 0.09	0.24 ± 0.05	1.12 ± 0.18
	Fe					**Cr**				
0	243 ± 0.9	302 ± 0.8	336 ± 1.0	342 ± 0.6	212 ± 1.2	61.0 ± 0.4	63.3 ± 0.2	73.5 ± 0.4	76.5 ± 0.1	69.8 ± 0.3
6	242 ± 1.0	300 ± 0.6	334 ± 1.1	334 ± 0.9	210 ± 0.9	67.2 ± 0.4	66.0 ± 0.4	80.8 ± 0.2	78.5 ± 0.2	68.6 ± 0.2
12	222 ± 1.1	191 ± 0.9	331 ± 1.2	298 ± 1.0	209 ± 0.5	54.4 ± 0.2	51.0 ± 0.2	66 ± 0.6	57.5 ± 0.4	49.7 ± 0.2
18	221 ± 1.2	189 ± 1.0	209 ± 1.1	195 ± 0.9	210 ± 0.8	44.8 ± 0.5	50.7 ± 0.2	55.2 ± 0.4	48.5 ± 0.2	53.3 ± 0.1
24	220 ± 1.1	189 ± 0.9	207 ± 0.6	198 ± 1.0	212 ± 0.6	40.4 ± 0.2	45.5 ± 0.2	54.0 ± 0.2	49.0 ± 0.2	48.6 ± 0.4
30	220 ± 1.1	188 ± 1.1	198 ± 0.8	183 ± 1.1	213 ± 0.9	38.5 ± 0.6	35.1 ± 0.1	40.0 ± 0.1	40.0 ± 0.2	48.0 ± 0.2

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

heavy metals during the composting process was also due to the metals forming complexes with humic substances (Singh and Kalamdhad, 2013a). The threshold limit of leachable heavy metals for composts in mg/kg is 20 for Cd, 100 for Cr and 100 for Pb (USEPA, 1992). Therefore, the composts were safe for agriculture use. The leachable fraction of heavy metals of the final composts was reduced in all trials in the following order:

Zn: T4 (54.1%) > T3 (40.1%) > T2 (35.0%) > T1 (31.1%) > T5 (21.1%)
Cu: T4 (51.3%) > T3 (40.0%) > T2 (36.9%) > T1 (36.0%) > T5 (31.0%)
Mn: T3 (43.6%) > T4 (33.7%) > T2 (25.1%) > T1 (4.6%) > T5 (2.2%)
Fe: T4 (46.5%) > T3 (41.1%) > T2 (37.6%) > T1 (9.3%) > T5 (−0.9%*)
Ni: T4 (51.3%) > T3 (39.2%) > T2 (37.3%) > T1 (31.8%) > T5 (31.2%)
Pb: T4 (28.3%) > T2 (27.7%) > T3 (27.2%) > T1 (26.8%) > T5 (19.1%)
Cd: T4 (89.6%) > T3 (87.3%) > T2 (74.6%) > T1 (63.7%) > T5 (59.9%)
Cr: T4 (47.7%) > T3 (45.6%) > T2 (44.6%) > T1 (36.9%) > T5 (31.3%)

(Note: T–trial, *–increase)

The order of leachable fraction of heavy metals of the final phumdi biomass composts was Mn > Fe > Zn > Cr > Pb > Cu > Ni > Cd. The pH increased within the optimum range for formation of insoluble complexes consequently reducing the solubility and bioavailability of the heavy metals (Cambier and Charlatchka, 1999). ANOVA analysis showed significant differences in the leachable concentration of all heavy metals for all trials ($P < 0.05$). The order of the concentration of the bioavailable forms of heavy metals of the final phumdi biomass composts indicates that the bioavailability is not dependent on the total metal concentrations. The total metal concentration of Pb of the final composts was high (third highest) but the bioavailable form of Pb was among the lowest. Pb forms strong complex with OM and is the least mobile heavy metal both under reducing and non-acidic condition (Lazzari et al., 2000).

4.3 ROTARY DRUM COMPOSTING OF PHUMDI BIOMASS

4.3.1 TEMPERATURE PROFILE

The temperature profile during the phumdi biomass composting in the rotary drum composter is presented in Fig. 4.3.1. The temperature profiles in the drum trials were higher than pile composting and were in the range 21.1–53.1ºC. The highest peak temperature (53.1ºC) was indicated earlier on day 6 also in trial 4 having highest proportion of cattle manure (Chen et al., 2010). The composting process was enhanced during rotary drum composting due to the warm and moist environment of the reactor coupled with abundant amount of oxygen from proper aeration facilitating high growth of aerobic microbes (Kalamdhad et al., 2008). The temperature profiles during pile and drum composting largely established that trial 4 i.e. 5 phumdi: 4 cattle manure: 1 rice husk combination provided the optimum carbon and nitrogen and physical condition of the composting materials for the growth and activity of the microorganisms.

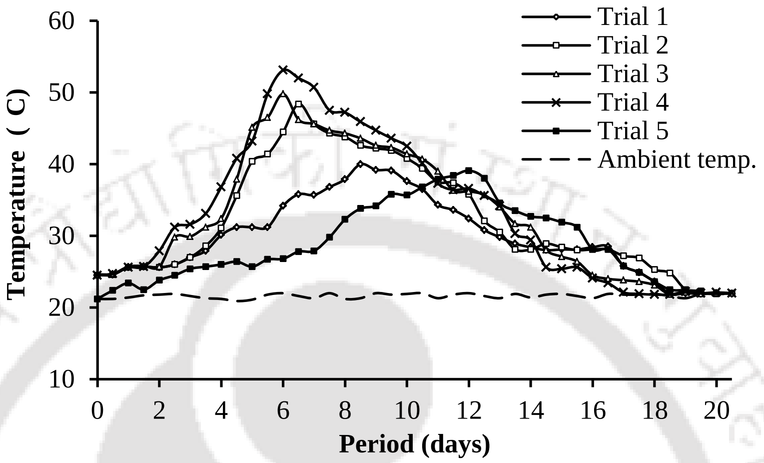

Fig. 4.3.1. Temperature profiles during drum composting of phumdi

4.3.2 PHYSICO-CHEMICAL AND BIO-CHEMICAL ANALYSIS

The pH values increased in all trials and the maximum pH observed was 7.64 in trial 4 at the end of the drum composting process (Fig. 4.3.2a). Variation of pH in all trials was statistically significant ($P < 0.05$). The pH values increased due to the regular turning of the drum that provided sufficient aeration to increase the microbial activity thereby enhancing the degradation of the organic acids and subsequent release of CO_2 (Cayuela et al., 2008).

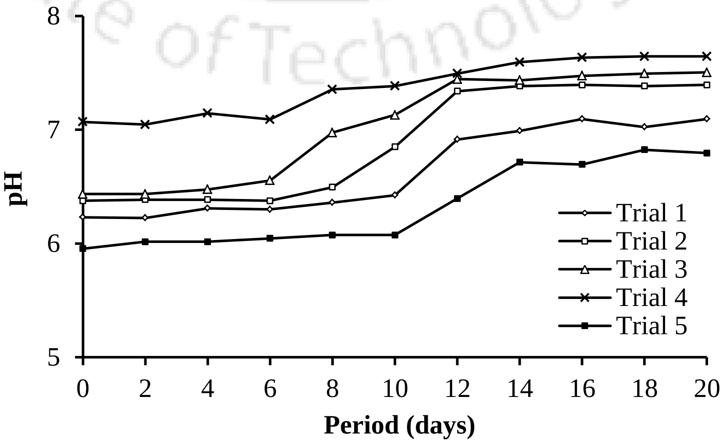

Fig. 4.3.2a. Variation of pH values during drum composting of phumdi

EC of all trials initially increased due to the net loss of weight and release of soluble salts through decomposition activity in the composting process (Fig. 4.3.2b). The EC of trial 4 reduced to 3.36 dS/m indicating precipitation of mineral salts and/or formation of insoluble complexes with the metal ions (Wong et al., 2001; Amir et al., 2005). ANOVA test showed that EC varied significantly amongst all the trials ($P < 0.05$).

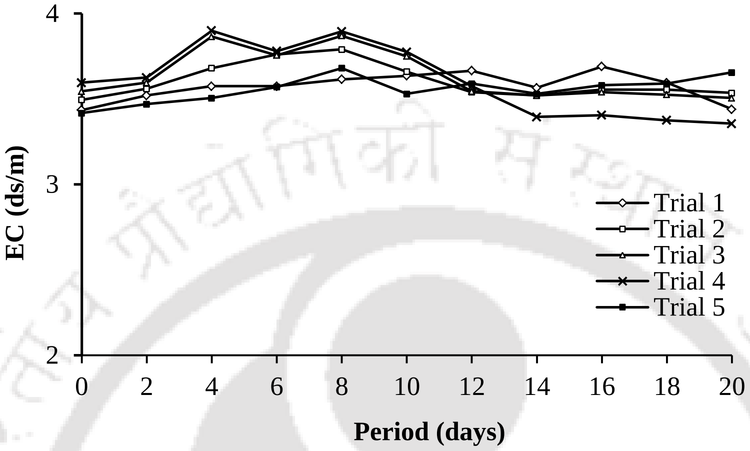

Fig. 4.3.2b. Variation of EC during drum composting of phumdi

The highest and lowest moisture loss of trial 4 (29.0%) and 5 (13.3%) after the process corroborated with the highest and lowest heat generation of trial 4 and 5 during the process (Fig. 4.3.2c). Leachate formation was not observed during the drum composting period. ANOVA test indicated that the variation in moisture content among the trials during the composting process was statistically significant ($P < 0.05$).

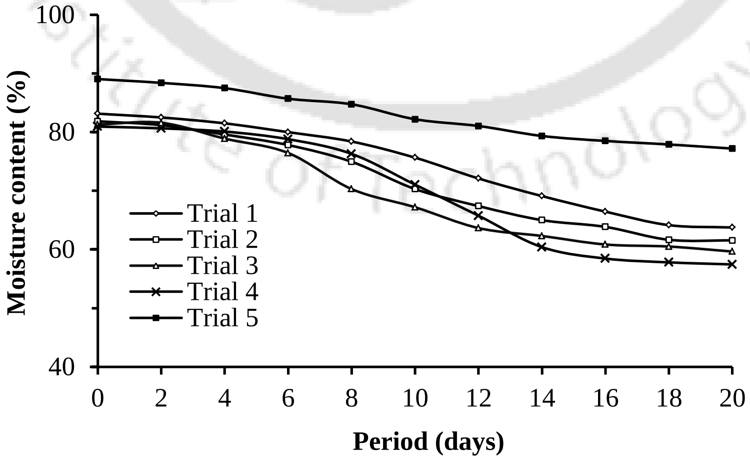

Fig. 4.3.2c. Variation of MC during drum composting of phumdi

Fig. 4.3.2d shows the variation of VS of the phumdi composts during the drum composting. The drum composting process rapidly degraded and transformed the OM to stable humic compounds. The maximum reduction of VS was observed in trial 4 (22.2%; K_b = 0.51) followed by trial 3 (21.2%; K_b = 0.49), trial 2 (20.6%; K_b = 0.48), trial 1 (18.7%; K_b = 0.45) and trial 5 (11.1%; K_b = 0.30). The highest K_b and VS loss of trial 4 was in agreement with the highest temperature profile. ANOVA analysis indicated that variation of OM loss of all the trials was statistically significant ($P < 0.05$).

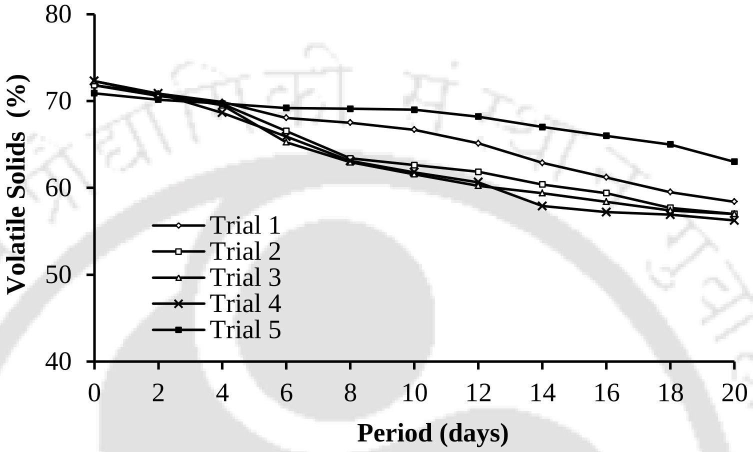

Fig. 4.3.2d. Variation of VS during drum composting of phumdi

The soluble BOD decreased in all trials (Fig. 4.3.2e) due to degradation of easily degradable WS compounds. Trial 4 recorded highest reduction of soluble BOD (81.2%) followed by trial 3 (79.1%) after 20 days. There were no significant changes in soluble BOD concentrations of the phumdi composts of trial 3 and 4 after 18 days. ANOVA analysis indicated significant difference in the reduction of soluble BOD of all trials during the composting process ($P < 0.05$).

During the drum composting of phumdi, the OUR and CO_2 evolution rate in trial 2, 3 and 4 showed temporal decrease after 6 days. OUR and CO_2 evolution rate of trial 3 and 4 indicated that the respiration rate was reduced with no significant variation by 18th day (Fig. 4.3.2f and 4.3.2g). The OUR of trial 3 and 4 respectively reduced to 3.3 and 3.4 mg/g VS/day on day 20. The CO_2 evolution rate of trial 3 and 4 also decreased to 1.2 and 1.1 mg/g VS/day, respectively. The soluble BOD concentration, CO_2 evolution rate and OUR of trial 3 and 4 indicated that the microbial activity was reduced considerably with no significant variation after day 18. The results show that effective phumdi biomass composting can be achieved with cattle manure and rice husk in appropriate proportions and obtained stable compost. From the results of CO_2 evolution rate and OUR, the phumdi compost of trial 4 and 3 can be considered stable (TMECC, 2002).

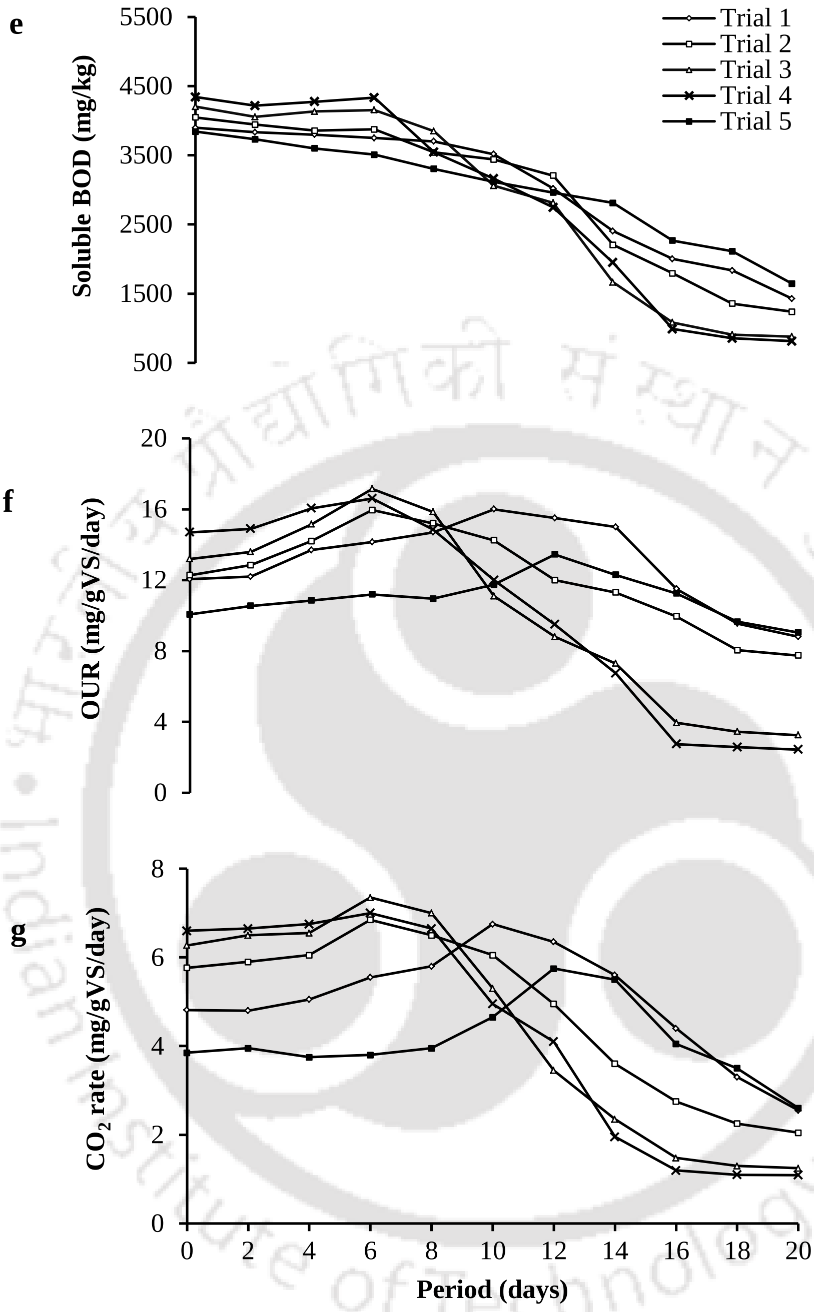

Fig. 4.3.2 e. Variation of soluble BOD during drum composting of phumdi
f. Variation of OUR during drum composting of phumdi
g. Variation of CO_2 evolution rate during drum composting of phumdi

4.3.3 NUTRIENTS

Trial 4 showed the highest increase in the concentration of TKN (38.7%) followed by trial 3 (35.8%) due to the higher loss of dry mass (Fig. 4.3.3a). ANOVA analysis shows significant difference of the variation of TKN concentration among all the drum composting trials of phumdi biomass ($P < 0.05$). The concentration of NH_4–N of all trials after the composting were low (≤ 400 mg/kg) and there was no risk of phytotoxicity (Bernal et al., 1998). The intermediate increase in the concentration of NH_4–N that occurred during pile composting of phumdi biomass was not prominent in the case of drum composting of phumdi biomass due to the enhanced degradation caused by higher aeration from the regular turning of the drum.

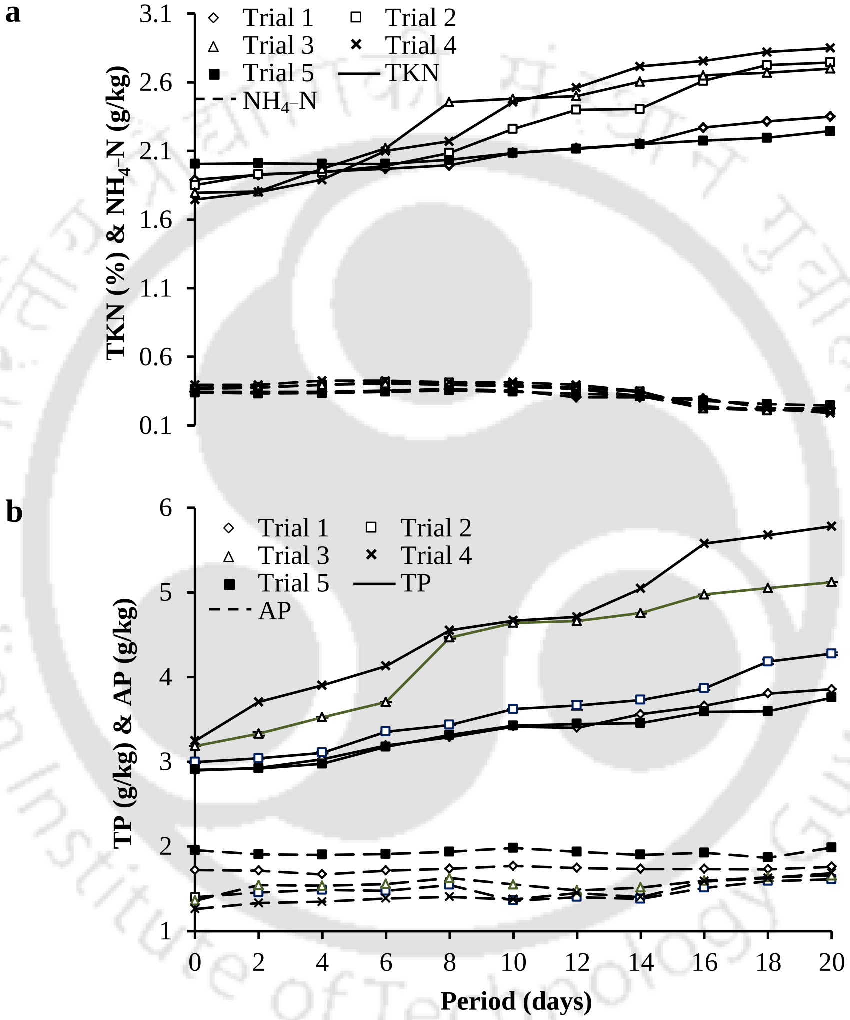

Fig. 4.3.3 a. Variation of TKN and NH_4–N during drum composting of phumdi
b. Variation of TP and AP during drum composting of phumdi

The concentration of TP during the drum composting gradually increased also due to net loss in dry mass (Fig. 4.3.3b).The increase in AP (highest increase was 34.7% in trial 4) was lower compared with the increase in TP (highest increase was 78.1% in trial 4). The result further validated the argument that AP variation is dependent on the type of the initial feedstock increasing with OM loss but decreasing with the formation of complexes and/or phosphates with calcium and magnesium ions (Chanyasak et al., 1983; Traore et al., 1999).

The concentrations of total Na, K, Ca and Mg increased in all trials after the drum composting process (Table 4.3.1). The highest increase of Na, K, Ca and Mg during drum composting were also in trial 4 (70.9, 51.4, 40.0 and 33.0%, respectively) and the increase was higher than trial 4 of phumdi pile composting (68.1, 42.5, 34.3 and 23.9%, respectively) due to higher loss in dry mass. The concentration of the nutrients of the final composts of all trials i.e. K (1.2–1.5%), Ca (0.5–0.8%), Mg (0.5–0.7%) was near the prescribed limits. The order of the range of total nutrients concentrations of compost was K > Na > Ca > Mg.

Table 4.3.1. Variation of total Na, K, Ca and Mg during drum composting of phumdi

Days	Total nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	5388 ± 20	5280 ± 25	5185 ± 42	4800 ± 24	5492 ± 42
4	5491 ± 30	6087 ± 22	6069 ± 40	6039 ± 25	5587 ± 41
8	5692 ± 40	6428 ± 34	6999 ± 30	6786 ± 50	6046 ± 35
12	6520 ± 50	7268 ± 35	7880 ± 28	8015 ± 45	6642 ± 65
16	6772 ± 42	7410 ± 36	8205 ± 29	8175 ± 42	6772 ± 30
20	6887 ± 35	7645 ± 32	8323 ± 30	8202 ± 44	6911 ± 28
	K				
0	9674 ± 218	9490 ± 158	9289 ± 154	9171 ± 146	12252 ± 194
4	10225 ± 175	9667 ± 118	10813 ± 144	9885 ± 199	12349 ± 114
8	10675 ± 475	9886 ± 161	12386 ± 248	11322 ± 144	13950 ± 150
12	11552 ± 294	10412 ± 165	13495 ± 130	13743 ± 156	14244 ± 213
16	11842 ± 153	10756 ± 199	13074 ± 149	13824 ± 146	14611 ± 190
20	12103 ± 215	11988 ± 191	13587 ± 175	13888 ± 102	14623 ± 198
	Ca				
0	4180 ± 51	4941 ± 43	5031 ± 47	5195 ± 61	3901 ± 42
4	4499 ± 63	5195 ± 48	5288 ± 54	5304 ± 41	3954 ± 32
8	4815 ± 77	5627 ± 60	5458 ± 32	5785 ± 64	4469 ± 44
12	4968 ± 43	5799 ± 53	6035 ± 32	6763 ± 93	4845 ± 69
16	5106 ± 57	5940 ± 39	6199 ± 23	6857 ± 53	4921 ± 45
20	5216 ± 38	6161 ± 68	6705 ± 57	7716 ± 62	4805 ± 37
	Mg				
0	4802 ± 12	4940 ± 9	5139 ± 10	5205 ± 16	4678 ± 14
4	4261 ± 14	4722 ± 10	5296 ± 15	5379 ± 15	4916 ± 12
8	4685 ± 12	5023 ± 11	5889 ± 12	5738 ± 9	4920 ± 14
12	5023 ± 11	4845 ± 12	5980 ± 14	6924 ± 10	4962 ± 15
16	5177 ± 10	5043 ± 14	6089 ± 11	6924 ± 12	5139 ± 18
20	5319 ± 14	5494 ± 12	6226 ± 12	6924 ± 15	5174 ± 12

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

There was also no particular trend in the variation of WS nutrients similar to agitated pile composting of phumdi biomass which might also be to the formation of insoluble precipitates or complexes at different stages of the composting process. The WS Na, K, Ca and Mg of the final composts of all trials increased in the range of about 13.4–86.8% for Na, 22.0–50.8% for K, 10.5–36.5% for Ca and 19.7–25.7% for Mg (Table 4.3.2). The highest increase of the WS Na, K, Ca and Mg after drum composting of phumdi biomass was in trial 3, 3, 2 and 3 respectively. The variation in concentration of WS nutrients among all trials was statistically significant ($P < 0.05$). The order of the concentration of WS nutrients of the final compost was K > Ca > Mg > Na.

Table 4.3.2 Variation of WS Na, K, Ca and Mg during drum composting of phumdi

Days	WS nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	693±10	678±16	659±11	639±12	707±8
4	717±12	690±15	681±8	689±11	725±9
8	873±9	901±14	978±10	1127±12	815±6
12	858±10	878±11	1089±12	1102±14	779±8
16	886±8	944±12	1198±16	1121±11	787±7
20	916±9	956±10	1231±14	1098±12	801±4
	K				
0	4150 ± 24	4055 ± 30	3928 ± 32	3725 ± 31	5580 ± 30
4	4388 ± 25	4264 ± 30	4171 ± 34	4006 ± 26	5802 ± 23
8	5160 ± 21	4976 ± 24	5283 ± 28	5299 ± 24	6808 ± 32
12	5170 ± 34	5044 ± 25	5789 ± 22	5519 ± 27	6359 ± 26
16	5230 ± 32	5252 ± 26	5884 ± 21	5502 ± 28	6424 ± 25
20	5566 ± 23	5597 ± 27	5925 ± 20	5514 ± 29	6811 ± 27
	Ca				
0	1432 ± 10	1519 ± 15	1639 ± 18	1693 ± 10	1349 ± 11
4	1440 ± 14	1747 ± 16	1816 ± 10	1520 ± 15	1388 ± 14
8	1712 ± 14	1969 ± 14	2146 ± 12	2150 ± 16	1429 ± 14
12	1689 ± 25	1968 ± 16	2210 ± 11	2142 ± 18	1455 ± 12
16	1737 ± 12	2014 ± 12	2124 ± 14	2200 ± 19	1471 ± 14
20	1734 ± 14	2073 ± 16	2134 ± 13	2201 ± 12	1491 ± 16
	Mg				
0	818 ± 4	855 ± 6	886 ± 5	921 ± 4	852 ± 4
4	856 ± 5	857 ± 5	889 ± 8	928 ± 5	903 ± 4
8	1038 ± 7	965 ± 4	1117 ± 6	1170 ± 8	1031 ± 6
12	1041 ± 8	1020 ± 10	1098 ± 4	1191 ± 6	1040 ± 8
16	1038 ± 10	1024 ± 12	1104 ± 10	1130 ± 8	1047 ± 12
20	1042 ± 8	1027 ± 11	1114 ± 8	1129 ± 10	1049 ± 8

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

4.3.4 TOTAL HEAVY METALS

The total concentrations of Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr of phumdi composts increased in all trials (Table 4.3.3). The order of the range of total heavy metals concentrations of final phumdi biomass composts after drum composting was Fe > Pb > Mn > Ni > Zn > Cr > Cd > Cu. The concentrations of the total heavy metals were highest

Table 4.3.3. Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of phumdi

Days	Total heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	172 ± 2.9	165 ± 3.6	163 ± 2.4	161 ± 2.8	181 ± 2.8	216 ± 1.5	207 ± 5.3	195 ± 6.7	182 ± 2.8	245 ± 7.7
4	175 ± 3.4	171 ± 1.4	168 ± 3.3	166 ± 3.4	183 ± 1.5	220 ± 4.7	215 ± 4.0	202 ± 2.8	186 ± 1.4	246 ± 0.5
8	188 ± 3.5	179 ± 3.7	200 ± 3.8	183 ± 2.8	190 ± 2.6	227 ± 3.1	226 ± 4.1	226 ± 1.8	209 ± 1.1	262 ± 2.0
12	193 ± 3.7	182 ± 3.6	205 ± 2.9	188 ± 2.7	197 ± 1.9	227 ± 7.0	230 ± 4.2	232 ± 4.5	223 ± 4.7	255 ± 2.8
16	198 ± 1.5	193 ± 3.1	207 ± 2.0	206 ± 3.8	204 ± 2.8	231 ± 2.5	228 ± 2.5	243 ± 4.2	230 ± 4.4	250 ± 5.7
20	202 ± 3.3	196 ± 3.8	211 ± 2.5	220 ± 2.5	209 ± 1.1	237 ± 3.5	231 ± 3.6	246 ± 2.0	239 ± 4.4	263 ± 3.3
	Cu					**Pb**				
0	51.7 ± 0.5	42.6 ± 0.5	39.5 ± 0.4	39.6 ± 0.6	55.0 ± 0.6	708 ± 7.5	661 ± 5.3	658 ± 2.4	643 ± 08.3	745 ± 12.0
4	55.0 ± 0.6	44.1 ± 0.5	40.3 ± 0.3	36.3 ± 0.7	55.3 ± 0.4	698 ± 7.5	695 ± 7.0	679 ± 5.1	695 ± 06.4	771 ± 13.0
8	55.5 ± 0.3	49.5 ± 0.9	41.8 ± 0.3	42.9 ± 0.6	59.0 ± 0.3	772 ± 7.0	773 ± 8.0	800 ± 6.5	798 ± 09.4	853 ± 14.0
12	59.8 ± 0.8	51.9 ± 0.5	46.9 ± 0.9	47.5 ± 0.9	61.8 ± 0.8	826 ± 9.0	804 ± 8.0	850 ± 5.2	823 ± 11.1	876 ± 12.0
16	62.5 ± 0.5	54.1 ± 0.7	50.6 ± 0.6	49.5 ± 0.8	65.2 ± 0.4	853 ± 8.0	816 ± 7.0	899 ± 5.9	905 ± 08.2	893 ± 11.0
20	66.7 ± 0.7	56.3 ± 0.4	52.6 ± 0.4	53.4 ± 0.9	66.8 ± 0.2	878 ± 7.5	827 ± 5.0	924 ± 3.0	936 ± 08.1	905 ± 14.0
	Mn					**Cd**				
0	706 ± 7.2	616 ± 4.8	593 ± 5.1	589 ± 5.7	727 ± 4.3	67.0 ± 0.10	64.9 ± 0.80	62.0 ± 0.20	50.8 ± 0.18	70.0 ± 0.19
4	713 ± 5.5	611 ± 5.3	626 ± 6.4	614 ± 2.3	736 ± 2.3	68.3 ± 0.20	68.1 ± 0.25	62.9 ± 0.17	52.9 ± 0.17	69.1 ± 0.15
8	802 ± 9.5	716 ± 7.3	777 ± 6.1	717 ± 2.5	792 ± 1.5	71.6 ± 0.10	73.4 ± 0.28	67.3 ± 0.19	57.7 ± 0.21	72.0 ± 0.23
12	789 ± 9.2	709 ± 6.0	770 ± 5.0	765 ± 4.5	796 ± 1.5	73.1 ± 0.28	72.1 ± 0.28	75.1 ± 0.15	61.8 ± 0.15	73.8 ± 0.16
16	814 ± 1.5	774 ± 3.8	800 ± 8.4	806 ± 1.5	812 ± 7.2	74.5 ± 0.24	74.8 ± 0.21	77.2 ± 0.13	65.1 ± 0.17	73.9 ± 0.17
20	811 ± 5.6	788 ± 5.4	836 ± 1.9	845 ± 4.0	823 ± 5.1	76.4 ± 0.20	77.2 ± 0.21	78.9 ± 0.13	66.5 ± 0.16	75.3 ± 0.23
	Fe					**Cr**				
0	14330 ± 156	13730 ± 150	13463 ± 117	12795 ± 152	14490 ± 065	98 ± 2.5	114 ± 2.9	116 ± 1.0	121 ± 4.3	97 ± 5.9
4	14415 ± 167	14192 ± 192	15156 ± 033	14163 ± 199	14526 ± 002	105 ± 5.8	127 ± 2.9	132 ± 2.5	130 ± 5.4	102 ± 3.7
8	15423 ± 160	15301 ± 190	16882 ± 139	16939 ± 196	15352 ± 109	128 ± 3.4	152 ± 1.8	145 ± 4.7	159 ± 2.8	112 ± 3.5
12	15814 ± 188	16983 ± 191	17274 ± 151	17758 ± 027	15749 ± 118	130 ± 1.9	163 ± 0.6	157 ± 3.5	176 ± 2.0	118 ± 1.0
16	16526 ± 199	16882 ± 139	17716 ± 073	17900 ± 009	16072 ± 086	135 ± 4.8	154 ± 5.0	160 ± 1.0	174 ± 4.8	122 ± 2.3
20	16664 ± 180	17078 ± 157	18033 ± 041	17982 ± 040	16263 ± 169	134 ± 6.6	157 ± 3.8	163 ± 2.5	176 ± 6.0	121 ± 2.1

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Table 4.3.4. Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of phumdi

Days	WS heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	11.8 ± 0.02	11.9 ± 0.02	9.1 ± 0.01	8.3 ± 0.02	13.1 ± 0.07	–	–	–	–	–
4	12.0 ± 0.02	11.3 ± 0.01	10.3 ± 0.02	9.6 ± 0.02	12.8 ± 0.01	–	–	–	–	–
8	12.0 ± 0.02	10.4 ± 0.03	12.0 ± 0.01	10.8 ± 0.01	12.6 ± 0.04	–	–	–	–	–
12	10.3 ± 0.03	9.4 ± 0.01	7.9 ± 0.01	7.8 ± 0.04	12.9 ± 0.01	–	–	–	–	–
16	10.1 ± 0.03	9.8 ± 0.02	7.3 ± 0.01	7.2 ± 0.01	12.6 ± 0.07	–	–	–	–	–
20	9.6 ± 0.01	9.0 ± 0.06	7.2 ± 0.01	6.6 ± 0.01	12.4 ± 0.08	–	–	–	–	–
	Cu					**Pb**				
0	7.5 ± 0.01	7.2 ± 0.02	8.4 ± 0.03	8.3 ± 0.02	8.9 ± 0.09	10.8 ± 0.03	9.2 ± 0.05	8.8 ± 0.05	7.2 ± 0.04	11.5 ± 0.05
4	7.4 ± 0.01	7.0 ± 0.06	9.3 ± 0.02	9.2 ± 0.05	8.7 ± 0.05	6.1 ± 0.07	4.6 ± 0.04	5.0 ± 0.05	4.9 ± 0.05	6.8 ± 0.07
8	7.9 ± 0.05	7.8 ± 0.05	8.5 ± 0.02	8.4 ± 0.05	8.5 ± 0.05	5.1 ± 0.02	4.3 ± 0.01	3.6 ± 0.05	4.4 ± 0.04	4.3 ± 0.04
12	7.7 ± 0.05	7.3 ± 0.10	8.0 ± 0.05	8.0 ± 0.09	8.4 ± 0.05	4.6 ± 0.03	4.0 ± 0.04	3.2 ± 0.03	3.4 ± 0.05	4.7 ± 0.02
16	7.5 ± 0.05	7.1 ± 0.05	7.7 ± 0.05	7.7 ± 0.05	8.5 ± 0.05	3.7 ± 0.05	3.7 ± 0.02	2.7 ± 0.01	3.8 ± 0.02	4.4 ± 0.02
20	7.4 ± 0.05	6.8 ± 0.01	7.5 ± 0.05	7.3 ± 0.05	8.5 ± 0.10	3.5 ± 0.04	3.1 ± 0.06	2.5 ± 0.05	1.6 ± 0.05	4.1 ± 0.07
	Mn					**Cd**				
0	77.9 ± 0.4	63.3 ± 0.8	74.0 ± 0.8	67.9 ± 0.4	84.7 ± 0.5	–	–	–	–	–
4	80.6 ± 0.2	66.6 ± 0.5	75.2 ± 0.3	73.2 ± 0.6	83.5 ± 0.4	–	–	–	–	–
8	72.5 ± 0.2	50.4 ± 0.8	52.4 ± 0.4	52.4 ± 0.4	77.7 ± 0.5	–	–	–	–	–
12	75.1 ± 0.2	49.4 ± 0.9	50.9 ± 0.5	48.6 ± 0.5	75.0 ± 0.4	–	–	–	–	–
16	70.9 ± 0.3	47.5 ± 0.9	44.9 ± 0.2	42.7 ± 0.6	77.8 ± 0.4	–	–	–	–	–
20	68.7 ± 0.4	45.9 ± 0.8	44.0 ± 0.3	39.1 ± 0.5	74.5 ± 0.4	–	–	–	–	–
	Fe					**Cr**				
0	91 ± 0.17	89 ± 0.21	98 ± 0.24	99 ± 0.24	104 ± 0.48	8.8 ± 0.02	10.0 ± 0.05	9.8 ± 0.01	9.4 ± 0.01	12.8 ± 0.01
4	92 ± 0.45	91 ± 0.38	97 ± 0.27	95 ± 0.15	102 ± 0.59	7.8 ± 0.02	10.5 ± 0.05	10.9 ± 0.01	9.8 ± 0.01	13.3 ± 0.01
8	94 ± 0.35	97 ± 0.19	102 ± 0.31	103 ± 0.62	108 ± 0.70	8.0 ± 0.02	6.7 ± 0.05	8.7 ± 0.02	5.6 ± 0.04	11.6 ± 0.06
12	90 ± 0.42	90 ± 0.49	96 ± 0.25	87 ± 0.57	107 ± 0.75	8.5 ± 0.05	7.1 ± 0.05	8.0 ± 0.02	5.1 ± 0.01	10.8 ± 0.04
16	88 ± 0.27	86 ± 0.58	93 ± 0.43	86 ± 0.35	108 ± 0.82	7.0 ± 0.06	6.8 ± 0.00	7.1 ± 0.05	3.9 ± 0.02	10.6 ± 0.04
20	83 ± 0.41	80 ± 0.28	86 ± 0.27	85 ± 0.65	104 ± 0.93	6.5 ± 0.05	5.6 ± 0.02	5.3 ± 0.02	3.8 ± 0.01	9.9 ± 0.02

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

in the compost of trial 4 due to higher net loss of dry mass. The total concentrations of the heavy metals of the composts obtained after drum composting were also higher than the total concentrations of heavy metals of the composts obtained after agitated pile composting of the phumdi biomass. The variation of the concentration of total heavy metals among all the drum trials was statistically significant ($P < 0.05$).

4.3.5 BIOAVAILABILITY OF HEAVY METALS

4.3.5.1 WS heavy metals

The concentration of the WS forms of Zn, Cu, Mn, Fe Pb and Cr reduced significantly ($P < 0.05$) in all trials during drum composting of phumdi biomass (Table 4.3.4). The highest reduction of WS heavy metals was mostly in trial 4. In some of the trials, there was initial increase in the concentration of WS metals during the process due to the intermediate release of soluble organic acids which were further degraded by the microbial action (Ahmed et al., 2007). The concentration of the WS metals is regulated by the net loss in dry mass of the compost and the formation of insoluble complexes with the humus substances of the compost (Cai et al., 2007; Singh and Kalamdhad, 2013a). The order of reduction of WS heavy metals in the trials was as below:

Zn: T2 (24.9%) > T4 (20.6%) > T3 (20.5%) > T1 (19.1%) > T5 (06.0%)
Cu: T4 (13.0%) > T3 (11.7%) > T2 (06.1%) > T5 (04.8%) > T1 (02.6%)
Mn: T4 (42.5%) > T3 (40.6%) > T2 (27.6%) > T5 (12.1%) > T1 (11.8%)
Fe: T4 (13.8%) > T3 (12.4%) > T2 (09.7%) > T1 (09.4%) > T5 (00.4%)
Pb: T4 (67.9%) > T3 (55.2.8%) > T2 (50.6%) > T1 (49.1%) > T5 (47.1%)
Cr: T4 (59.6%) > T3 (45.9%) > T2 (43.9%) > T1 (26.1%) > T5 (22.4%)

(Note: T–trial)

The order of the concentration of WS heavy metals of the final composts was similar to the composts after pile composting of phumdi biomass (Fe > Mn > Zn > Pb = Cu = Cr).

4.3.5.2 DTPA extractable heavy metals

The variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during the drum composting process of phumdi biomass is shown in Table 4.3.5. DTPA extractable Cd was not detected in the phumdi composts of all trials. DTPA extractable heavy metals were reduced in all trials during the drum composting process in the following order:-

Zn: T4 (26.5%) > T3 (24.4%) > T2 (19.4%) > T1 (15.7%) > T5 (14.6%)
Cu: T4 (32.5%) > T3 (24.5%) > T1 (28.1%) > T2 (25.7%) > T5 (18.2%)

Table 4.3.5. Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of phumdi

Days	DTPA extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	98.5 ± 0.1	85.0 ± 0.1	82.0 ± 0.1	77.0 ± 0.1	107.0 ± 0.2	1.12 ± 0.002	0.92 ± 0.006	0.75 ± 0.004	0.9 ± 0.009	1.39 ± 0.004
4	95.0 ± 0.2	83.5 ± 0.1	83.0 ± 0.1	80.0 ± 0.1	106.0 ± 0.2	1.02 ± 0.001	0.8 ± 0.007	0.67 ± 0.007	0.82 ± 0.002	1.32 ± 0.007
8	97.5 ± 0.1	72.5 ± 0.2	84.0 ± 0.1	81.0 ± 0.2	104.5 ± 0.2	0.81 ± 0.001	0.62 ± 0.005	0.68 ± 0.008	0.89 ± 0.006	1.2 ± 0.005
12	89.5 ± 0.2	72.5 ± 0.2	68.5 ± 0.1	63.0 ± 0.2	97.0 ± 0.2	0.68 ± 0.004	0.55 ± 0.008	0.49 ± 0.004	0.63 ± 0.008	1.07 ± 0.004
16	82 ± 0.2	66.5 ± 0.2	63.0 ± 0.1	57.2 ± 0.2	90.5 ± 0.1	0.62 ± 0.005	0.47 ± 0.001	0.31 ± 0.007	0.44 ± 0.007	1.02 ± 0.005
20	83 ± 0.2	68.5 ± 0.2	62.0 ± 0.1	56.6 ± 0.1	91.4 ± 0.1	0.55 ± 0.005	0.45 ± 0.005	0.3 ± 0.008	0.39 ± 0.008	0.92 ± 0.007
	Cu					**Pb**				
0	9.8 ± 0.04	10.7 ± 0.03	11.1 ± 0.07	10 ± 0.02	12.4 ± 0.08	18.9 ± 0.07	14.6 ± 0.01	13.7 ± 0.01	10.2 ± 0.04	20.3 ± 0.04
4	9.3 ± 0.03	10.8 ± 0.02	12 ± 0.01	11.3 ± 0.04	13.1 ± 0.09	13.8 ± 0.07	11.3 ± 0.04	8.8 ± 0.04	8.9 ± 0.04	15.4 ± 0.02
8	10.1 ± 0.02	12.1 ± 0.04	12.8 ± 0.05	12.5 ± 0.03	12.5 ± 0.03	11.5 ± 0.04	9.8 ± 0.05	7.6 ± 0.03	8.8 ± 0.03	14.2 ± 0.01
12	7.5 ± 0.01	9.9 ± 0.01	9.8 ± 0.03	7.1 ± 0.04	10.7 ± 0.09	10.8 ± 0.02	9.2 ± 0.06	6.7 ± 0.02	5.0 ± 0.02	12.4 ± 0.01
16	7.2 ± 0.03	8.5 ± 0.07	10.1 ± 0.02	7.3 ± 0.03	10 ± 0.05	9.0 ± 0.01	7.1 ± 0.04	5.9 ± 0.03	4.0 ± 0.01	11.9 ± 0.03
20	7.1 ± 0.02	7.9 ± 0.02	8.4 ± 0.03	6.8 ± 0.03	10.2 ± 0.06	8.8 ± 0.01	6.6 ± 0.05	5.7 ± 0.04	4.0 ± 0.01	10.3 ± 0.04
	Mn					**Cd**				
0	268 ± 1.0	225 ± 0.4	268 ± 0.8	257 ± 0.4	289 ± 0.4	0.86 ± 0.001	0.5 ± 0	0.43 ± 0	0.59 ± 0	0.93 ± 0
4	265 ± 1.1	226 ± 0.5	264 ± 0.7	250 ± 0.5	284 ± 0.5	0.71 ± 0.001	0.3 ± 0	0.29 ± 0	0.43 ± 0	0.8 ± 0
8	254 ± 1.2	192 ± 0.4	220 ± 1.5	191 ± 0.4	290 ± 0.6	0.69 ± 0	0.34 ± 0	0.34 ± 0	0.39 ± 0	0.76 ± 0
12	234 ± 1.0	181 ± 1.3	221 ± 0.7	198 ± 1.3	283 ± 1.4	0.62 ± 0	0.33 ± 0.001	0.22 ± 0	0.21 ± 0	0.68 ± 0.001
16	224 ± 0.9	173 ± 0.7	212 ± 0.6	186 ± 0.6	271 ± 1.0	0.6 ± 0.001	0.36 ± 0	0.24 ± 0	0.19 ± 0.001	0.55 ± 0
20	215 ± 1.5	170 ± 0.9	187 ± 0.5	166 ± 0.6	266 ± 1.1	0.51 ± 0.001	0.32 ± 0	0.2 ± 0	0.19 ± 0	0.51 ± 0
	Fe					**Cr**				
0	132 ± 1.1	133 ± 1.3	153 ± 1.4	158 ± 1.6	123 ± 1.8	13.29 ± 0.01	11.99 ± 0.01	10.16 ± 0.01	10.54 ± 0.001	7.41 ± 0.00
4	148 ± 1.1	150 ± 1.2	170 ± 1.4	175 ± 1.3	145 ± 1.7	12.83 ± 0.001	11.24 ± 0.004	9.62 ± 0.002	9.30 ± 0.001	7.80 ± 0.00
8	119 ± 1.2	115 ± 1.1	145 ± 1.3	148 ± 1.8	118 ± 1.9	12.52 ± 0.01	9.08 ± 0.008	6.61 ± 0.001	6.59 ± 0.001	6.39 ± 0.001
12	98 ± 0.9	94 ± 1.3	105 ± 1.8	100 ± 1.9	86 ± 0.5	11.42 ± 0.01	9.49 ± 0.007	6.94 ± 0.002	7.09 ± 0.004	6.41 ± 0.01
16	87 ± 0.7	89 ± 0.4	101 ± 0.3	91 ± 0.6	80 ± 0.8	10.80 ± 0.002	8.26 ± 0.004	6.08 ± 0.002	5 ± 0.001	5.98 ± 0.01
20	80 ± 0.5	81 ± 0.5	98 ± 0.7	90 ± 0.4	76 ± 0.6	10.02 ± 0.004	8.24 ± 0.003	5.5 ± 0.001	4.45 ± 0.00	5.88 ± 0.007

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Mn: T4 (35.4%) > T3 (30.3%) > T2 (24.6%) > T1 (19.9%) > T5 (8.1%)
Fe: T4 (42.9%) > T2 (39.5%) > T1 (39.0%) > T5 (38.3%) > T3 (35.8%)
Ni: T3 (59.3%) > T4 (56.7%) > T1 (50.9%) > T2 (50.8%) > T5 (33.9%)
Pb: T4 (60.9%) > T3 (58.4%) > T2 (54.8%) > T1 (53.3%) > T5 (49.5%)
Cd: T4 (68.2%) > T3 (53.5%) > T5 (45.2%) > T1 (40.9%) > T2 (37.0%)
Cr: T4 (57.4%) > T3 (45.9%) > T2 (31.3%) > T1 (24.6%) > T5 (20.6%)

(Note: T–trial)

The "ŋ" of the DTPA extractable heavy metals also decreased for all trials during the drum composting process (Fig. 4.3.5). The "ŋ" of the final compost were in the range 21.1–37.3% for Zn, 9.0–13.6% for Cu, 19.7–32.2% for Mn, 0.5% for Fe, 0.1–0.4% for Ni, 0.4–1.1% for Pb, 0.3–0.7% for Cd and 2.5–7.5% for Cr. The highest reduction of the concentration of DTPA extractable Cu after drum composting of phumdi biomass (26.5%) was lower than that obtained after the pile composting of phumdi biomass (66.7%). However, the variation of "ŋ" of DTPA extractable Cu of the phumdi biomass compost after pile composting (9.2–13.3%) and drum composting (9.0–13.6%) was not significant. The lower reduction of the concentration of DTPA extractable Cu of the phumdi biomass compost compared with drum composting was due to higher net loss of dry mass. The order of the concentration of the DTPA extractable heavy metals of the phumdi biomass compost after drum composting was Mn > Fe > Zn > Pb > Cr > Cu > Cd = Ni. The variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during the drum composting process of phumdi biomass was statistically significant ($P < 0.05$).

4.3.5.3 TCLP extraction for heavy metals

The changes in leachability of Zn, Cu, Mn, Fe, Ni, Cd, Pb and Cr during the drum composting of phumdi biomass are given in Table 4.3.6. Leachability of heavy metals was reduced in all trials during the composting in the order below:

Zn: T3 (38.3%) > T4 (29.6%) > T2 (21.2%) > T1 (18.1%) > T5 (16.2%)
Cu: T4 (41.3%) > T3 (37.4%) > T2 (32.8%) > T1 (31.5%) > T5 (25.1%)
Mn: T3 (36.8%) > T4 (32.6%) > T2 (27.5%) > T1 (23.8%) > T5 (19.4%)
Fe: T4 (23.6%) > T3 (21.2%) > T2 (21.0%) > T1 (18.6%) > T5 (16.6%)
Ni: T4 (59.8%) > T3 (55.6%) > T2 (50.5%) > T1 (23.7%) > T5 (26.4%)
Pb: T4 (58.1%) > T3 (55.0%) > T2 (40.5%) > T1 (34.3%) > T5 (22.1%)
Cr: T4 (54.8%) > T3 (51.8%) > T2 (48.6%) > T1 (33.7%) > T5 (32.6%)

(Note: T–trial)

The order of the concentration of the leachable heavy metals of the final phumdi biomass composts after drum composting was Mn > Fe > Zn > Cr > Pb > Cu > Ni > Cd. ANOVA analysis showed significant differences in the leachable concentration of Zn, Cu, Fe, Mn, Fe, Ni, Pb, Cd and Cr of all trials ($P < 0.05$).

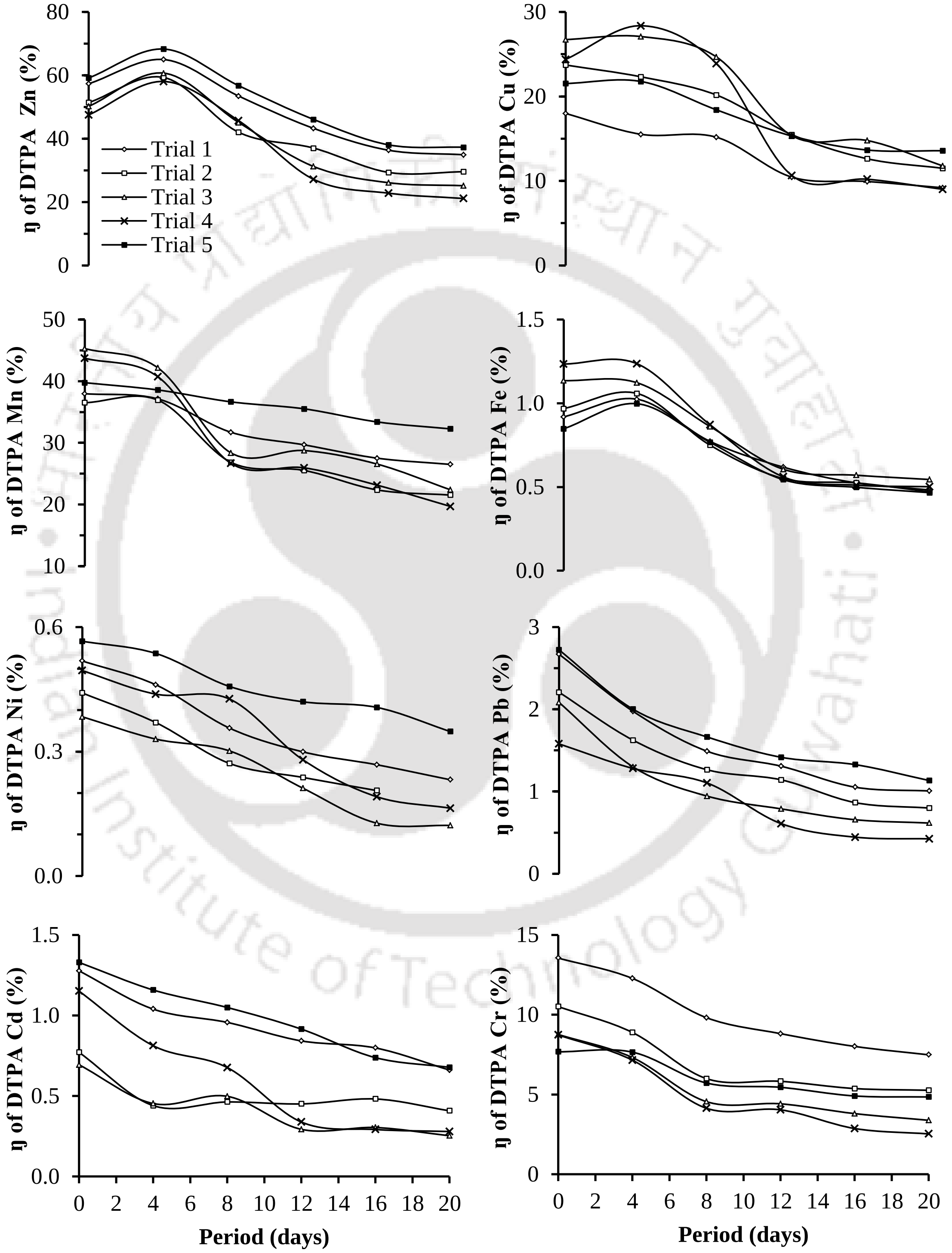

Fig. 4.3.5. Variation of "ŋ" of DTPA extractable heavy metals during drum composting of phumdi biomass.

Table 4.3.6. Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of phumdi

Days	TCLP extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	94.8 ± 0.6	90.4 ± 0.5	82.1 ± 0.4	71.1 ± 0.4	106.8 ± 0.4	6.97 ± 0.01	6 ± 0.02	5.5 ± 0.005	5 ± 0.01	7.4 ± 0.01
4	96.8 ± 0.5	97.5 ± 0.4	81.5 ± 0.5	71.9 ± 0.5	105.5 ± 0.5	6.43 ± 0.01	5.52 ± 0.03	4.87 ± 0.008	4.05 ± 0.002	6.96 ± 0.03
8	74.8 ± 0.5	78.7 ± 0.5	65 ± 0.4	53 ± 0.6	92 ± 0.6	6.57 ± 0.009	4.14 ± 0.003	4.27 ± 0.01	4.1 ± 0.006	6.4 ± 0.008
12	81.1 ± 0.6	78.8 ± 0.6	66.1 ± 0.3	52 ± 0.7	91 ± 0.6	5.77 ± 0.01	3.92 ± 0.004	3.75 ± 0.008	2.12 ± 0.004	6.2 ± 0.002
16	83.1 ± 0.7	74.2 ± 0.7	53.3 ± 0.2	52.3 ± 0.4	93 ± 0.7	5.6 ± 0.001	3.29 ± 0.005	3.14 ± 0.009	2.09 ± 0.006	5.61 ± 0.009
20	77.6 ± 0.4	71.2 ± 0.4	50.8 ± 0.5	50 ± 0.3	89.5 ± 0.3	5.32 ± 0.004	2.97 ± 0.004	2.44 ± 0.01	2.01 ± 0.001	5.45 ± 0.004
	Cu					**Pb**				
0	13.3 ± 0.01	12.6 ± 0.01	12.1 ± 0.02	11.4 ± 0.01	14.0 ± 0.01	30.6 ± 0.09	29 ± 0.04	25.7 ± 0.09	25.5 ± 0.18	34.8 ± 0.16
4	12.9 ± 0.04	12.1 ± 0.05	11.9 ± 0.04	11.5 ± 0.04	13.0 ± 0.01	28.6 ± 0.08	28.3 ± 0.09	26.3 ± 0.1	24.7 ± 1.7	35.8 ± 0.19
8	9 ± 0.09	8.4 ± 0.05	8.5 ± 0.02	8.0 ± 0.05	8.8 ± 0.02	27 ± 0.07	24.6 ± 0.1	22.9 ± 0.2	18.9 ± 0.19	31.9 ± 0.09
12	9.4 ± 0.02	8.3 ± 0.04	8.5 ± 0.01	7.6 ± 0.03	10.2 ± 0.03	27.7 ± 0.07	24.8 ± 0.1	17.4 ± 0.1	11.5 ± 0.19	35.2 ± 0.12
16	9.3 ± 0.04	8.4 ± 0.03	8.3 ± 0.04	7.4 ± 0.01	10.8 ± 0.01	22.4 ± 0.1	22 ± 0.1	12.4 ± 0.11	11 ± 0.11	31.6 ± 0.08
20	9.1 ± 0.04	8.5 ± 0.02	7.6 ± 0.05	6.7 ± 0.05	10.5 ± 0.01	20.1 ± 0.1	17.3 ± 0.09	11.6 ± 0.1	10.7 ± 0.19	27.1 ± 0.09
	Mn					**Cd**				
0	406 ± 1.0	416 ± 1.0	437 ± 1.9	442 ± 0.8	396 ± 0.8	2.9 ± 0.04	2.1 ± 0.01	2.63 ± 0.045	2.46 ± 0.025	2.76 ± 0.06
4	394 ± 1.0	424 ± 1.0	424 ± 0.9	422 ± 0.9	383 ± 0.8	2.8 ± 0.045	1.97 ± 0.025	2.38 ± 0.045	2.25 ± 0.01	2.79 ± 0.05
8	386 ± 1.0	378 ± 1.0	395 ± 0.9	391 ± 0.8	364 ± 0.9	2.19 ± 0.045	1.61 ± 0.01	1.49 ± 0.045	1.39 ± 0.025	2.83 ± 0.04
12	311 ± 1.1	311 ± 0.9	317 ± 1.0	337 ± 0.9	314 ± 0.9	2.06 ± 0.045	1.48 ± 0.025	1.23 ± 0.05	1.09 ± 0.055	2.72 ± 0.09
16	325 ± 1.0	284 ± 0.9	301 ± 0.9	306 ± 0.7	322 ± 0.8	2.08 ± 0.05	1.29 ± 0.055	0.89 ± 0.008	1.15 ± 0.09	2.62 ± 0.05
20	309 ± 1.0	301 ± 0.9	276 ± 0.9	298 ± 1.8	320 ± 1.0	1.9 ± 0.05	1.07 ± 0.02	0.79 ± 0.008	1.03 ± 0.04	2.5 ± 0.08
	Fe					**Cr**				
0	258 ± 1.1	317 ± 0.9	342 ± 1.1	357 ± 1	227 ± 1.2	73.2 ± 0.5	63.3 ± 0.4	83 ± 0.7	71.8 ± 0.7	69.8 ± 0.4
4	256 ± 1.1	310 ± 0.8	339 ± 1.1	334 ± 0.9	223 ± 0.9	67.2 ± 0.5	59 ± 0.6	80.8 ± 0.7	71.4 ± 0.5	70.4 ± 0.5
8	265 ± 1.4	289 ± 1.1	319 ± 0.9	345 ± 0.8	219 ± 0.9	64.4 ± 0.6	41.5 ± 0.3	62.1 ± 0.6	55.3 ± 0.6	60.2 ± 0.3
12	231 ± 1.3	268 ± 0.9	298 ± 0.8	306 ± 1.3	209 ± 0.9	54.8 ± 0.5	48.1 ± 0.7	56.8 ± 0.4	47.7 ± 0.4	57.3 ± 0.6
16	221 ± 1.1	251 ± 1.1	289 ± 1.1	291 ± 1.1	199 ± 1.1	50.4 ± 0.7	36.1 ± 0.8	35.7 ± 0.6	36.5 ± 0.6	51 ± 0.4
20	210 ± 1.2	250 ± 0.9	270 ± 0.8	275 ± 1.2	189 ± 0.9	48.5 ± 0.4	32.6 ± 0.5	40 ± 0.5	32.5 ± 0.5	47 ± 0.6

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

4.4 VERMICOMPOSTING OF PHUMDI BIOMASS

4.4.1 EARTHWORM BIOMASS

The changes in the number of earthworms, cocoons and new hatchings are shown at Fig. 4.4.1. The number of earthworms (adults and young non-clitellated) initially decreased in trial 1, 2 and 5. Mortality was not indicated in trial 3 and 4 during the process. The numbers of earthworms were found increased in all trials on day 45 with the highest number of earthworms in trial 4 (242±4 nos.) followed by trial 3 (235±2 nos.). Trial 4 substrate had the highest proportion of cattle manure containing easily metabolizable OM and non-assimilated carbohydrates essential for the growth and reproduction of earthworms (Gupta et al., 2007). The number of earthworms of trial 5 having no cattle manure was higher than trial 1 and 2 indicating that the growth of earthworms was not totally dependent on the proportion of cattle manure. This is inconsistent with the vermicomposting of water hyacinth where the growth of adult earthworms was totally dependent on the proportion of cattle manure (Singh and Kalamdhad, 2013b). The phumdi biomass contains considerable portion of decayed matter and silt trapped inside the roots. The decayed detritus OM associated with the phumdi biomass might also be suitable food for the earthworms. The order of earthworm numbers on day 45 was trial 4 (242±4 nos.) > trial 3 (235±2 nos.) > trial 5 (222±2 nos.) > trial 2 (206±1 nos.) > trial 1 (191±1 nos.). The cocoon population was seen in all trials during monitoring of the vermireactors on day 15. The production of cocoons in different feed mixtures is also related to the biochemical quality of the feed and the microbial mass and decomposition activities (Suthar, 2007). New hatchings were seen during sampling on day 30. The total earthworm biomass was highest in trial 4 (227.2±2.2 g) followed by trial 3 (219.7±1.4 g) on day 45. However, the total biomass of trial 5 (200.0±1.3 g) was higher than trial 1 and 2 (180.1±1.4 and 191.3±1.3 g respectively) during the vermicomposting period. The highest total biomass growth rate was in trial 4 (4.7 g/day) from day 30 to 45 due to new hatchings and their rapid growth. The relatively lower total biomass growth rate in trial 4 (1.9 g/day) from day 0 to 30 was due to the assimilative phase and energy consumed by the adult earthworms for production of cocoons which otherwise would have been utilised for tissue growth (Chaudhari and Bhattacharjee, 2002). The variation in the number of adult earthworms, cocoons and hatchlings and the total earthworm biomass showed statistical significance for all trials ($P < 0.05$). The growth, population increase and fecundity of the earthworms are indicators of the suitability for vermicomposting of the substrates (Chaudhari and Bhattacharjee, 2002). In the present study, the growth and fecundity was not totally dependent on cattle manure as indicated by the growth pattern of trial 1, 2 and 5. The phumdi biomass is associated with detritus OM which might be easily available food for the earthworms.

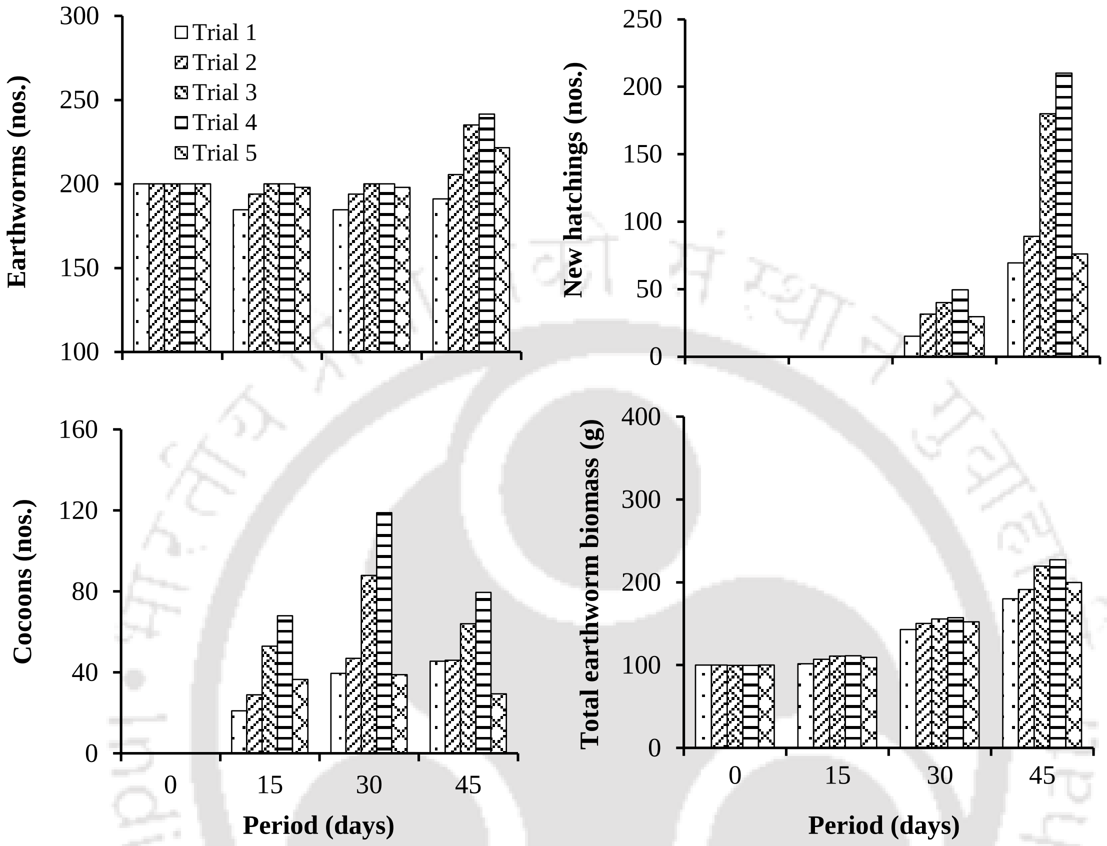

Fig. 4.4.1. Variations in the no. of earthworms, cocoons, hatchings and total earthworm biomass during phumdi vermicomposting

4.4.2 PHYSICO-CHEMICAL AND BIO-CHEMICAL ANALYSIS

The pH in all vermicompost trials initially decreased on day 15 of the process and then increased on day 30 and 45. The decrease in pH was due to the production of CO_2 and organic acid by microbial decomposition during vermicomposting process. The increase in pH at the latter stage of the process is not consistent with the findings of many researchers who have reported decrease in pH during vermicomposting (Nedgwa and Thompson, 2000; Gupta and Garg, 2008). The inconsistency in the findings is because different substrates resulted in the production of different intermediate species and different wastes showing different pH behaviours (Gupta and Garg, 2008). The increase in pH during vermicomposting was corroborated by some researchers like Hait and Tare (2010), Kaur et al., (2010), Singh and Kalamdhad (2013), Huang et al., (2014).

The decomposition of OM leads to the formation of NH_4^+ ions and humic acids. The presence of carboxylic and phenolic groups in humic acids caused lowering of pH whereas ammonium ions increased the pH of the system. The combined effect of these two processes regulates the pH of vermicompost leading to a shift of pH towards neutrality (Pramanik et al., 2007). Earthworms selectively increased the populations of catabolically more active microbes (Aira et al., 2007) and in the process the degradation of short chain fatty acids and secretion of calcium carbonate might be another cause for the increase in pH during vermicomposting (Tognetti et al., 2005). The amorphous calcium carbonate in bio-minerals fulfills the functions of skeletal growth and maintenance in higher organisms which is not relevant in the case of earthworms. The secretion of calcium carbonate appears to be related to pH regulation with calcium carbonate precipitating when HCO_3^- ions are in excess of those required to buffer tissue fluid pH (Versteegh et al., 2014). Further, the excess organic nitrogen that was not entailed by microbes and released as ammonia might have dissolved in the moisture of the substrates and increased the pH of the vermicompost (Vig et al., 2011). The highest pH was in trial 4 (7.41±0.01) on day 45. The bamboo reactor design might have also provided better aeration to the substrates in controlling anaerobic conditions. The variation of pH among all the trials was statistically significant ($P< 0.05$).

The EC of trial 1, 2, 3, 4 and 5 initially increased from 3.15, 3.15, 3.13, 3.11 and 3.41dS/m on day 0 to 3.27, 3.31, 3.22, 3.89 and 3.53 dS/m on day 15 and then decreased to 3.08, 3.03, 2.15, 2.17 and 3.03 dS/m on day 45, respectively. The loss of OM and release of different mineral salts in available forms such as phosphate, ammonium, potassium, etc. might be the reason for the increase in EC (Garg et al., 2006). Some of these ions are essential for plant growth (K^+, Ca^{2+}, Mg^{2+}, etc.) while others are often undesirable (Na^+, NH_4^+, etc.). The precipitation of mineral salts could be the reason for the final decrease in EC and this corroborates the result of pH. ANOVA analysis shows significant difference in the variation of EC among all trials ($P < 0.05$).

VS, indicator of OM content, decreased during the vermicomposting process due to mineralization of the substrates (Fig 4.4.2c). In addition to the metabolic activity of the earthworms, the associated active microorganisms thriving in the microclimatic conditions promoted by the earthworms might have degraded the organic components resulting in loss of C in the form of CO_2 during microbial respiration and subsequent mineralization (Orozco et al., 1996; Elvira et al., 1996; Vig et al., 2011). The loss of VS in the trials was in the order trial 4 (23.4%; $K_b = 0.53$) > trial 3 (21.5%; $K_b = 0.50$) > trial 5

(20.9%; $K_b = 0.49$) > trial 2 (18.4%; $K_b = 0.45$) > trial 1 (17.3%; $K_b = 0.43$). The earthworm biomass gained per day for trial 5 (1.1 g/day) was higher than that of trial 1 and 2 (0.7 and 0.9 g/day respectively) which was in agreement with the higher reduction of VS in trial 5 compared with trial 2 and 1. The phumdi biomass associated with detritus OM was consumed as food by the earthworms. The reduction of VS concentration was statistically significant among all trials ($P < 0.05$).

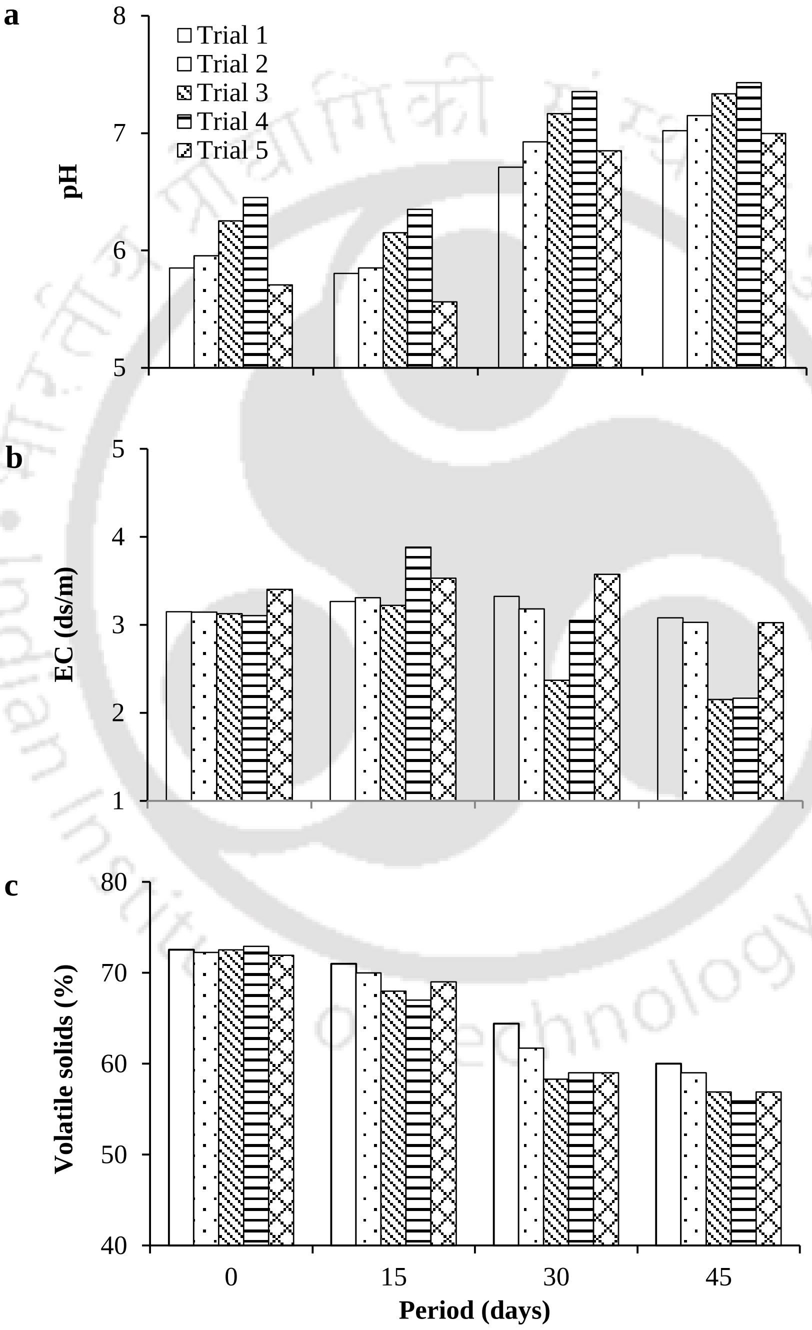

Fig. 4.4.2 a. Variation of pH during vermicomposting of phumdi biomass
b. Variation of EC during vermicomposting of phumdi biomass
c. Variation of VS during vermicomposting of phumdi biomass

All trials showed decrease in soluble BOD due to the combine action of the earthworm enzymes and the associated microbes (Fig. 4.4.2d). The order of soluble BOD reduction was trial 4 (80.6%) > trial 3 (79.0%) > trial 5 (78.2%) > trial 2 (77.6%) > trial 1 (75.3%). The variation of soluble BOD was not significant ($P > 0.05$).

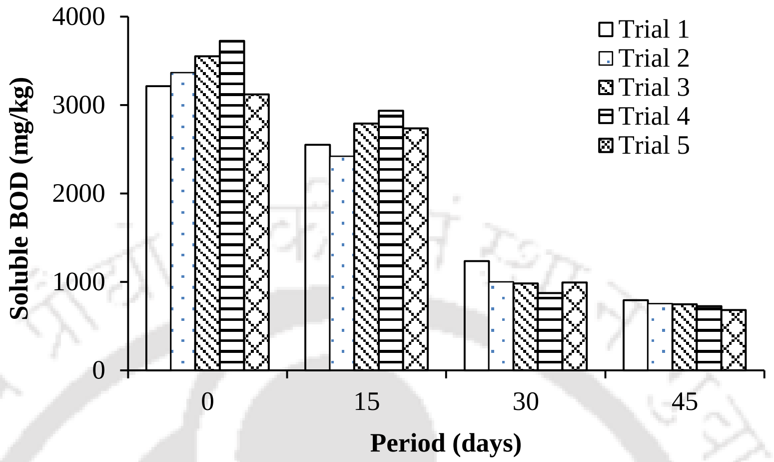

Fig. 4.4.2d. Variation of soluble BOD during vermicomposting of phumdi

The CO_2 evolution rate and the OUR decreased during the vermicomposting process (Fig. 4.4.2 e, f). The lowest CO_2 evolution rate and OUR was indicated in the vermicompost of trial 4 (1.6 and 4.3 mg/g VS/day, respectively) on day 45. The OUR and CO_2 evolution rate of the final phumdi vermicompost was higher than phumdi composts generated from agitated pile composting and rotary drum composting due to higher microbial activity of the vermicompost. However, the results were within the limits prescribed for stable composts (TMECC, 2002). The variation of CO_2 evolution rate and OUR during the vermicomposting were not significant among the trials ($P > 0.05$).

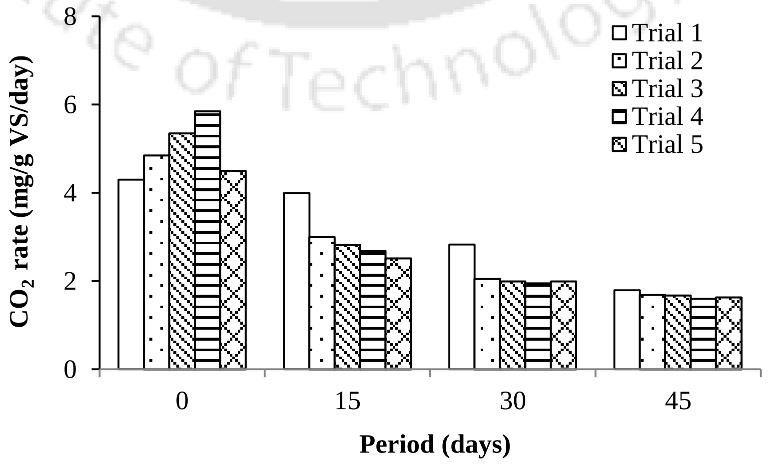

Fig. 4.4.2e. Variation of CO_2 evolution rate during phumdi vermicomposting

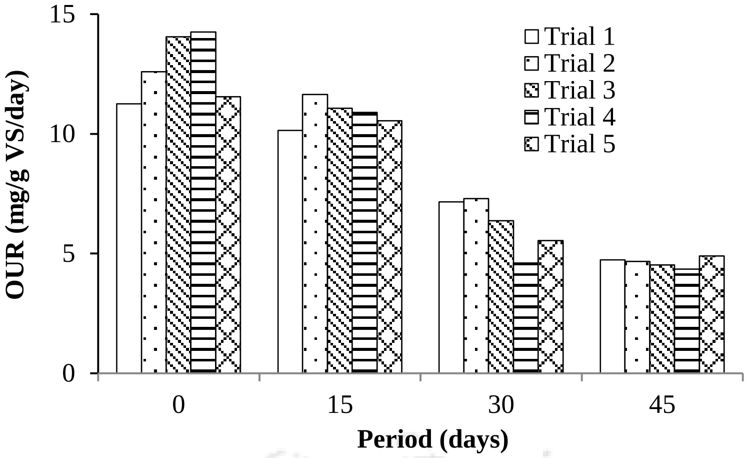

Fig. 4.4.2f. Variation of OUR during vermicomposting of phumdi

4.4.3 NUTRIENTS

The TKN increased in trial 1, 2, 3, 4 and 5 increased from 1.81, 1.77, 1.73, 1.69 and 2.00 to 2.28, 2.28, 2.67, 2.84 and 2.63, respectively (Fig. 4.4.3a). The highest increase was in trial 4 (40.4%) followed by trial 3 (35.1%). The final content of nitrogen after vermicomposting is dependent on initial nitrogen present in the waste and the extent of decomposition (Viel et al., 1987). The reduction in dry mass (organic carbon in terms of CO_2) due to substrate utilization by microbes and worms for their metabolic activities as well as water loss by evaporation during mineralization of OM (Crawford, 1983) might have led to relative increase in nitrogen. Earthworm activity enriches the nitrogen profile of vermicompost through microbial mediated nitrogen transformation and through addition of mucus and nitrogenous wastes secreted by earthworms (Suthar, 2007; Prabha et al., 2008). These nitrogen rich substances were not originally present in feed substrates. The NH_4–N decreased during the vermicomposting process. The decreased in NH_4–N concentration during the vermicomposting process can be for many reasons such as immobilization or assimilation of NH_4–N by the microorganisms; and nitrification. The increased in pH during the process coupled with burrows of the earthworms facilitating aeration might have released some NH_4–N as ammonia. The NH_4–N contents of the composts of all trials were low (≤ 400 mg/kg) and there was no risk of phytotoxicity (Bernal et al., 1998).

The concentration of TP also gradually increased due to the mineralization of OM (Fig. 4.4.3b). The TP of trial 1, 2, 3, 4 and 5 increased from 2.75, 2.80, 2.79, 2.81 and 2.90 g/kg to 4.27, 8.50, 12.50, 13.40 and 6.80 g/kg and the highest increase was in trial 4 (79.1%) followed by trial 3 (77.7%). The AP also increased after the process. The highest increase was also in trial 4 (45.0%) followed by trial 3 (38.2%). When the organic materials passed through the gut of the earthworms some of the phosphorous were converted into bioavailable forms mediated by the gut phosphatase. Further release of phosphorous occurred due to the action of the phosphorous solubilizing microorganisms present in the worm casts (Lee, 1992; Ghosh et al., 1999). The accelerating effects of vermicomposting was due to the rich microbial population, especially phosphate solubilizing bacteria in the earthworm intestine, that transformed the organic phosphorous into mineral forms, solubilized the unavailable forms of phosphorous and kept the magnitude of fixation of released phosphorous into insoluble inorganic forms at low level (Bhattacharya and Chattopadhyay, 2002; Ghosh et al., 1999). The variation of TKN, NH_4–N, TP and AP concentrations for the 5 trials were statistically significant ($P < 0.05$).

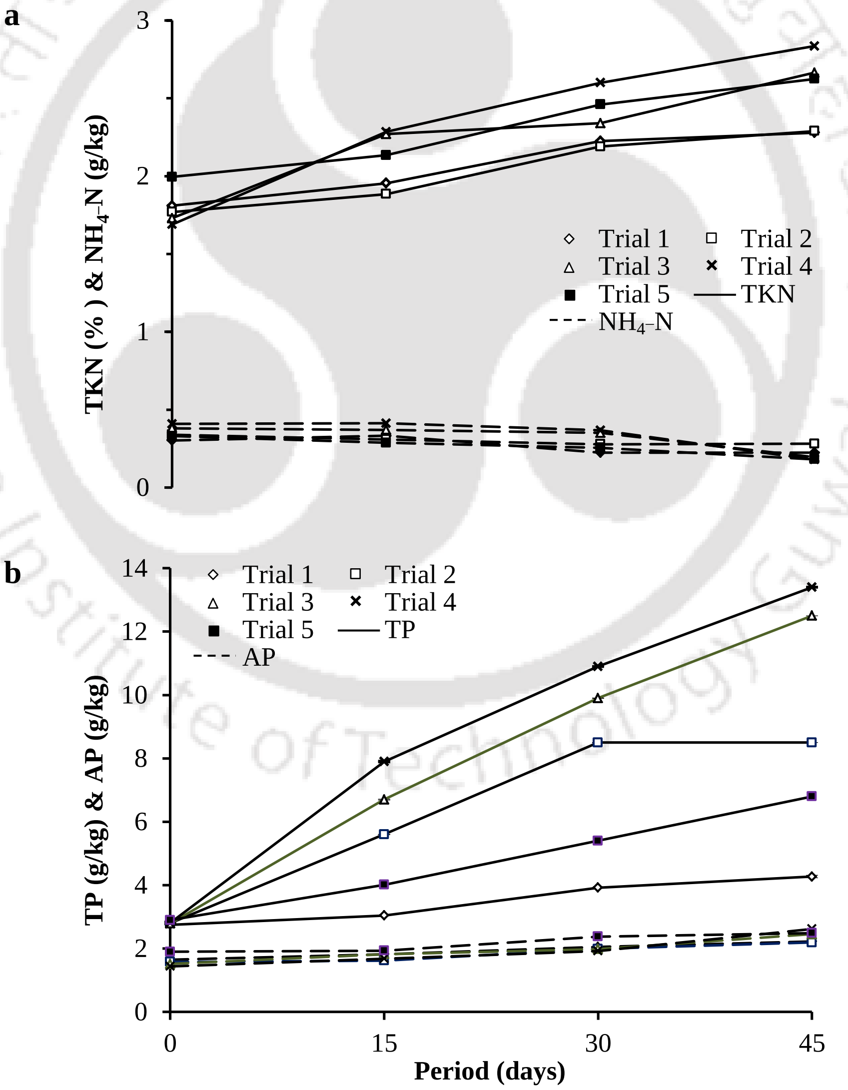

Fig. 4.4.3 a. Variation of TKN and NH_4–N during vermicomposting of phumdi biomass
b. Variation of TP and AP during vermicomposting of phumdi biomass

The other nutrients Na, K, Ca and Mg are needed in very less quantity for earthworm metabolism compared to the initial content of the substrate. K, Ca and Mg are essential for plant growth but Na in high concentration is often undesirable. Ca and Na in the form of oxides or hydroxides or carbonates in composts when applied to soil may counteract soil acidification making soil nutrients more available to plants. The total nutrients in all trials show final increase on day 45 (Table 4.4.1). The micro flora present in the gut of earthworms, the associated microbial activity during the vermicomposting enhancing mineralization and the net loss in dry mass increased the concentration of the nutrients of the vermicompost (Suthar, 2010; Hait and Tare, 2010a, b). Similar increasing trend of the nutrient contents during vermicomposting of municipal and industrial sludge was reported by other authors (Khwairakpam and Bhargava, 2009; Singh et al., 2010).

Table 4.4.1 Variation of total Na, K, Ca and Mg during vermicomposting of phumdi

Days	Total nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	4578 ± 26	4332 ± 21	4086 ± 15	3840 ± 16	5239 ± 18
15	4595 ± 25	4623 ± 14	4312 ± 12	4051 ± 20	5426 ± 14
30	4842 ± 20	5275 ± 12	5980 ± 14	6832 ± 15	6423 ± 15
45	5457 ± 12	5423 ± 14	6823 ± 16	7041 ± 18	7432 ± 12
	K				
0	9917 ± 18	8797 ± 26	7678 ± 24	6559 ± 19	12185 ± 22
15	9933 ± 21	9089 ± 22	7904 ± 21	7642 ± 17	12372 ± 24
30	10180 ± 14	9590 ± 25	8339 ± 19	8018 ± 16	12959 ± 15
45	10795 ± 16	9739 ± 17	10961 ± 18	9994 ± 15	14567 ± 18
	Ca				
0	4095 ± 21	4277 ± 15	4458 ± 22	4640 ± 22	4080 ± 22
15	4112 ± 20	4568 ± 11	4685 ± 24	5724 ± 23	4267 ± 21
30	4459 ± 14	5369 ± 19	5732 ± 23	6875 ± 26	4754 ± 24
45	5074 ± 12	5518 ± 18	6027 ± 27	7145 ± 25	5243 ± 19
	Mg				
0	4589 ± 12	4749 ± 19	4909 ± 21	5069 ± 21	4586 ± 21
15	4606 ± 14	5040 ± 18	5135 ± 24	6153 ± 24	4773 ± 25
30	4853 ± 21	5542 ± 14	5570 ± 25	7010 ± 22	5360 ± 21
45	5468 ± 15	5890 ± 16	6645 ± 26	7808 ± 22	6124 ± 28

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

The WS nutrients are the most available forms of nutrients for the plants and they also increased during the process also due to net loss of dry mass. The presence of large number of micro-organisms and enzymes during vermicomposting played an important role in transforming various plant nutrients to more soluble and available forms, thereby increasing the concentration in vermicompost (Aira et al., 2007). When the organic substrates pass through the gut of worm some fraction of organic minerals are converted into more available species of nutrients (i.e. exchangeable forms) due to the action of endogenic and/or exogenic enzymes (Suthar, 2010). The order of availability of WS nutrients was: K > Ca > Mg > Na. The highest increase of WS nutrients was in trial 4 (89.7% for Na, 62.7% for K, 55.1% for Ca and 44.0% for Mg). In evaluating the contents of nutrients or undesirable plant salts, it is to be borne in mind that compost is primarily an organic soil conditioner and the use of pure compost is not recommended (CCME, 2005). The variation of nutrients during the composting process amongst all trials was significant (*P* < 0.05).

Table 4.4.2 Variation of WS Na, K, Ca and Mg during vermicomposting of phumdi

Days	WS nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	693 ± 4	692 ± 5	692 ± 5	691 ± 4	711 ± 6
15	701 ± 5	755 ± 6	710 ± 4	719 ± 5	718 ± 3
30	724 ± 7	818 ± 5	811 ± 2	836 ± 6	759 ± 5
45	750 ± 5	805 ± 4	1012 ± 3	1310 ± 7	989 ± 4
	K				
0	4335 ± 10	3806 ± 14	3277 ± 14	2748 ± 8	5583 ± 11
15	4389 ± 12	3869 ± 12	3295 ± 14	2776 ± 5	5590 ± 10
30	4343 ± 11	4231 ± 11	3706 ± 15	3879 ± 7	6031 ± 9
45	4462 ± 12	4419 ± 14	4405 ± 9	4472 ± 9	6421 ± 12
	Ca				
0	1388 ± 11	1547 ± 12	1707 ± 12	1866 ± 12	1352 ± 17
15	1398 ± 12	1560 ± 14	1716 ± 10	1872 ± 16	1390 ± 16
30	1408 ± 14	1823 ± 11	2016 ± 15	2674 ± 14	1550 ± 18
45	1423 ± 15	1810 ± 16	2114 ± 12	2894 ± 11	1608 ± 19
	Mg				
0	800 ± 5	810 ± 7	820 ± 4	830 ± 11	855 ± 8
15	868 ± 6	822 ± 5	829 ± 5	836 ± 9	893 ± 8
30	879 ± 7	905 ± 8	987 ± 8	996 ± 8	893 ± 9
45	867 ± 8	912 ± 9	1123 ± 10	1198 ± 11	1098 ± 10

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, *P* < 0.05

4.4.4 TOTAL HEAVY METALS

The variations of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during the vermicomposting are shown at Table 4.4.3. The total concentration of the heavy metals in the final vermicompost increased in the range 7.8–10.4% for Zn, 4.3–16.9% for Cu, 18.3–25.0% for Mn, 2.3–4.6% for Fe, 2.4–5.7% for Cr, 9.5–22.0% for Ni, 7.0–15.4% for Pb and 1.1–19.3% for Cd due to reduction in the weight and volume of the phumdi biomass after the process (Vig et al., 2011). Increase in heavy metals concentration in the vermicompost of different wastes was also reported by Kaushik and Garg (2003). The concentration of total heavy metals of the phumdi biomass vermicomposts was lower when compared with phumdi biomass composts due to bio-accumulation of the heavy metals in the earthworm tissues (Azizi et al., 2013). The order of the total metal concentration of the final vermicompost was Fe > Pb > Mn > Ni > Zn > Cr > Cd > Cu. The variation of the total metal concentrations amongst different trials was statistically significant ($P < 0.05$).

4.4.5 BIOAVAILABILITY OF HEAVY METALS

4.4.5.1 WS heavy metals

Evaluation of the bio-chemically dynamic WS heavy metals of the vermicomposts is also necessary before agronomic application because their potential for contaminating the food chain (Iwegbue et al., 2007; Hait and Tare, 2012). Water solubility of metals was reduced in the range of about 10.5–48.2% for Zn, 18.5–55.9% for Cu, 14.0–38.2% for Mn, 13.7–38.2% for Fe, 12.7–68.5% for Pb and 18.4–64.3% for Cr during the vermicomposting process (Table 4.4.4). WS concentration of Ni and Cd were not detected during the vermicomposting of Phumdi. The decrease of WS heavy metals was statistically significant ($P < 0.05$) in all the trials. Hait and Tare (2012) also reported that vermicomposting caused a significant increase in total heavy metals (Cu, Co, Fe, Mn, Zn, Cr) contents and a significant decrease in WS heavy metals contents during vermicomposting of sewage sludge. When the OM passes through the gut of earthworm some part of it was digested, and the pH and the microbial activity of the gut were enhanced. Consequently, the bioaccumulation of WS fraction of metals by *Eisenia fetida* and the formation of organometallic complexes increased (Suthar, 2009; Singh and Kalamdhad, 2013a, 2013b). The mobility and bioavailability of the heavy metals were reduced in vermicomposting by two major types of cellular adaptation to the toxicity of metals: one involves binding of metals to nuclear proteins and the formation of inclusion nuclear bodies; the second type is a cytoplasmic process involving synthesis of a specific metal binding protein, metallothionein within the chloragogenous tissue (Hait and Tare, 2012). The order of concentration of WS heavy metals of the final phumdi biomass vermicompost was Fe > Mn > Cr > Zn > Cu = Pb.

4.4.5.2 DTPA extractable heavy metals

The DTPA extractable form of heavy metals was reduced in the range of about 14.1–54.7% for Zn, 23.0–61.1% for Cu, 10.6–58.7% for Mn, 18.3–44.5% for Fe, 37.0–74.0% for Cd, 21.1–60.3% for Ni, 43.4–62.7% for Pb and 16.0–65.1% for Cr during the vermicomposting process of phumdi biomass (Table 4.4.5). The conversion of highly

Table 4.4.3. Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi

Days	Total heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	200 ± 2.5	222 ± 2.8	203 ± 2.5	194 ± 3.6	178 ± 1.9	266 ± 6.2	261 ± 3.8	266 ± 2.3	258 ± 1.5	257 ± 1.6
15	223 ± 2.0	226 ± 3.9	229 ± 3.8	210 ± 2.5	206 ± 1.5	276 ± 8.8	261 ± 2.3	266 ± 2.8	264 ± 1.8	276 ± 1.8
30	219 ± 3.8	216 ± 3.8	216 ± 2.3	210 ± 3.5	199 ± 1.5	294 ± 3.8	293 ± 2.5	283 ± 2.5	276 ± 1.8	275 ± 1.5
45	223 ± 2.5	245 ± 2.8	218 ± 3.3	210 ± 2.0	194 ± 1.8	313 ± 2.5	319 ± 6.3	300 ± 1.5	288 ± 1.5	281 ± 1.8
	Cu					**Pb**				
0	50.3 ± 0.75	48.8 ± 0.25	47.0 ± 0.50	40.3 ± 0.25	53.0 ± 0.42	741 ± 3.8	723 ± 30	750 ± 2.5	746 ± 3.8	749 ± 1.8
15	47.5 ± 0.50	46.0 ± 0.30	51.5 ± 0.15	42.0 ± 0.31	55.5 ± 0.51	771 ± 3.3	620 ± 2.0	780 ± 2.0	801 ± 1.8	790 ± 1.5
30	49.5 ± 0.50	55.5 ± 0.50	49.5 ± 0.25	43.5 ± 0.25	53.0 ± 0.50	715 ± 2.5	815 ± 2.5	819 ± 2.3	813 ± 1.5	789 ± 1.3
45	54.0 ± 0.50	57.0 ± 0.21	49.0 ± 0.21	43.0 ± 0.41	57.0 ± 0.52	845 ± 1.5	834 ± 1.8	835 ± 2.5	819 ± 1.8	801 ± 1.8
	Mn					**Cd**				
0	568 ± 5.0	550 ± 2.0	501 ± 2.4	495 ± 1.4	641 ± 1.8	60.6 ± 0.59	57.5 ± 0.55	53.2 ± 0.42	51.8 ± 0.43	64.3 ± 0.80
15	680 ± 4.1	481 ± 1.3	577 ± 1.3	587 ± 3.5	685 ± 2.5	66.3 ± 0.43	58.8 ± 0.43	51.1 ± 0.56	46.8 ± 0.48	65.0 ± 0.75
30	716 ± 6.3	672 ± 1.2	578 ± 1.8	581 ± 2.4	704 ± 1.3	61.7 ± 0.42	44.8 ± 0.53	56.9 ± 0.49	52.0 ± 0.40	57.3 ± 0.63
45	695 ± 2.5	687 ± 3.4	597 ± 1.3	586 ± 2.1	761 ± 1.6	72.3 ± 0.63	59.0 ± 0.52	54.5 ± 0.65	54.0 ± 0.51	65.0 ± 0.54
	Fe					**Cr**				
0	14080 ± 21	13730 ± 32	12046 ± 19	10830 ± 18	14490 ± 23	95 ± 0.91	100 ± 1.16	128 ± 1.14	137 ± 1.11	87 ± 1.09
15	14891 ± 22	14321 ± 23	14561 ± 16	7219 ± 19	14762 ± 18	92 ± 0.81	109 ± 1.21	120 ± 1.13	136 ± 1.18	68 ± 1.06
30	15608 ± 19	14651 ± 25	13421 ± 21	7226 ± 20	15431 ± 19	95 ± 1.45	110 ± 1.14	126 ± 1.16	140 ± 1.18	76 ± 1.14
45	14589 ± 24	14351 ± 27	12601 ± 23	11102 ± 24	14821 ± 24	97 ± 1.31	104 ± 1.18	133 ± 1.11	145 ± 1.16	92 ± 1.12

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Table 4.4.4. Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi

Days	WS heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	13.8 ± 0.05	13.3 ± 0.05	11.9 ± 0.08	11.0 ± 0.10	14.4 ± 0.10	–	–	–	–	–
15	12.9 ± 0.01	12.3 ± 0.04	11.3 ± 0.04	10.5 ± 0.09	13.7 ± 0.10	–	–	–	–	–
30	12.7 ± 0.05	11.2 ± 0.08	8.1 ± 0.09	6.9 ± 0.08	12.9 ± 0.09	–	–	–	–	–
45	12.3 ± 0.10	11.0 ± 0.04	7.4 ± 0.08	5.7 ± 0.04	12.2 ± 0.08	–	–	–	–	–
	Cu					**Pb**				
0	6.9 ± 0.005	6.5 ± 0.009	6 ± 0.008	5.6 ± 0.01	8.0 ± 0.005	7.92 ± 0.010	6.93 ± 0.05	5.94 ± 0.010	4.95 ± 0.004	9.90 ± 0.010
15	6.4 ± 0.007	5.4 ± 0.002	5.1 ± 0.015	4.7 ± 0.01	7.7 ± 0.005	7.69 ± 0.005	5.18 ± 0.075	4.76 ± 0.008	3.45 ± 0.005	9.07 ± 0.004
30	5.5 ± 0.008	4.8 ± 0.006	3.5 ± 0.01	4.1 ± 0.01	7.2 ± 0.004	4.99 ± 0.006	3.88 ± 0.010	2.16 ± 0.010	2.68 ± 0.005	8.78 ± 0.005
45	5.1 ± 0.010	4.5 ± 0.006	2.7 ± 0.01	3.9 ± 0.01	6.5 ± 0.003	4.50 ± 0.007	2.01 ± 0.008	1.87 ± 0.009	2.4 ± 0.006	8.64 ± 0.010
	Mn					**Cd**				
0	47.1 ± 0.1	43.7 ± 0.05	40.2 ± 0.07	36.8 ± 0.08	55.5 ± 0.1	–	–	–	–	–
15	41.4 ± 0.18	40.3 ± 0.15	37.9 ± 0.1	29.4 ± 0.08	52.7 ± 0.09	–	–	–	–	–
30	43.6 ± 0.15	34.5 ± 0.16	27.7 ± 0.16	27.6 ± 0.06	53.6 ± 0.15	–	–	–	–	–
45	37.2 ± 0.15	32.3 ± 0.14	24.9 ± 0.15	23.5 ± 0.09	47.7 ± 0.09	–	–	–	–	–
	Fe					**Cr**				
0	241 ± 0.50	226 ± 1.01	215 ± 1.02	202 ± 1.01	268 ± 1.08	28.5 ± 0.04	25.6 ± 0.12	22.8 ± 0.11	20.0 ± 0.10	34.5 ± 0.05
15	228 ± 0.90	187 ± 1.02	206 ± 0.98	184 ± 0.87	265 ± 1.02	23.2 ± 0.10	20.4 ± 0.08	16.4 ± 0.06	14.6 ± 0.18	30.3 ± 0.18
30	195 ± 0.80	172 ± 0.98	145 ± 0.78	136 ± 1.02	261 ± 1.05	20.2 ± 0.09	10.9 ± 0.12	14.1 ± 0.15	11.0 ± 0.19	29.4 ± 0.19
45	189 ± 0.79	151 ± 0.67	125 ± 0.87	126 ± 1.04	231 ± 0.98	18.4 ± 0.09	9.2 ± 0.08	13.1 ± 0.19	9.9 ± 0.19	28.1 ± 0.09

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

toxic form Cr(VI) to nontoxic form Cr(III) after vermicomposting with *Eisenia fetida* was reported (Jain et al., 2004). The reduction of other DTPA extractable metals (Cd and Cu) during vermicomposting was also reported by other researchers (Suthar 2009, Singh and Kalamdhad 2013c). The "ŋ" of the DTPA extractable heavy metals were also reduced after the vermicomposting process (Fig. 4.4.5). The variation of "ŋ" of DTPA extractable heavy metals during vermicomposting depend on the bio-accumulation of total heavy metals by the earthworm tissues and the interaction of the humic acid with metal ions which affects the partitioning of the heavy metals (Hait and Tare 2012). Vermicomposting of organic wastes accelerates OM stabilisation and gives chelating and phyto-hormonal elements that have a high content of microbial matter and stabilised humic substances (Gupta and Garg, 2008; Suthar, 2009; Hait and Tare, 2012). The order of the concentration of DTPA extractable heavy metals of the vermicomposts was Fe > Mn > Zn > Cr > Pb > Ni > Cu > Cd. The variation of DTPA extractable heavy metals during the vermicomposting process were found statistically different ($P < 0.05$) in all the trials. The lowest "ŋ" of the DTPA extractable heavy metals after pile composting, drum composting and vermicomposting of phumdi biomass of all trials was:

Zn: VC (17.0%, trial 4), PC (11.5%, trial 4), DC (21.1%, trial 4)
Cu: VC (7.1%, trial 4), PC (9.2%, trial 4), DC (9.0%, trial 4)
Mn: VC (14.1%, trial 3), PC (20.2%, trial 4), DC (19.7%, trial 4)
Fe: VC (1.3%, trial 3), PC (0.5%, trial 4), DC (0.5%, trial 4)
Ni: VC (1.6%, trial 3), PC (0.2%, trial 4), DC (0.1%, trial 3)
Pb: VC (0.7%, trial 4), PC (1.1%, trial 4), DC (0.4%, trial 4)
Cr: VC (7.2%, trial 4), PC (3.1%, trial 4), DC (2.5%, trial 4)
Cd: VC (0.3%, trial 4), PC (0.4%, trial 3), DC (0.3%, trial 3)

*VC– vermicomposting, PC– pile composting, DC– drum composting

4.4.5.3 TCLP extractable heavy metals

The leachable fraction of heavy metals was reduced in the range 13.0–43.5% for Zn, 12.2–58.7% for Cu, 17.4–47.8% for Mn, 13.6–43.8% for Fe, 29.3–60.5% for Ni, 15.4–55.8% for Pb, 39.2–77.0 for Cd and 16.5–58.6% for Cr during the vermicomposting process (Table 4.4.6). Reduction of leachable concentration of metals during vermicomposting of phumdi biomass might be due to accumulation of metals in the earthworm tissues (Jain et al., 2004). Increased pH of the vermicompost caused an increase in the surface negative charge which caused cationic adsorption, formation of

Table 4.4.5. Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi

Days	WS heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	91.1 ± 0.12	89.6 ± 0.15	78.9 ± 0.08	78.7 ± 0.08	94.6 ± 0.08	14.3 ± 0.05	13.4 ± 0.05	12.3 ± 0.05	11.3 ± 0.01	17.6 ± 0.01
15	87.8 ± 0.18	88.2 ± 0.15	74.3 ± 0.08	74.6 ± 0.09	92.2 ± 0.07	13.4 ± 0.05	12.5 ± 0.05	11.4 ± 0.05	10.4 ± 0.05	16.7 ± 0.05
30	83.2 ± 0.14	83.2 ± 0.08	69.4 ± 0.17	48.4 ± 0.11	91.8 ± 0.14	11 ± 0.03	8.9 ± 0.05	7.9 ± 0.05	7.5 ± 0.05	14.2 ± 0.05
45	70.0 ± 0.09	67.0 ± 0.09	50.4 ± 0.09	35.7 ± 0.15	81.2 ± 0.07	9 ± 0.04	7 ± 0.05	4.9 ± 0.05	5 ± 0.09	13.9 ± 0.07
	Cu					**Pb**				
0	8.7 ± 0.02	8.4 ± 0.02	8.1 ± 0.01	7.8 ± 0.01	9.8 ± 0.05	25.1 ± 0.01	21.9 ± 0.01	18.8 ± 0.05	15.7 ± 0.08	31.4 ± 0.05
15	8.5 ± 0.01	7.8 ± 0.02	7.3 ± 0.06	7.1 ± 0.04	9.4 ± 0.01	21.5 ± 0.09	17.4 ± 0.07	14.4 ± 0.07	11.3 ± 0.09	28.6 ± 0.09
30	7.1 ± 0.01	7.3 ± 0.03	6.7 ± 0.05	4.5 ± 0.02	9.0 ± 0.05	20.3 ± 0.05	17.0 ± 0.06	13.6 ± 0.08	9.8 ± 0.12	27.2 ± 0.09
45	6.7 ± 0.01	5.4 ± 0.01	5.5 ± 0.02	3.0 ± 0.03	6.0 ± 0.04	11.9 ± 0.07	11.6 ± 0.01	10.0 ± 0.09	5.9 ± 0.08	18.1 ± 0.12
	Mn					**Cd**				
0	203 ± 1.5	203 ± 1.2	204 ± 1.1	204 ± 1.4	220 ± 1.0	0.86 ± 0.001	0.5 ± 0.008	0.43 ± 0.004	0.59 ± 0.001	0.93 ± 0.008
15	196 ± 1.3	205 ± 1.1	187 ± 1.2	210 ± 1.2	216 ± 0.9	0.69 ± 0.002	0.34 ± 0.002	0.34 ± 0.003	0.39 ± 0.002	0.76 ± 0.002
30	189 ± 1.4	200 ± 1.2	98 ± 1.2	195 ± 1.1	209 ± 1.1	0.62 ± 0.004	0.33 ± 0.009	0.22 ± 0.002	0.18 ± 0.004	0.68 ± 0.009
45	181 ± 1.5	124 ± 1.4	84 ± 1.2	130 ± 1.1	143 ± 1.2	0.51 ± 0.005	0.32 ± 0.007	0.2 ± 0.01	0.15 ± 0.005	0.51 ± 0.007
	Fe					**Cr**				
0	290 ± 1.0	296 ± 1.3	302 ± 1.1	308 ± 0.9	314 ± 1.1	41.2 ± 0.2	37.5 ± 0.1	33.4 ± 0.1	30.0 ± 0.1	50.5 ± 0.1
15	260 ± 1.1	280 ± 1.1	265 ± 1.2	266 ± 0.9	296 ± 1.1	39.4 ± 0.1	35.1 ± 0.1	27.0 ± 0.1	28.9 ± 0.1	48.5 ± 0.1
30	244 ± 1.0	266 ± 1.4	212 ± 1.3	250 ± 0.9	263 ± 1.1	36.4 ± 0.1	30.0 ± 0.1	21.5 ± 0.1	16.9 ± 0.1	44.3 ± 0.1
45	164 ± 0.9	169 ± 0.9	167 ± 1.1	173 ± 1.1	256 ± 1.2	31.7 ± 0.1	25.5 ± 0.1	19.4 ± 0.1	10.5 ± 0.1	42.5 ± 0.1

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, *P* < 0.05

Table 4.4.6. Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of phumdi

Days	WS heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	108 ± 0.41	99 ± 0.27	89 ± 0.29	81 ± 0.33	129 ± 0.41	164 ± 1.4	144 ± 1.4	124 ± 1.8	103 ± 1.3	205 ± 1.4
15	103 ± 0.06	90 ± 0.35	74 ± 0.34	74 ± 0.41	125 ± 0.50	156 ± 1.6	126 ± 1.6	113 ± 1.6	89 ± 1.1	200 ± 1.2
30	94 ± 0.49	84 ± 0.19	72 ± 0.44	72 ± 0.30	121 ± 0.51	150 ± 1.4	120 ± 1.2	94 ± 1.7	79 ± 1.4	178 ± 1.1
45	88 ± 0.29	73 ± 0.21	65 ± 0.41	46 ± 0.34	112 ± 0.41	128 ± 1.7	96 ± 1.4	58 ± 1.4	41 ± 1.2	145 ± 1.6
	Cu					**Pb**				
0	19.6 ± 0.05	18.1 ± 0.01	16.7 ± 0.05	15.3 ± 0.02	23.1 ± 0.05	52.1 ± 0.10	45.9 ± 0.10	39.8 ± 0.05	33.6 ± 0.08	62.7 ± 0.10
15	17.1 ± 0.04	16.4 ± 0.05	14.7 ± 0.05	13.5 ± 0.05	22.4 ± 0.05	44.5 ± 0.09	45.6 ± 0.07	37.6 ± 0.07	43.8 ± 0.09	65 ± 0.09
30	17 ± 0.04	15.2 ± 0.02	12.2 ± 0.05	10.6 ± 0.14	21.5 ± 0.12	38.3 ± 0.05	33.9 ± 0.06	23.4 ± 0.08	27.6 ± 0.12	56.9 ± 0.09
45	16.5 ± 0.04	14.2 ± 0.05	9.0 ± 0.14	6.3 ± 0.06	20.3 ± 0.14	32.6 ± 0.07	30.1 ± 0.10	15.6 ± 0.09	10.4 ± 0.08	53 ± 0.12
	Mn					**Cd**				
0	282 ± 1.2	298 ± 1.0	314 ± 1.4	330 ± 1.0	291 ± 0.9	2.9 ± 0.001	2.8 ± 0.008	2.7 ± 0.001	2.6 ± 0.008	2.4 ± 0.004
15	273 ± 1.1	293 ± 1.0	307 ± 1.2	324 ± 1.1	287 ± 0.8	2.2 ± 0.002	2.1 ± 0.002	1.3 ± 0.002	1.5 ± 0.002	2.3 ± 0.003
30	246 ± 1.2	275 ± 1.1	198 ± 1.1	277 ± 1.0	269 ± 1.1	1.4 ± 0.004	1.1 ± 0.009	1.2 ± 0.004	0.7 ± 0.009	1.7 ± 0.002
45	231 ± 1.0	240 ± 1.2	164 ± 1.1	230 ± 1.1	240 ± 1.0	1.3 ± 0.005	1.0 ± 0.007	0.9 ± 0.005	0.6 ± 0.007	1.5 ± 0.01
	Fe					**Cr**				
0	413 ± 1.9	396 ± 1.1	382 ± 1.2	366 ± 1.1	474 ± 1.4	55 ± 0.2	49.6 ± 0.1	44.5 ± 0.3	39.4 ± 0.1	66.4 ± 0.1
15	394 ± 1.4	367 ± 1.2	271 ± 1.1	318 ± 1.2	452 ± 1.3	50.3 ± 0.1	44.1 ± 0.1	39.4 ± 0.1	29.7 ± 0.2	65.4 ± 0.1
30	383 ± 1.2	374 ± 1.3	283 ± 1.2	357 ± 1.2	444 ± 1.1	46.5 ± 0.1	33.8 ± 0.1	30.0 ± 0.2	19.4 ± 0.2	60.2 ± 0.1
45	321 ± 1.2	305 ± 1.4	265 ± 1.4	206 ± 1.4	409 ± 1.6	32.3 ± 0.1	29.1 ± 0.1	25.4 ± 0.1	16.3 ± 0.1	55.4 ± 0.1

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

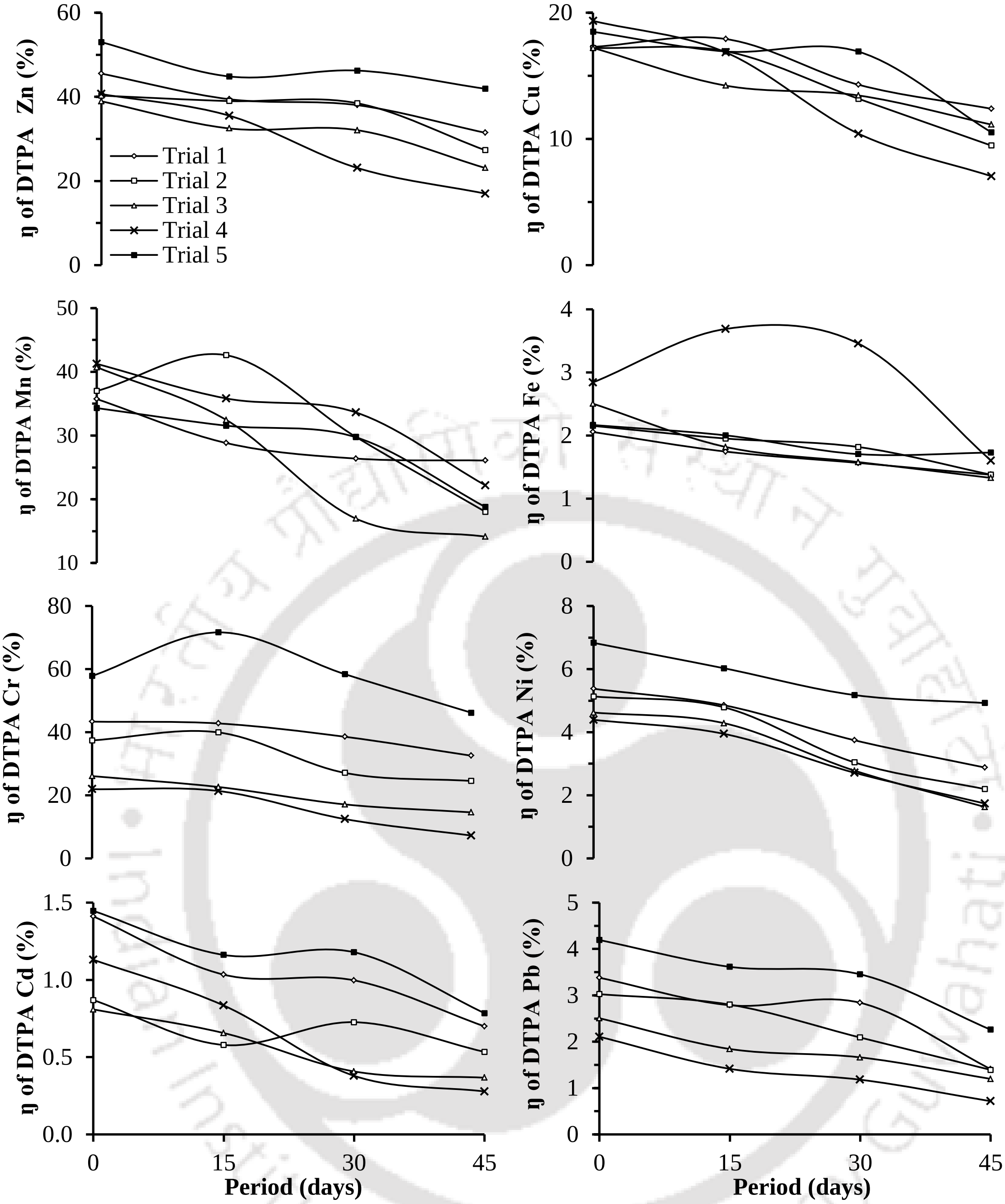

Fig. 4.4.5. Variation of "ŋ" of DTPA extractable heavy metals during vermicomposting of phumdi biomass.

metal hydroxyl species that have a greater affinity for adsorption sites than the individual metal cations, and precipitation of metal as metal hydroxides (Maity et al., 2008). Moreover, the cutaneous absorption of metals was also evidenced in earthworms (Suthar 2009). The reduction of leachable metal concentration during vermicomposting might be due to affinity of metals with functional groups −OH or −COOH of humic substances (Kang et al., 2011). The order of leachable heavy metal concentration of the final phumdi biomass vermicompost was Fe > Mn > Ni > Zn > Cr > Pb > Cu > Cd.

Chapter 5

COMPOSTING AND VERMICOMPOSTING OF *SALVINIA NATANS*

This chapter is about the discussion of the results of composting study carried out for *Salvinia natans* weed as Phase 2 of the research using agitated pile composting, rotary drum composting and vermicomposting techniques. The variations of the physico-chemical and bio-chemical parameters as well as the concentration of the total, bioavailable and leachable forms of heavy metals were determined to assess the efficacy of the composting technologies during the composting of *Salvinia natans* weed.

5.1 INITIAL CHARACTERISTICS OF *SALVINIA NATANS* AND OTHER FEEDSTOCK MATERIALS

The initial characteristics of *Salvinia natans* and other composting materials used in phase 2 of the study are shown at Table 5.1. The initial moisture content (MC) of *Salvinia natans* of Loktak Lake was also high (90.5%). Therefore, either rice husk or sawdust was used to adjust the MC (Table 5.1a) during the composting of *Salvinia natans* also. The concentrations of volatile solids (VS), total Kjeldahl nitrogen (TKN) and total phosphorous (TP) of *Salvinia natans* (76.8±0.80, 2.2±0.05 and 0.21±0.004%, respectively) were comparable with phumdi biomass. The initial pH of *Salvinia natans* (5.71±0.01) was also within the range required for the development of bacteria (6.0–7.5) and fungi (5.5–8.0) (Amir et al., 2005) or for the survival of earthworms (5.5–8.5) (Yadav and Garg, 2011) during composting or vermicomposting process. The soluble BOD and COD concentrations (3678±30, 7600±40 mg/kg dry mass, respectively), oxygen uptake rate (OUR) (11.8±0.15 mg/g VS/day) and the CO_2 evolution rate (5.6±0.06 mg/g VS/day) of *Salvinia natans* were also lower than cattle manure. The electrical conductivity (EC) of *Salvinia natans* was higher than phumdi biomass indicating higher presence of exchangeable sodium, chloride, potassium, nitrate, sulphate and ammonia salts (Wong et al., 2001) or the highly conductive metal ions (Singh and Kalamdhad, 2012). The concentrations of K, Ca, Mg and Na of *Salvinia natans* were higher than phumdi biomass and were in the order K > Ca > Mg > Na (Table 5.1b). Similar to phumdi biomass, the water soluble (WS) fractions of K, Ca, Mg and Na of

Salvinia natans were significantly lower than their total concentrations. The concentrations of the WS fractions of nutrients of the composts were also in the order K > Ca > Mg > Na.

Table 5.1. Initial characterization of *Salvinia natans* and other feedstock
a. Physico-chemical and bio-chemical parameters

Parameters	Feed stock materials			
	S. natans	Cattle manure	Rice husk	Sawdust
MC (%)	90.5 ± 1.2	86.4 ± 0.8	9.6 ± 0.14	10.0 ±0.10
pH	5.71 ± 0.01	7.04 ± 0.04	6.59 ± 0.05	6.1 ± 0.05
EC (dS/m)	3.5 ± 0.03	3.7 ± 0.03	1.7 ± 0.02	0.8 ± 0.02
VS (%)	76.8 ± 0.80	72.0 ± 0.50	78.9 ± 0.51	79.4 ± 2.1
TKN (%)	2.2 ± 0.05	1.5 ± 0.02	0.7 ± 0.01	0.4 ± 0.03
Ammonical nitrogen (NH_4–N) (mg/kg)	591 ± 1.4	658 ± 1.4	40 ± 0.4	41 ± 0.5
TP (mg/kg dry mass)	2100 ± 40	3200 ± 25	1004 ± 14.8	205 ± 1.90
AP (mg/kg dry mass)	700 ± 5	1800 ± 12	700 ± 2	80 ± 0.20
Soluble BOD (mg/kg wet mass)	3678 ± 30	4567 ± 19	1254±18	1550 ± 10
Soluble COD (mg/kg wet mass)	7600 ± 40	9260 ± 35	4500 ± 25	4020 ± 12
OUR (mg/g VS/day)	11.8 ± 0.15	12.9 ± 0.25	1.9 ± 0.11	1.4 ± 0.08
CO_2 evolution rate (mg/g VS/day)	5.6 ± 0.06	5.7 ± 0.06	0.7 ± 0.04	0.6 ± 0.05

(Mean ± SD, n = 9) SD –standard deviation, n –no. of observations, $P < 0.05$

Table 5.1. Initial characterization of *Salvinia natans* and other feedstock
b. Total and WS nutrients

Parameters	Feedstock materials (mg/kg dry mass)			
	S. natans	Cattle manure	Rice husk	Sawdust
Total nutrients				
Na	6995 ± 34	2800 ± 7	2112 ± 12	1109 ± 12
K	18920 ± 95	988 ± 11	8250 ± 14	698 ± 9
Ca	9337 ± 90	5890 ± 17	3885 ± 12	2416 ± 12
Mg	7277 ± 55	6957 ± 21	999 ± 17	3024 ± 11
WS nutrients				
Na	1545 ± 21.5	702 ± 7.5	545 ± 7.5	297 ± 5.3
K	3532 ± 16.4	290 ± 6.5	397 ± 7.5	198 ± 6.4
Ca	3255 ± 22.5	2493 ± 31.2	1398 ± 28.5	420 ± 12.4
Mg	2058 ± 19.1	954 ± 11.5	572 ± 14.5	820 ± 2.4

(Mean ± SD, n = 9) SD –standard deviation, n –no. of observations, $P < 0.05$

Salvinia natans weed also indicated presence of heavy metals in the order Fe > Mn > Pb > Ni > Zn > Cr > Cd > Cu. The WS fractions of Cd and Ni and the diethylene triamine penta-acetic acid (DTPA) extractable fraction of Cd were not detected in *Salvinia natans*. However, all the eight metals were present during the toxicity characteristics leaching procedure (TCLP) tests. The effectiveness of *Salvinia natans* in removing pollutants and heavy metals from water was already discussed (Dhir and Srivastava, 2011; Kumari and Tripathi, 2014). Therefore, investigation of the fate of the heavy metals was also required during *Salvinia natans* composting.

Table 5.1. Initial characterization of *Salvinia natans* composting materials
c. Total, WS, DTPA extractable and TCLP extractable heavy metals

Parameters	Feed stock materials (mg/kg dry mass)			
	S. natans	Cattle manure	Rice husk	Sawdust
Total heavy metals				
Zn	210 ± 0.50	160 ± 2.0	117 ± 2.5	107 ± 2.3
Cu	53.5 ± 0.50	47.8 ± 0.8	29.5 ± 1.0	20.5 ± 1.0
Mn	999 ± 7.0	527 ± 1.5	189 ± 8.5	143 ± 3.5
Fe	6754 ± 32	1861 ± 12	3650 ± 16	2749 ± 12
Ni	265 ± 1.8	238 ± 2.2	140 ± 2.1	279 ± 1.5
Cd	53.8 ± 2.2	47.8 ± 1.1	41.0 ± 0.8	57.9 ± 0.8
Pb	756 ± 10.5	747.4 ± 7.5	60.5 ± 1.2	769.0 ± 5.0
Cr	143 ± 1.22	124 ± 4.0	10 ± 0.08	79.7 ± 0.20
WS heavy metals				
Zn	14.7 ± 0.05	6.4 ± 0.05	4.7 ± 0.08	2.1 ± 0.03
Cu	8.0 ± 0.15	3.8 ± 0.8	2.5 ± 1.0	0.9 ± 0.02
Mn	55.5 ± 1.5	21.4 ± 0.9	22.5 ± 0.8	5.2 ± 0.20
Fe	268 ± 2.5	140 ± 12.8	74 ± 1.9	124 ± 2.30
Ni	ND	ND	ND	ND
Cd	ND	ND	ND	ND
Pb	9.9 ± 0.15	ND	ND	ND
Cr	34.5 ± 0.05	6.4 ± 0.05	1.2 ± 0.04	2.1 ± 0.16
DTPA extractable heavy metals				
Zn	94.5 ± 0.5	46.4 ± 1.5	34.7 ± 1.1	10.8 ± 0.70
Cu	9.8 ± 0.1	6.8 ± 0.6	5.5 ± 0.5	1.7 ± 0.20
Mn	220 ± 5.5	227 ± 1.5	75 ± 2.5	40.4 ± 0.90
Fe	314 ± 14.5	375 ± 12.5	190 ± 3.5	8.2 ± 0.40
Ni	17.4 ± 0.1	0.1 ± 0.01	ND	0.08 ± 0.03
Cd	ND	ND	ND	ND
Pb	31.4 ± 0.5	ND	ND	ND
Cr	50.4 ± 0.2	12.4 ± 0.2	1.8 ± 0.05	0.6 ± 0.02
TCLP extractable heavy metals				
Zn	129.1 ± 0.6	32.4 ± 1.5	28.7 ± 1.1	15.5 ± 1.50
Cu	23.1 ± 0.6	8.8 ± 0.6	7.5 ± 0.5	2.1 ± 0.10
Mn	291 ± 3.5	450 ± 5.5	85 ± 2.5	43.9 ± 1.30
Fe	474 ± 9.5	320 ± 12.5	144 ± 11.5	13.0 ± 0.20
Ni	205 ± 1.5	1.9 ± 0.04	0.8 ± 0.02	0.9 ± 0.05
Cd	2.40 ± 0.05	1.42 ± 0.05	3.12 ± 0.05	7.91 ± 0.10
Pb	64.7 ± 0.21	2.82 ± 0.24	7.81 ± 0.14	0.91 ± 0.04
Cr	66.6 ± 0.32	14.52 ± 0.05	5.41 ± 0.08	4.01 ± 0.15

(Mean ± SD, n = 9) SD –standard deviation, n –no. of observations, $P < 0.05$

5.2 AGITATED PILE COMPOSTING OF *SALVINIA NATANS*

5.2.1 TEMPERATURE PROFILE

Fig. 5.2.1 shows the temperature profile of the five *Salvinia natans* piles during the agitated pile composting. The temperatures of the piles increased rapidly from 4th day of the composting process. The highest temperature (52.2ºC) was measured on 6th day in trial 3 pile whereas the maximum temperature of trial 4 pile was 49.8ºC on the 8th day. Piles of trial 1 and 2 respectively showed maximum temperatures of 42.3 and 43.2ºC on the 9th day of the composting. The pile of control trial 5 showed maximum temperature of only 32.2ºC on the 6th day of the process indicating that that pile composting of *Salvinia natans* without addition of cattle manure and rice husk was also not feasible. The result was inconsistent with the pile composting of phumdi biomass where trial 4 having highest proportion of cattle manure showed highest increase in temperature but was in agreement with the pile composting of water hyacinth (Singh and Kalamdhad, 2012). The temperature of trial 4 having highest amount of cattle manure was lower than trial 3 indicating that the microbial activity in trial 3 pile was higher causing higher release of heat in the pile. The microbial activity of the piles depend upon many factors as discussed earlier such as availability of nutrients in appropriate proportions, MC, air permeability of the composting materials, etc.

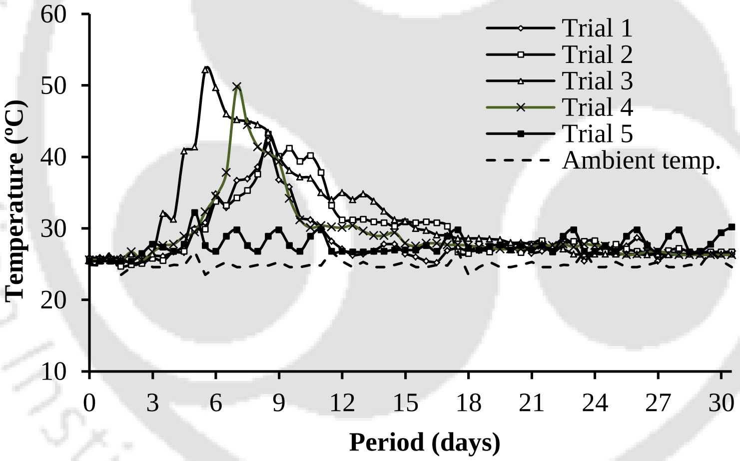

Fig. 5.2.1. Temperature profiles during pile composting of *Salvinia natans*

5.2.2 PHYSICO-CHEMICAL AND BIO-CHEMICAL ANALYSIS

The variation of pH of the composting materials during the agitated pile composting of *Salvinia natans* is shown at Fig. 5.2.2a. The pH of all the trials increased significantly ($P < 0.05$) during the process from 6.2 to 7.2, 6.2 to 7.4, 6.1 to 7.5, 6.2 to 7.7 and 5.6 to 6.8 in trial 1, 2, 3, 4 and 5, respectively. The pH of trial 4, having highest proportion of cattle manure and least void spaces, showed initial decrease due to the absorption of CO_2 and formation of organic acids preventing pH rise. In case of control trial 5 without cattle manure and sawdust, the initial pH of *Salvinia natans* was below 6. The pH increased due to availability of sufficient oxygen from regular turning and the low temperature profile of the pile (below 40°C) (Smars et al., 2002). Similar variation of pH was indicated during the pile composting of water hyacinth (Prasad et al., 2013, Singh and Kalamdhad, 2013a, b).

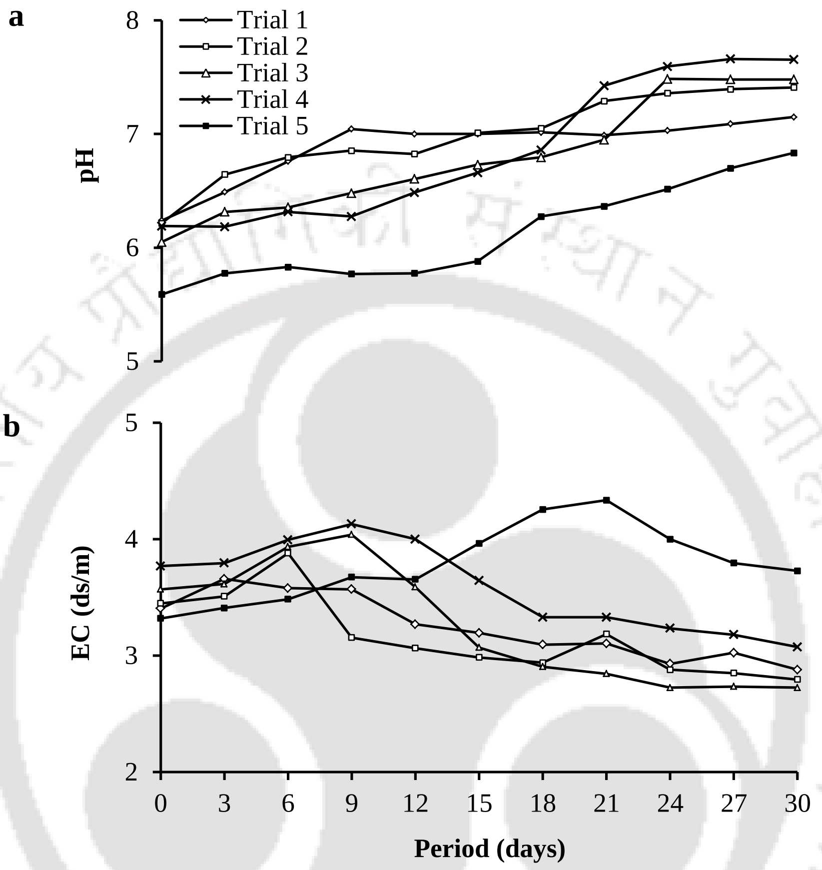

Fig. 5.2.2 a. Variation of pH during pile composting of *Salvinia natans*
b. Variation of EC during pile composting of *Salvinia natans*

Fig. 5.2.2b shows that there was an initial increase in the EC of the *Salvinia natans* composts of all trials due to the release of mineral salts such as phosphates, ammonium ions, etc. during the decomposition of organic matter (OM) (Fang and Wong, 1999). As discussed for phumdi biomass composting, the precipitation of mineral salts or probable volatization (pH > 7) or assimilation of ammonia could be the reasons for the subsequent decrease of EC in all trials (Wong et al., 2001). The ECs of the final composts of trial 1, 2, 3 and 4 reduced to 2.9, 2.8, 2.7 and 3.1 dS/m, respectively. But, the final EC (3.7 dS/m) was higher than the initial EC (3.3 dS/m) for trial 5 compost. The ECs were however within the safe limits (< 4 dS/M) prescribed for composts (Gao et al., 2010). The variation of EC among all trials was statistically significant ($P < 0.05$).

The order of moisture loss of the *Salvinia natans* piles was trial 3 (30.9%) > trial 4 (24.9%) > trial 2 (20.8%) > trial 1 (17.0%) > trial 5 (13.2%) (Fig. 5.2.2c). Therefore, trial 3 had the highest decomposition rate which was in agreement with the highest temperature profile of trial 3. The MCs in all the piles were mostly above 60% during the active phase. ANOVA analysis shows significant variation of moisture content among the trials ($P < 0.05$).

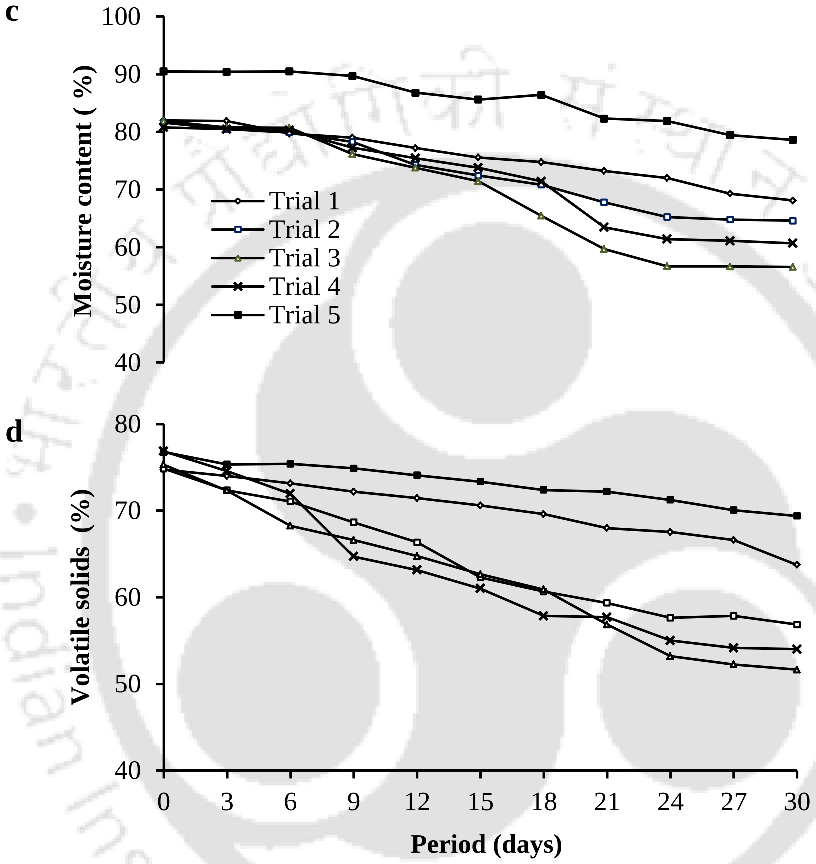

Fig. 5.2.2 c. Variation of MC during pile composting of *Salvinia natans*
d. Variation of VS during pile composting of *Salvinia natans*

The decreasing order of reduction of VS of the trials after *Salvinia natans* pile composting was trial 3 (31.4%, $K_b = 0.65$) > trial 4 (29.7%; $K_b = 0.62$) > trial 2 (24.1%; $K_b = 0.56$) > trial 1 (14.7%; $K_b = 0.41$) > trial 5 (9.6%; $K_b = 0.31$) (Fig. 5.2.2d). The order was also in agreement with the order of moisture loss after the process. Highest degradation of VS occurred in trial 3 due to higher microbial activity indicated by highest temperature rise. The higher degradation of VS due to high temperature profile especially during the thermophilic stage of the composting process was also in agreement with the pile composting of water hyacinth carried out by Sarika et al. (2014).

The low reduction of VS in trial 5 was due to the low microbial activity caused by the high MC of *Salvinia natans* weed. The light physical properties of *Salvinia natans* was also not favourable for retention of the minimal heat released in the piles during the pile composting of the weed without suitable material amendments.

The soluble BOD decreased after the composting process in all trials (Fig. 5.2.2e). The order of reduction of soluble BOD in all trials after 30 days was trial 3 (80.1%) > trial 4 (78.3%) > trial 2 (58.9%) > trial 1 (55.8%) > trial 5 (28.3%). There were no significant changes in the soluble BOD concentrations of the *Salvinia natans* compost of trial 3 and 4 after 24 days. The variation in the reduction of soluble BOD of all trials during the composting process was statistically significant ($P < 0.05$). The higher temperature profiles during the pile composting of *Salvinia natans* and the higher reduction of MCs, VSs and soluble BODs after the composting process when compared with phumdi biomass composting was clear indication that phumdi biomass was slower in degradation.

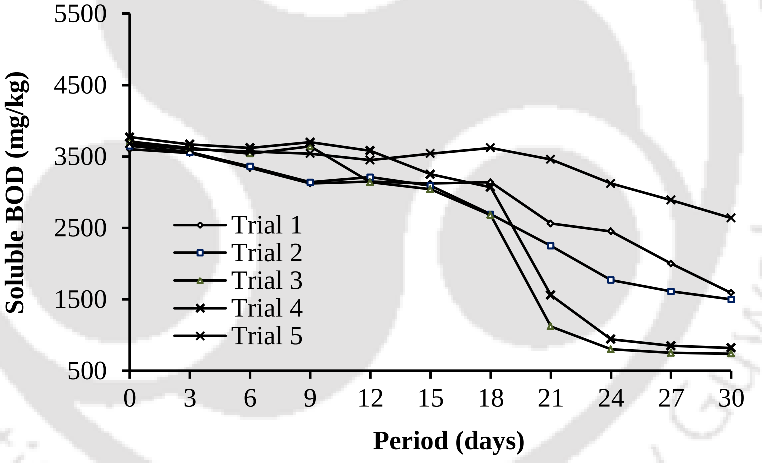

Fig. 5.2.2 e. Variation of soluble BOD during pile composting of *Salvinia natans*

The CO_2 evolution rate of trial 3 and 4 decreased significantly from day 15 (Fig. 5.2.2f). On day 30, the CO_2 evolution rate of trial 3 (1.0 mg/g VS/day) was the lowest followed by trial 4 (1.1 mg/g VS/day). The OUR of the trial 3 and 4 also decreased significantly from the 15th day and the variation trend was in agreement with the CO_2 evolution rate (Fig. 5.2.8). The lowest OUR was also observed in trial 3 (2.3 mg/g VS/day) followed by trial 4 (2.5 mg/g VS/day). A comparison of the variation of soluble BOD concentration, CO_2 evolution rate and OUR of trial 3 and 4 indicates that the respiration rate was reduced with no significant variation after 24 days due to decrease in soluble BOD concentration. From the results of CO_2 evolution rate and OUR, the *Salvinia natans* composts of trail 3 and 4 containing higher proportions of cattle manure were stable (TMECC, 2002). Therefore, effective pile composting of *Salvinia natans* can also be achieved with appropriate use of bulking agents.

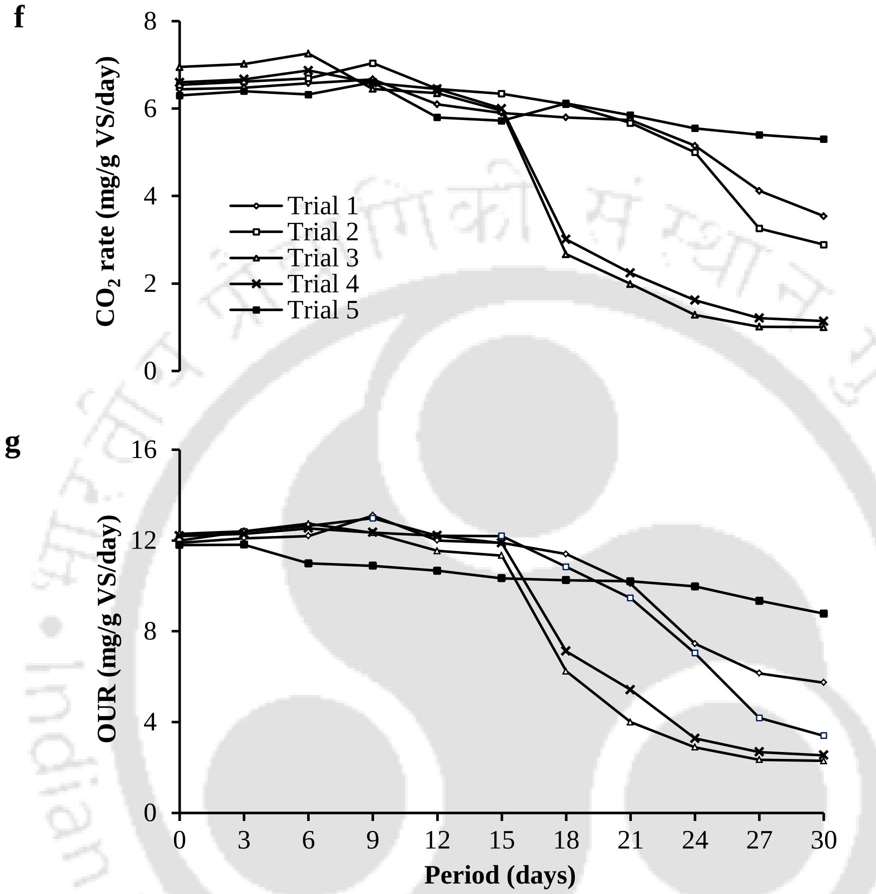

Fig. 5.2.2 f. Variation of CO_2 evolution rate during pile composting of *Salvinia natans*
g. Variation of OUR during pile composting of *Salvinia natans*

5.2.3 NUTRIENTS

The initial TKN concentration was highest in trial 5 containing only green *Salvinia natans*. Trial 3 showed the highest increase of the concentration of TKN (32.1%) followed by trial 4 (30.2%) due to the higher loss of dry mass (Fig. 5.2.3a). The increase of TKN concentration after *Salvinia natans* pile composting was higher than phumdi biomass pile composting. The variation of TKN concentration among all the *Salvinia natans* trials during the pile composting period was significant ($P < 0.05$).

Trial 3 and 4 indicated initial increasing trend of NH_4–N contents before reducing to 0.20 and 0.22 g/kg after the process. The NH_4–N contents of *Salvinia natans* composts of all trials after 30 days were also low (≤ 400 mg/kg) and there was no risk of phytotoxicity (Bernal et al. 1998). ANOVA analysis also indicates significant difference in the variation of NH_4–N concentration of all trials during the composting ($P < 0.05$).

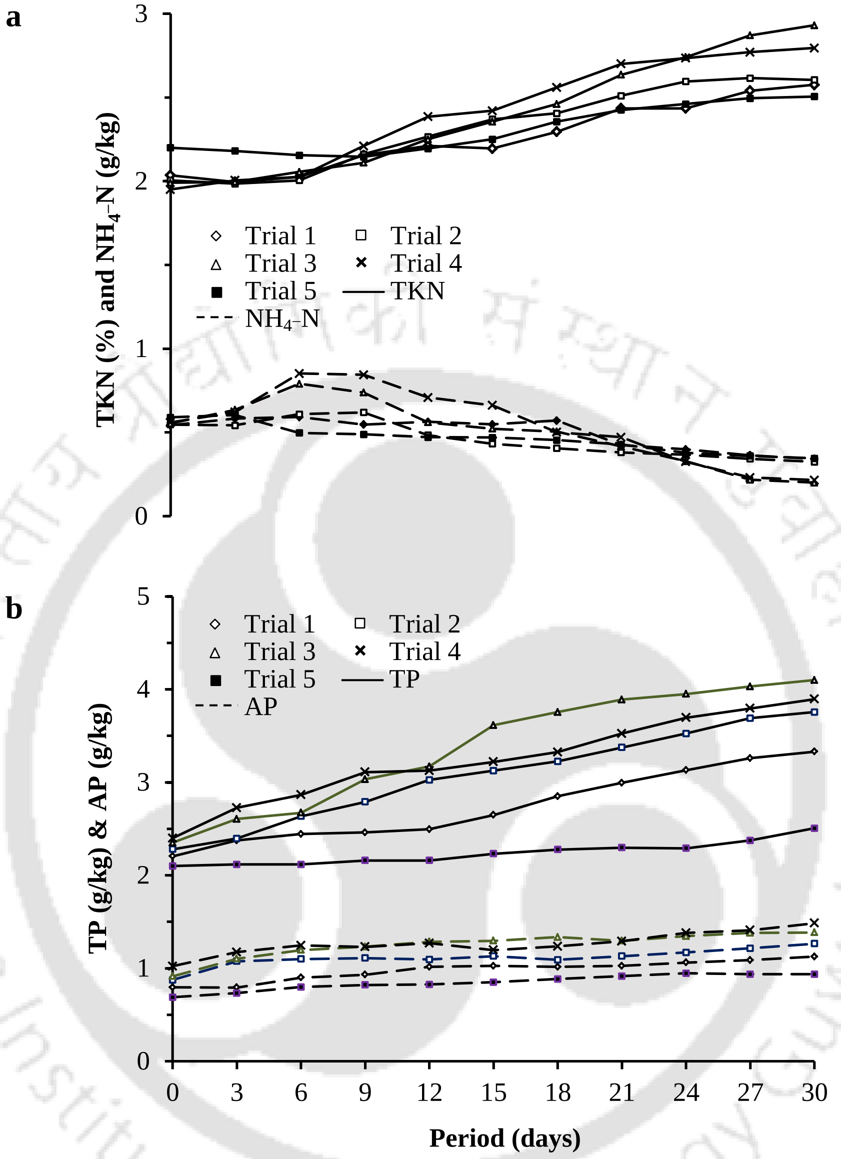

Fig. 5.2.3 a. Variation of N and NH_4–N during pile composting of *Salvinia natans*
b. Variation of TP and AP during pile composting of *Salvinia natans*

Similar to pile composting of phumdi biomass, the concentration of TP during the pile composting of *Salvinia natans* also gradually increased due to net loss of dry mass (Fig. 5.2.3b). Due to net loss of dry mass, “concentration effect” occurred where carbon, hydrogen and nitrogen were lost with the exit gas as CO_2, H_2O and probably NH_3 but TP was retained in the sample (Wei et al., 2015). The available phosphorous (AP) increased prominently in all the composts obtained from the trials. The change in AP is dependent on the type of the initial feedstock and increases due to OM loss and conversion of the phosphorous (P) to WS, sodium bicarbonate extractable and citric acid extractable forms including phosphates, phospholipids, DNA, and simple phosphate monoesters (Turner and Leytem, 2004; Wei et al., 2015) but decreases due to formation of complexes with calcium and magnesium ions (Chanyasak et al. 1983; Traore et al. 1999). Differences in composting processes and materials influenced the amounts and relative distribution of P fractions in composts (Sharpley and Moyer, 2000).

The increase in concentrations of total Na, K, Ca and Mg are shown at Table 5.2.1. The concentrations of the nutrients of the final composts of all trials (K (1.4–2.1%), Ca (1.1–1.2%) and Mg (0.74–0.80%)) were also near the prescribed limits (Barker, 1997; Bord na More, 2003; ALCL, 2005). The order of the range of total nutrients concentrations of *Salvinia natans* compost was K > Ca > Mg > Na.

Table 5.2.1. Variation of total Na, K, Ca and Mg during pile composting of *S. natans*

Days	Total nutrients concentration (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	5918 ± 50	5488 ± 50	5059 ± 50	4629 ± 50	6835 ± 50
6	6261 ± 30	6083 ± 45	5804 ± 55	5725 ± 85	7035 ± 20
12	6786 ± 52	6878 ± 40	6654 ± 35	6625 ± 35	7230 ± 45
18	6686 ± 28	6963 ± 35	7255 ± 47	6810 ± 30	7515 ± 40
24	7126 ± 48	7018 ± 41	7839 ± 40	6945 ± 45	7850 ± 35
30	7516 ± 42	7668 ± 40	8239 ± 50	7310 ± 40	7755 ± 60
	K				
0	16232 ± 21	14439 ± 20	12746 ± 19	10953 ± 20	19020 ± 35
6	17066 ± 22	14788 ± 18	14337 ± 18	12261 ± 22	19055 ± 30
12	17296 ± 31	15007 ± 21	15910 ± 16	12746 ± 19	18878 ± 34
18	18173 ± 24	16654 ± 18	16306 ± 21	14067 ± 21	19895 ± 21
24	18567 ± 15	16921 ± 21	17578 ± 22	14909 ± 18	20126 ± 28
30	18894 ± 18	17755 ± 20	18358 ± 24	15113 ± 25	21759 ± 24
	Ca				
0	8400 ± 25	8130 ± 25	7718 ± 53	7385 ± 50	9357 ± 35
6	8999 ± 63	9195 ± 48	10088 ± 54	8811 ± 43	9954 ± 32
12	10060 ± 37	9727 ± 60	10958 ± 32	9707 ± 18	10469 ± 44
18	10313 ± 43	9899 ± 33	11635 ± 42	10201 ± 25	10845 ± 19
24	10451 ± 17	10440 ± 39	12182 ± 32	10637 ± 62	10921 ± 45
30	11483 ± 37	11228 ± 27	12414 ± 10	10876 ± 22	11266 ± 32
	Mg				
0	6373 ± 28	6131 ± 32	5928 ± 29	5675 ± 26	7184 ± 46
6	6922 ± 15	6522 ± 25	6996 ± 40	6204 ± 17	7522 ± 21
12	7174 ± 49	6873 ± 49	7489 ± 25	6757 ± 33	7670 ± 35
18	7294 ± 25	6952 ± 45	7580 ± 43	7273 ± 17	7712 ± 51
24	7358 ± 29	7012 ± 23	7855 ± 43	7479 ± 22	7889 ± 34
30	7566 ± 24	7352 ± 38	7980 ± 41	7540 ± 39	7951 ± 47

*Mean ± SD, n = 3, $P < 0.05$

The WS fractions of nutrients of the final composts of all trials increased in the range of about 10.9–66.4% for Na, 14.8–55.1% for K, 14.2–40.0% for Ca and 17.4–66.2% for Mg (Table 5.2.2). Lowest enhancement of water solubility of K, Ca and Mg was in trial 5 which contained only *Salvinia natans* biomass. Similar results were indicated during the agitated pile composting of phumdi biomass and the increase in concentration of WS nutrients was also due to weight loss of the dry matter during the decomposition and mineralization of the OM. The variation in concentration of WS nutrients among all trials was significant ($P < 0.05$). The order of the concentration of WS nutrients was Ca > K > Mg > Na.

Table 5.2.2. Variation of WS Na, K, Ca and Mg during pile composting of *S. natans*

Days	WS nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	1382 ± 10	1290 ± 22	1198 ± 30	1108 ± 22	1574 ± 15
6	1573 ± 12	1512 ± 14	1341 ± 26	1317 ± 26	1599 ± 18
12	1576 ± 10	1546 ± 15	1656 ± 29	1275 ± 28	1605 ± 20
18	1560 ± 11	1768 ± 16	1758 ± 32	1423 ± 31	1666 ± 14
24	1576 ± 10	1845 ± 25	1894 ± 34	1542 ± 23	1727 ± 18
30	1625 ± 12	1943 ± 28	1993 ± 42	1645 ± 34	1745 ± 16
	K				
0	2895 ± 14	2558 ± 21	2272 ± 21	1958 ± 23	3496 ± 18
6	3100 ± 12	2643 ± 22	2256 ± 22	1978 ± 24	3602 ± 16
12	3241 ± 11	2765 ± 14	2562 ± 24	2249 ± 26	3700 ± 18
18	3572 ± 12	2760 ± 16	2784 ± 26	2201 ± 29	3895 ± 21
24	3669 ± 16	3342 ± 18	3142 ± 29	2774 ± 21	3987 ± 20
30	3743 ± 18	3546 ± 21	3524 ± 30	2878 ± 24	4014 ± 15
	Ca				
0	3082 ± 10	3005 ± 11	2929 ± 12	2853 ± 10	3344 ± 19
6	3201 ± 9	3280 ± 18	3090 ± 10	3209 ± 18	3560 ± 11
12	3540 ± 11	3201 ± 19	3210 ± 14	3260 ± 19	3650 ± 10
18	3501 ± 18	3876 ± 10	3949 ± 19	3210 ± 18	3712 ± 12
24	3687 ± 17	4021 ± 10	3891 ± 18	3646 ± 17	3678 ± 19
30	3740 ± 16	4208 ± 19	4043 ± 19	3876 ± 19	3820 ± 18
	Mg				
0	1918 ± 10	1817 ± 12	1709 ± 10	1595 ± 10	2059 ± 12
6	1898 ± 9	1843 ± 14	1924 ± 12	2084 ± 12	2042 ± 5
12	2015 ± 8	2078 ± 8	2687 ± 14	2354 ± 6	2040 ± 4
18	2214 ± 5	2070 ± 9	2645 ± 8	2340 ± 7	1972 ± 8
24	2340 ± 6	2165 ± 12	2754 ± 9	2401 ± 8	2343 ± 12
30	2434 ± 12	2345 ± 8	2840 ± 10	2432 ± 9	2418 ± 7

*Mean ± SD, n = 3, $P < 0.05$

5.2.4 TOTAL HEAVY METALS

The total concentrations of the heavy metals increased during the pile composting of *Salvinia natans* as shown at Table 5.2.3. The highest increase of the total concentration

Table 5.2.3. Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of *S. natans*

Days	Total heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	195 ± 0.9	193 ± 0.8	186 ± 1.1	183 ± 0.9	208 ± 0.9	247 ± 4.5	245 ± 4.5	243 ± 4.5	248 ± 4.5	268 ± 4.5
6	204 ± 0.8	201 ± 0.7	196 ± 0.9	188 ± 0.9	214 ± 0.8	260 ± 4.5	260 ± 3.0	264 ± 1.5	274 ± 4.5	280 ± 2.3
12	209 ± 0.7	217 ± 1.0	234 ± 0.9	224 ± 0.9	221 ± 1.0	271 ± 3.5	269 ± 1.5	267 ± 2.5	275 ± 3.5	300 ± 5.3
18	216 ± 1.0	228 ± 1.1	249 ± 0.9	240 ± 1.0	227 ± 1.0	281 ± 2.0	278 ± 1.5	279 ± 2.5	287 ± 3.5	304 ± 3.0
24	224 ± 0.8	234 ± 0.8	257 ± 0.9	248 ± 0.9	231 ± 0.9	302 ± 2.5	296 ± 3.0	318 ± 4.5	309 ± 2.0	318 ± 1.0
30	238 ± 0.9	243 ± 0.9	260 ± 1.0	254 ± 0.9	232 ± 1.1	311 ± 3.0	313 ± 3.0	325 ± 2.5	322 ± 2.5	319 ± 2.0
	Cu					**Pb**				
0	49.5 ± 0.5	49.0 ± 0.5	48.5 ± 0.4	47.9 ± 0.4	52.8 ± 0.3	626 ± 2.1	567 ± 2.3	507 ± 1.9	448 ± 1.9	755 ± 1.4
6	56.8 ± 0.3	48.8 ± 0.6	55.8 ± 0.4	50.0 ± 0.6	54.9 ± 0.4	636 ± 1.5	572 ± 2.1	541 ± 1.4	490 ± 1.6	763 ± 1.5
12	61.3 ± 0.3	54.9 ± 0.9	60.1 ± 0.3	59.0 ± 0.6	57.2 ± 0.3	674 ± 1.4	625 ± 1.5	598 ± 1.9	512 ± 1.8	783 ± 1.6
18	64.8 ± 0.8	68.1 ± 0.4	68.1 ± 0.6	70.0 ± 0.5	64.0 ± 0.5	692 ± 2.5	656 ± 1.9	625 ± 1.7	534 ± 1.4	832 ± 1.3
24	65.5 ± 0.5	74.0 ± 0.2	74.4 ± 0.4	72.2 ± 0.3	65.5 ± 0.4	711 ± 2.1	657 ± 1.7	657 ± 1.9	542 ± 1.3	837 ± 1.4
30	67.0 ± 0.5	75.9 ± 0.5	76.5 ± 0.5	75.0 ± 0.5	66.2 ± 0.4	725 ± 1.5	669 ± 1.8	665 ± 0.9	554 ± 1.2	849 ± 1.9
	Mn					**Cd**				
0	853 ± 04	806 ± 02	759 ± 03	712 ± 09	986 ± 01	54.2 ± 0.8	54.2 ± 0.5	53.1 ± 0.6	53.1 ± 0.5	53.1 ± 0.8
6	927 ± 05	915 ± 06	963 ± 05	788 ± 02	1009 ± 09	58.1 ± 0.7	66.1 ± 0.5	62.2 ± 0.2	59.1 ± 0.5	54.2 ± 0.6
12	928 ± 03	904 ± 07	984 ± 07	776 ± 09	1035 ± 08	64.2 ± 0.3	67.1 ± 0.5	64,1 ± 0.9	60.2 ± 0.5	54.1 ± 0.3
18	951 ± 05	936 ± 06	1025 ± 06	805 ± 06	1076 ± 06	66.1 ± 0.7	69.2 ± 0.8	69.3 ± 0.5	64.3 ± 0.4	55.3 ± 0.3
24	987 ± 03	952 ± 05	1052 ± 04	873 ± 07	1121 ± 05	69.3 ± 1.2	73.1 ± 1.1	72.1 ± 0.3	69.2 ± 0.3	59.2 ± 0.5
30	1033 ± 02	1034 ± 04	1082 ± 05	914 ± 06	1129 ± 05	70.1 ± 1.3	75.2 ± 1.1	74.1 ± 0.3	71.1 ± 0.5	62.1 ± 0.9
	Fe					**Cr**				
0	5895 ± 30	5403 ± 32	4931 ± 16	4441 ± 15	6737 ± 27	123 ± 1.1	121 ± 1.5	119 ± 1.5	118 ± 1.5	143 ± 1.1
6	6012 ± 19	5603 ± 44	5675 ± 22	4901 ± 23	6858 ± 20	128 ± 2.0	127 ± 0.5	125 ± 0.5	126 ± 1.4	150 ± 0.5
12	6444 ± 31	5979 ± 31	6141 ± 26	5104 ± 30	7087 ± 22	129 ± 1.2	141 ± 1.8	143 ± 1.3	139 ± 3.5	155 ± 1.5
18	6682 ± 28	6522 ± 38	6625 ± 22	5604 ± 30	7272 ± 21	144 ± 1.5	153 ± 0.6	171 ± 1.5	154 ± 3.5	173 ± 1.5
24	6750 ± 25	6848 ± 36	6734 ± 20	5704 ± 21	7497 ± 23	151 ± 1.0	162 ± 1.2	172 ± 1.2	164 ± 1.1	176 ± 1.1
30	6970 ± 25	6933 ± 28	6761 ± 27	5736 ± 27	7666 ± 21	165 ± 1.0	175 ± 0.5	184 ± 1.5	172 ± 1.3	186 ± 1.2

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

of all the heavy metals was in trial 3 which also indicated highest loss of net dry mass. The order of the concentrations of total heavy metals of the final *Salvinia natans* composts after pile composting was Fe > Mn > Pb > Ni > Zn > Cr > Cu > Cd. ANOVA analysis indicates that the variation of the concentration of the total heavy metals was significant for all trials ($P < 0.05$).

5.2.5 BIOAVAILABILITY OF HEAVY METALS

5.2.5.1 WS heavy metals

The concentration of the WS forms of Zn, Cu, Mn, Fe Pb and Cr reduced significantly ($P < 0.05$) in all trials during the pile composting of *Salvinia natans* (Table 5.2.4). The orders of reduction of the concentration of WS heavy metals of all the trials were as below:

Zn: T4 (25.4%) > T3 (24.7%) > T1 (23.7%) > T5 (20.8%) > T2 (18.4%)
Cu: T4 (38.4%) > T3 (36.4%) > T2 (32.6%) > T1 (27.7%) > T5 (19.8%)
Mn: T3 (39.6%) > T4 (27.9%) > T5 (19.1%) > T2 (16.0%) > T1 (14.3%)
Fe: T3 (51.1%) > T4 (44.9%) > T1 (37.7%) > T2 (35.6%) > T5 (23.3%)
Pb: T3 (39.7%) > T4 (35.7%) > T2 (28.0%) > T1 (20.8%) > T5 (14.1%)
Cr: T3 (28.3%) > T4 (24.4%) > T2 (21.3%) > T1 (16.0%) > T5 (14.2%)

(Note: T–trial)

WS forms of Ni and Cd were not detected in the composts similar to the results of phumdi biomass compost. Reduction of WS forms of Zn, Cu, Mn, Fe, Pb and Cr in all trials during the process was also attributed to the binding of the metals with the −OH and −COOH groups enriched by cattle manure. The newly formed humus increased the binding sites and combined with the metals released during mineralization of organic biomass to form insoluble and immobile complexes (Guan et al., 2011; Singh and Kalamdhad, 2013a). During pile composting of phumdi biomass, highest reduction of WS heavy metals were all indicated in trial 4 (i.e. 5 phumdi biomass : 4 cattle manure : 1 rice husk) but in the case of pile composting of *Salvinia natans*, highest reduction of WS Mn, Fe, Pb and Cr was indicated in trial 3. There was increase in the concentration of WS Fe after pile composting of phumdi biomass without cattle manure and rice husk (trial 5), but the WS fraction of Fe was reduced in all trials after the pile composting of *Salvinia natans*. The total concentrations of Zn (232–260 mg/kg), Ni (311–319 mg/kg) and Pb (554–849 mg/kg) were higher than the total concentration of Cr (165.0–186.0 mg/kg) of the final *Salvinia natans* composts, but the WS forms of Zn (7.8–11.4 mg/kg),

Table 5.2.4. Variation of WS Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of *S. natans*

Days	WS heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	13.5 ± 0.10	13.5 ± 0.05	11.3 ± 0.11	10.5 ± 0.08	14.4 ± 0.07	–	–	–	–	–
6	13.1 ± 0.10	12.3 ± 0.08	11.1 ± 0.01	10.3 ± 0.08	13.7 ± 0.02	–	–	–	–	–
12	12.2 ± 0.00	12.4 ± 0.04	12.1 ± 0.14	10.4 ± 0.06	13.3 ± 0.09	–	–	–	–	–
18	11.8 ± 0.10	11.6 ± 0.07	10.5 ± 0.14	9.6 ± 0.05	12.1 ± 0.08	–	–	–	–	–
24	11.1 ± 0.10	11.1 ± 0.08	9.6 ± 0.08	8.7 ± 0.11	11.7 ± 0.06	–	–	–	–	–
30	10.3 ± 0.10	11.0 ± 0.05	8.5 ± 0.04	7.8 ± 0.06	11.4 ± 0.05	–	–	–	–	–
	Cu					**Pb**				
0	7.5 ± 0.09	7.1 ± 0.09	6.7 ± 0.10	6.3 ± 0.10	8.0 ± 0.10	7.7 ± 0.10	6.7 ± 0.10	5.7 ± 0.10	4.7 ± 0.05	9.7 ± 0.10
6	7.3 ± 0.08	7.0 ± 0.11	7.1 ± 0.09	6.5 ± 0.08	8.0 ± 0.09	7.6 ± 0.04	6.8 ± 0.05	5.8 ± 0.05	4.8 ± 0.05	9.7 ± 0.05
12	6.7 ± 0.10	6.6 ± 0.08	7.1 ± 0.12	6.6 ± 0.09	7.5 ± 0.10	7.4 ± 0.05	6.7 ± 0.05	6.1 ± 0.05	5.6 ± 0.10	9.8 ± 0.05
18	6.5 ± 0.09	6.1 ± 0.06	6.8 ± 0.08	5.4 ± 0.08	7.1 ± 0.11	6.9 ± 0.05	6.0 ± 0.10	4.2 ± 0.05	4.4 ± 0.05	9.3 ± 0.05
24	6.0 ± 0.08	5.1 ± 0.08	5.4 ± 0.08	4.1 ± 0.11	7.0 ± 0.12	6.5 ± 0.05	5.1 ± 0.1	3.5 ± 0.05	3.2 ± 0.05	8.8 ± 0.05
30	5.4 ± 0.10	4.8 ± 0.07	4.3 ± 0.07	3.9 ± 0.09	6.7 ± 0.09	6.5 ± 0.05	4.8 ± 0.05	3.4 ± 0.05	3.0 ± 0.05	8.3 ± 0.03
	Mn					**Cd**				
0	48.3 ± 0.10	44.9 ± 0.10	41.8 ± 0.10	38.1 ± 0.02	55 ± 0.04	–	–	–	–	–
6	45.6 ± 0.10	45.4 ± 0.09	43.6 ± 0.04	41.1 ± 0.08	54.2 ± 0.05	–	–	–	–	–
12	43.3 ± 0.09	42.8 ± 0.07	41.2 ± 0.05	39.3 ± 0.09	51.3 ± 0.05	–	–	–	–	–
18	43.4 ± 0.07	41.3 ± 0.05	32.2 ± 0.05	31.1 ± 0.07	51.0 ± 0.04	–	–	–	–	–
24	42.0 ± 0.05	38.0 ± 0.04	26.5 ± 0.04	28.1 ± 0.05	49.1 ± 0.06	–	–	–	–	–
30	41.4 ± 0.06	37.7 ± 0.08	25.2 ± 0.03	27.5 ± 0.04	44.5 ± 0.07	–	–	–	–	–
	Fe					**Cr**				
0	253 ± 1.0	240 ± 1.1	230 ± 0.9	214 ± 0.9	266 ± 1.5	27.9 ± 0.10	25.1 ± 0.1	23.0 ± 0.10	20.0 ± 0.08	34.0 ± 0.06
6	239 ± 1.1	230 ± 1.5	225 ± 0.8	213 ± 1.1	260 ± 0.8	27.8 ± 0.09	26.0 ± 0.10	25.8 ± 0.10	22.4 ± 0.06	33.1 ± 0.09
12	232 ± 1.1	223 ± 1.2	202 ± 0.9	223 ± 1.1	250 ± 0.7	23.9 ± 0.10	25.8 ± 0.05	24.9 ± 0.11	21.1 ± 0.05	32.9 ± 0.03
18	204 ± 1.2	202 ± 1.1	125 ± 1.1	193 ± 0.9	235 ± 1.0	23.7 ± 0.05	25.3 ± 0.10	20.8 ± 0.14	17.0 ± 0.05	32.4 ± 0.04
24	194 ± 1.2	168 ± 1.1	112 ± 1.0	131 ± 0.8	217 ± 1.1	23.5 ± 0.09	20.5 ± 0.10	18.1 ± 0.08	16.3 ± 0.09	31.4 ± 0.05
30	157 ± 1.2	154 ± 1.4	109 ± 1.1	118 ± 0.7	204 ± 1.1	23.4 ± 0.09	19.8 ± 0.11	16.5 ± 0.09	15.1 ± 0.07	29.2 ± 0.07

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Table 5.2.5. Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of *S. natans*

Days	DTPA extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	82.4 ± 0.09	77.4 ± 0.09	71.9 ± 0.14	66.5 ± 0.12	93.9 ± 0.10	14.1 ± 0.08	13.7 ± 0.09	12.9 ± 0.05	11.7 ± 0.05	17.4 ± 0.09
6	79.2 ± 0.10	77.5 ± 0.15	72.5 ± 0.12	66.7 ± 0.11	93.5 ± 0.18	13.9 ± 0.07	13.5 ± 0.07	12.9 ± 0.04	10.7 ± 0.09	17.1 ± 0.04
12	74.6 ± 0.05	70.3 ± 0.11	65.5 ± 0.16	58.6 ± 0.10	92.8 ± 0.17	13.3 ± 0.06	12.8 ± 0.06	10.7 ± 0.07	10.1 ± 0.1	16.9 ± 0.07
18	73.5 ± 0.10	69.1 ± 0.12	63.9 ± 0.18	60.2 ± 0.11	88.6 ± 0.16	13.1 ± 0.05	12.6 ± 0.04	10.3 ± 0.06	10 ± 0.07	16.5 ± 0.05
24	70.3 ± 0.12	66.2 ± 0.12	62.2 ± 0.09	53.6 ± 0.16	84.7 ± 0.14	13.1 ± 0.07	12.4 ± 0.06	10.3 ± 0.04	9.9 ± 0.06	16.2 ± 0.07
30	67.2 ± 0.12	63.2 ± 0.53	53.7 ± 0.11	50.5 ± 0.18	83.3 ± 0.12	11.9 ± 0.08	11.7 ± 0.08	9.9 ± 0.08	9.6 ± 0.07	16.3 ± 0.11
	Cu					**Pb**				
0	9.7 ± 0.04	9.6 ± 0.05	8.8 ± 0.05	7.9 ± 0.06	9.7 ± 0.02	28.7 ± 0.14	22.9 ± 0.19	23.2 ± 0.04	16.1 ± 0.12	31.4 ± 0.15
6	9.6 ± 0.04	9.4 ± 0.06	8.5 ± 0.03	7.6 ± 0.09	9.0 ± 0.06	28.1 ± 0.08	21.3 ± 0.19	21.2 ± 0.16	15.2 ± 0.05	30.2 ± 0.15
12	9.3 ± 0.03	8.8 ± 0.05	7.7 ± 0.03	7.2 ± 0.05	8.7 ± 0.05	24.3 ± 0.12	20.2 ± 0.13	20.7 ± 0.12	14.2 ± 0.08	28.5 ± 0.14
18	8.7 ± 0.09	8.6 ± 0.05	6.2 ± 0.04	6.1 ± 0.06	8.5 ± 0.01	21.8 ± 0.12	18.3 ± 0.14	18.2 ± 0.15	12.7 ± 0.11	26.8 ± 0.10
24	8.4 ± 0.04	7.7 ± 0.09	6.2 ± 0.02	6.1 ± 0.09	8.4 ± 0.03	22.5 ± 0.19	17.3 ± 0.11	15.9 ± 0.16	12.2 ± 0.05	26.3 ± 0.11
30	8.0 ± 0.02	7.6 ± 0.07	5.9 ± 0.02	5.6 ± 0.07	8.4 ± 0.04	21.8 ± 0.19	17.2 ± 0.09	14.6 ± 0.15	12.1 ± 0.05	25.9 ± 0.06
	Mn					**Cd**				
0	201 ± 0.89	210 ± 0.97	215 ± 1.01	221 ± 0.98	220 ± 0.87	–	–	–	–	–
6	187 ± 0.98	195 ± 0.85	209 ± 0.89	211 ± 0.98	216 ± 0.86	–	–	–	–	–
12	185 ± 0.97	197 ± 0.89	202 ± 0.98	203 ± 0.9	207 ± 0.89	–	–	–	–	–
18	181 ± 0.89	191 ± 0.86	191 ± 1.01	189 ± 0.94	201 ± 0.95	–	–	–	–	–
24	181 ± 0.78	183 ± 0.98	178 ± 0.79	179 ± 1.01	198 ± 0.95	–	–	–	–	–
30	179 ± 0.98	183 ± 0.89	166 ± 0.97	175 ± 0.85	197 ± 0.79	–	–	–	–	–
	Fe					**Cr**				
0	281 ± 0.3	293 ± 0.9	311 ± 1.8	316 ± 1.4	314 ± 1.6	45.3 ± 0.1	40.5 ± 0.5	35.4 ± 0.3	30.4 ± 0.2	50.3 ± 0.5
6	274 ± 1.1	264 ± 1.5	310 ± 1.3	309 ± 0.9	302 ± 0.7	42.0 ± 0.7	38.9 ± 0.3	34.2 ± 0.5	30.8 ± 0.9	49.2 ± 0.6
12	243 ± 1.5	253 ± 1.1	284 ± 1.1	238 ± 1.5	286 ± 1.6	39.8 ± 0.5	28.3 ± 0.6	31.2 ± 0.4	28.3 ± 0.4	48.1 ± 0.4
18	214 ± 1.2	231 ± 1.2	233 ± 1.6	251 ± 1.5	263 ± 1.4	37.4 ± 0.6	23.9 ± 0.2	25.8 ± 0.4	19.5 ± 0.4	46.7 ± 0.4
24	203 ± 1.9	211 ± 1.5	205 ± 1.5	216 ± 1.5	252 ± 1.5	35.1 ± 0.4	23.9 ± 0.7	16.2 ± 0.3	17.4 ± 0.5	43.3 ± 0.4
30	197 ± 1.3	202 ± 1.4	188 ± 1.5	212 ± 1.3	241 ± 1.4	31.2 ± 0.3	21.4 ± 0.4	15.6 ± 0.5	14.8 ± 0.1	41.7 ± 0.4

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Ni (NIL) and Pb (3.0–8.3 mg/kg) were lower than Cr (15.1–29.2 mg/kg) indicating that Cr was more bioavailable in addition to the higher toxicity potential. The order of the concentration of WS heavy metals of the final *Salvinia natans* composts was Fe > Mn > Cr > Zn > Cu = Pb.

5.2.5.2 DTPA extractable heavy metals

The variation of DTPA extractable heavy metals (Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr) during the composting process is shown at Table 5.2.5. DTPA extractable Cd was not detected in the *Salvinia natans* composts obtained from all trials. Highest reduction of DTPA extractable heavy metals in trial 3 was possibly due to the higher degradation and subsequent formation of humus which formed insoluble metal complexes at higher pH (Fang and Wong, 1999; Singh and Kalamdhad, 2013a). The heavy metals renovated into a more stable form during composting process due to increased pH and metal biosorption by the microbial biomass (Castaldi et al., 2006; Cai et al., 2007; Gupta and Sinha, 2007; Singh and Kalamdhad, 2014). The DTPA fraction of heavy metals was reduced in all trials after the *Salvinia natans* pile composting in the following order:

Zn: T3 (25.3%) > T4 (24.1%) > T1 (18.5%) > T2 (18.4%) > T5 (11.3%)
Cu: T3 (32.8%) > T4 (28.8%) > T2 (20.8%) > T1 (17.2%) > T5 (13.7%)
Mn: T3 (22.5%) > T4 (20.7%) > T2 (12.9%) > T1 (10.8%) > T5 (10.7%)
Fe: T3 (39.5%) > T4 (32.8%) > T2 (31.1%) > T1 (30.0%) > T5 (23.3%)
Ni: T3 (22.9%) > T4 (17.7%) > T1 (15.2%) > T2 (14.5%) > T5 (6.2%)
Pb: T3 (36.9%) > T4 (25.2%) > T2 (24.9%) > T1 (23.9%) > T5 (17.5%)
Cr: T3 (56.1%) > T4 (51.9%) > T2 (47.4%) > T1 (31.5%) > T5 (17.2%)

(Note: T–trial)

The order of the concentration of DTPA extractable heavy metals of the final *Salvinia natans* composts was Fe > Mn > Zn > Cr > Pb > Cu > Ni. The extractable efficiency “ŋ” of DTPA extractable heavy metals decreased during the pile composting of Salvinia natans (Fig. 5.2.5). The final “ŋ” of the DTPA extractable heavy metals of *Salvinia natans* composts were in the range 20.0–35.9% for Zn, 7.5–12.7% for Cu, 15.4–17.7% for Mn, 2.8–3.7% for Fe, 3.0–5.1% for Ni, 2.2–3.1% for Pb and 8.5–22.4% for Cr. In case of pile composting of phumdi biomass, the “ŋ” of the DTPA extractable heavy metals of the final phumdi biomass composts were in the range 11.5–38.5% for Zn, 9.2–13.3% for Cu, 20.2–30.5% for Mn, 0.5–0.6% for Fe, 0.2–0.3% for Ni, 1.1–1.7% for Pb, 0.4–1.2% for Cd and 3.1–12.4% for Cr. The intermittent increase of “ŋ” indicated during pile composting of phumdi biomass was not indicated during the pile composting of *Salvinia natans*. The variations of “ŋ” during the pile composting of *Salvinia natans* were also statistically significant among the trials ($P < 0.05$).

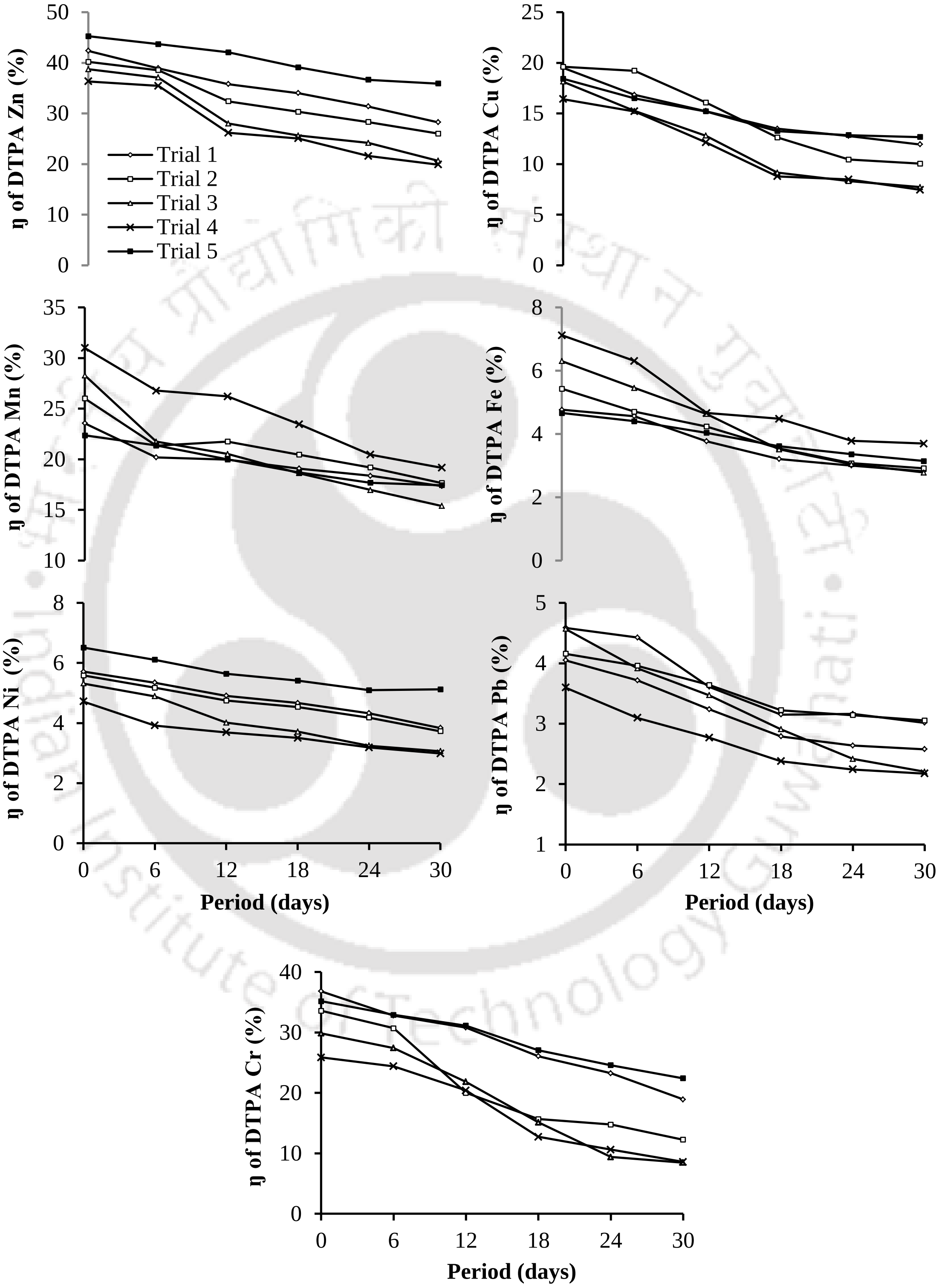

Fig. 5.2.5. Variation of “ŋ” of DTPA extractable heavy metals during pile composting of *Salvinia natans*

Table 5.2.6. Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during pile composting of Salvinia

Days	TCLP extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	113.4 ± 1.1	106.0 ± 0.7	98.0 ± 0.7	89.6 ± 0.7	129.1 ± 0.9	161 ± 1.1	144 ± 1.1	126 ± 1.5	109 ± 1.8	206 ± 1.7
6	109.6 ± 0.8	104.5 ± 0.8	96.1 ± 0.5	86.0 ± 0.7	128.0 ± 1.2	160 ± 1.5	138 ± 1.3	124 ± 1.5	100 ± 1.7	202 ± 1.0
12	108.4 ± 0.8	101.4 ± 0.5	92.9 ± 0.8	83.6 ± 0.6	122.8 ± 0.3	152 ± 1.3	124 ± 1.1	110 ± 1.5	92 ± 1.3	202 ± 1.5
18	103.0 ± 0.6	102.9 ± 0.4	84.1 ± 0.7	75.5 ± 0.4	124.2 ± 0.9	149 ± 1.0	114 ± 1.5	100 ± 1.4	89 ± 1.1	193 ± 1.4
24	101.1 ± 0.8	100.3 ± 0.7	77.3 ± 0.8	73.2 ± 0.6	122.0 ± 1.1	136 ± 1.1	107 ± 1.4	96 ± 1.1	86 ± 1.4	182 ± 1.1
30	97.2 ± 0.9	94.7 ± 0.8	76.8 ± 0.5	72.5 ± 0.7	121.3 ± 1.1	136 ± 1.4	104 ± 1.0	88 ± 1.1	81 ± 1.4	178 ± 1.1
	Cu					**Pb**				
0	20.7 ± 0.3	18.7 ± 0.4	17.3 ± 0.2	16.1 ± 0.2	23.1 ± 0.6	53 ± 0.2	49 ± 0.5	40 ± 0.6	34 ± 0.4	65 ± 0.2
6	20.2 ± 0.2	17.5 ± 0.6	16.0 ± 0.3	15.7 ± 0.2	22.2 ± 0.4	52 ± 0.2	47 ± 0.2	38 ± 0.3	32 ± 0.2	63 ± 0.4
12	19.3 ± 0.4	16.9 ± 0.3	14.0 ± 0.2	14.8 ± 0.4	22.1 ± 0.6	49 ± 0.3	43 ± 0.2	35 ± 0.3	31 ± 0.4	63 ± 0.1
18	17.2 ± 0.2	15.1 ± 0.5	12.0 ± 0.1	14.6 ± 0.2	19.1 ± 0.2	47 ± 0.3	42 ± 0.2	32 ± 0.4	29 ± 0.1	62 ± 0.1
24	16.2 ± 0.4	14.0 ± 0.4	11.2 ± 0.5	12.8 ± 0.5	19.0 ± 0.2	45 ± 0.2	40 ± 0.3	30 ± 0.5	28 ± 0.1	60 ± 0.2
30	15.6 ± 0.5	13.5 ± 0.2	11.0 ± 0.4	11.2 ± 0.2	18.5 ± 0.4	41 ± 0.3	36 ± 0.2	26 ± 0.7	22 ± 0.1	57 ± 0.4
	Mn					**Cd**				
0	300 ± 1.1	310 ± 1.3	330 ± 1.1	344 ± 1.2	296 ± 0.8	2.4 ± 0.03	2.3 ± 0.01	2.0 ± 0.02	1.5 ± 0.05	2.4 ± 0.01
6	289 ± 1.5	305 ± 1.1	319 ± 1.2	321 ± 1.1	284 ± 1.0	2.3 ± 0.03	2.3 ± 0.01	1.7 ± 0.01	1.3 ± 0.03	2.4 ± 0.02
12	286 ± 1.1	290 ± 1.1	313 ± 1.2	315 ± 1.6	275 ± 1.1	2.2 ± 0.04	2.1 ± 0.01	1.3 ± 0.02	1.1 ± 0.03	2.3 ± 0.01
18	273 ± 1.5	286 ± 1.4	295 ± 1.1	299 ± 1.2	272 ± 1.8	2.1 ± 0.04	1.9 ± 0.03	1.1 ± 0.01	0.9 ± 0.03	2.2 ± 0.02
24	260 ± 1.0	282 ± 1.2	281 ± 1.3	291 ± 1.2	267 ± 1.7	1.9 ± 0.04	1.6 ± 0.01	1.2 ± 0.07	0.8 ± 0.03	2.2 ± 0.02
30	259 ± 1.5	267 ± 1.2	268 ± 1.1	281 ± 1.4	265 ± 0.8	1.8 ± 0.01	1.4 ± 0.01	1.0 ± 0.03	0.8 ± 0.01	1.9 ± 0.02
	Fe					**Cr**				
0	430 ± 2.3	407 ± 1.2	399 ± 1.6	381 ± 1.6	477 ± 1.6	59.3 ± 0.4	50.2 ± 0.4	45.1 ± 0.2	36.2 ± 0.6	66.6 ± 0.3
6	414 ± 1.9	396 ± 1.6	406 ± 1.7	366 ± 1.5	462 ± 1.5	57.0 ± 0.1	47.1 ± 0.8	42.8 ± 0.3	35.2 ± 0.6	58.8 ± 0.5
12	389 ± 2.4	364 ± 1.3	345 ± 1.4	341 ± 1.2	456 ± 1.6	55.2 ± 0.1	42.3 ± 0.1	26.7 ± 0.3	32.0 ± 0.2	57.8 ± 0.5
18	359 ± 3.5	352 ± 1.5	291 ± 1.2	321 ± 1.1	447 ± 2.3	53.0 ± 0.2	39.6 ± 0.3	24.9 ± 0.5	26.1 ± 0.2	52.7 ± 0.8
24	358 ± 2.4	305 ± 1.2	285 ± 1.4	270 ± 1.7	441 ± 1.3	49.2 ± 0.5	33.4 ± 0.2	18.8 ± 0.1	25.0 ± 0.1	52.8 ± 0.6
30	330 ± 2.7	285 ± 1.3	275 ± 1.9	248 ± 1.9	423 ± 1.4	41.0 ± 0.1	31.6 ± 0.3	17.7 ± 0.2	21.0 ± 0.3	51.3 ± 0.4

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

5.2.5.3 TCLP extractable heavy metals

The TCLP extractable forms of Zn, Cu, Mn, Fe, Ni, Cd, Pb and Cr of all trials were reduced after the pile composting of *Salvinia natans* (Table 5.2.6) in the following order:

Zn: T3 (21.2%) > T4 (19.0%) > T1 (14.3%) > T2 (10.7%) > T5 (6.1%)
Cu: T3 (35.0%) > T4 (28.2%) > T2 (27.6%) > T1 (24.4%) > T5 (19.7%)
Mn: T3 (18.9%) > T4 (18.3%) > T2 (14.0%) > T1 (13.7%) > T5 (10.2%)
Fe: T4 (34.7%) > T3 (31.1%) > T2 (30.1%) > T1 (23.2%) > T5 (11.1%)
Ni: T3 (30.5%) > T4 (25.3%) > T2 (27.8%) > T1 (15.4%) > T5 (13.7%)
Pb: T3 (34.5%) > T4 (34.4%) > T2 (26.8%) > T1 (22.5%) > T5 (11.9%)
Cd: T3 (50.5%) > T4 (49.0%) > T2 (36.8%) > T1 (24.7%) > T5 (20.0%)
Cr: T3 (60.1%) > T4 (41.9%) > T2 (37.0%) > T1 (30.8%) > T5 (22.9%)

(Note: T–trial)

The reduction of leachable fraction of heavy metals was consistent with the results of pile composting of phumdi biomass and also with the findings of other researchers (Chiang et al., 2007; Singh and Kalamdhad, 2014). The results of TCLP test confirmed that the concentrations of heavy metals in all trials after *Salvinia natans* pile composting were also under the prescribed threshold limits of compost for agriculture purposes (USEPA, 1991). The bioavailability study during pile composting of *Salvinia natans* indicated that the formation of insoluble organo-metallic complex was higher in trial 3 and 4. Pile composting of phumdi biomass and *Salvinia natans* also indicated that the bioavailability of heavy metals was independent on the total concentration of the heavy metals. ANOVA analysis showed significant differences in the leachable concentration of heavy metals (Zn, Cu, Fe, Mn, Fe, Ni, Pb, Cd and Cr) of all trials ($P < 0.05$).

5.3 ROTARY DRUM COMPOSTING OF *SALVINIA NATANS*

5.3.1 TEMPERATURE PROFILE

The temperature profile of the trials during the rotary drum composting of *Salvinia natans* were in the range 22.9–54.2ºC (Fig. 5.3.1). The highest temperature (54.2ºC) was shown on day 4 in trial 3 indicating highest microbial activity in trial 3 during the drum composting process (Chen et al., 2010). The temperature profiles during pile composting and drum composting of *Salvinia natans* clearly indicated that the best combination for optimum available carbon, nitrogen, nutrients and other physical properties required for effective composting of *Salvinia natans* was provided in trial 3. The result was inconsistent with the rotary drum composting of phumdi biomass but agreed with the results during the rotary drum composting of water hyacinth (Singh and Kalamdhad, 2013a).

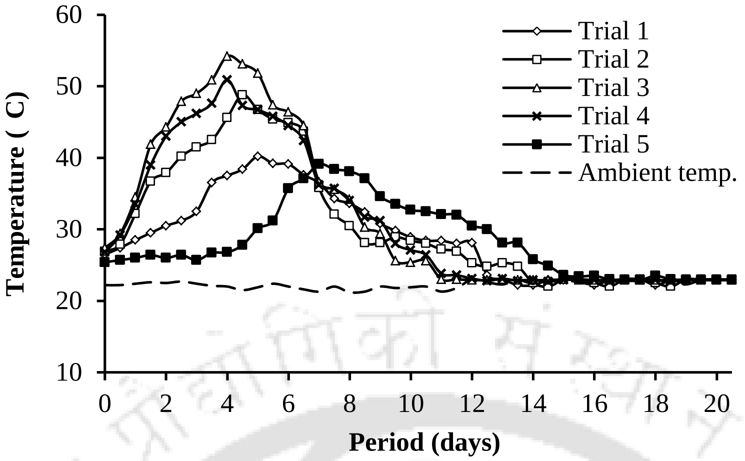

Fig. 5.3.1. Temperature profiles during drum composting of *Salvinia natans*

5.3.2 PHYSICO-CHEMICAL AND BIO-CHEMICAL ANALYSIS

The pH values increased in all trials during drum composting of *Salvinia natans* and the maximum pH observed was 7.51 and 7.50 in trial 3 and 4 at the end of composting process (Fig. 5.3.2a). Variation of pH in all trials was statistically significant ($P < 0.05$). The initial decreasing trends in trial 2, 3 and 4 might be to the release of organic and inorganic acids from the decomposition of OM (OM) (Wong et al. 2001). The pH consequently increased because the regular turning of the drum provided sufficient aeration for high microbial activity thereby enhancing the degradation of the organic acids and subsequent release of CO_2 (Cayuela et al., 2008).

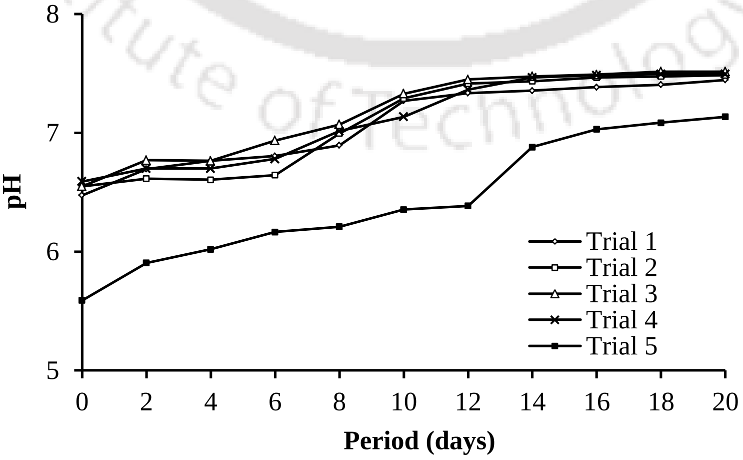

Fig. 5.3.2a. Variation of pH during drum composting of *Salvinia natans*

The EC of all trials after an initial increase decreased at the end of the composting process (Fig. 5.3.2b). All trials except trial 5 indicated net decrease of EC after the process. The ECs of all composts were less than 4dS/m and safe for plants. ANOVA test showed that EC varied significantly amongst all the trials ($P < 0.05$).

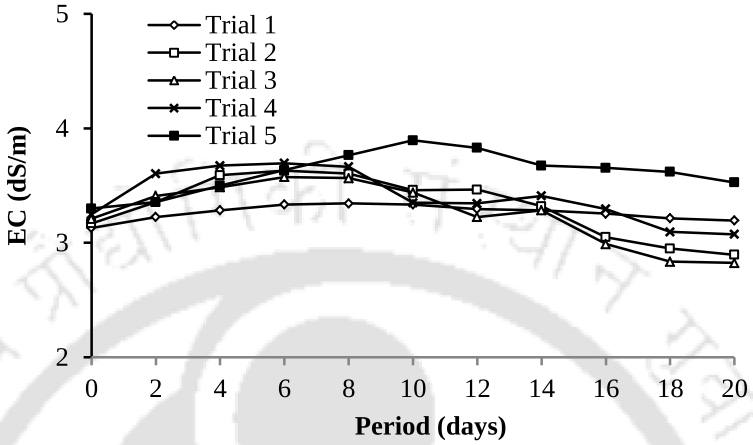

Fig. 5.3.2b. Variation of EC during drum composting of *S. natans*

Highest and lowest moisture loss occurred in trial 3 (31.4%) and trial 5 (17.1%) which corroborated the highest and lowest heat generation in trial 3 and 5, respectively (Fig. 5.3.2c). The highest moisture loss of the compost of trial 3 was higher than the highest moisture loss after pile composting of *Salvinia natans* (30.9% in trial 3). Leachate formation was not observed during the composting period. ANOVA test indicated that the variation of moisture content among the trials at different stages of the process was statistically significant ($P < 0.05$).

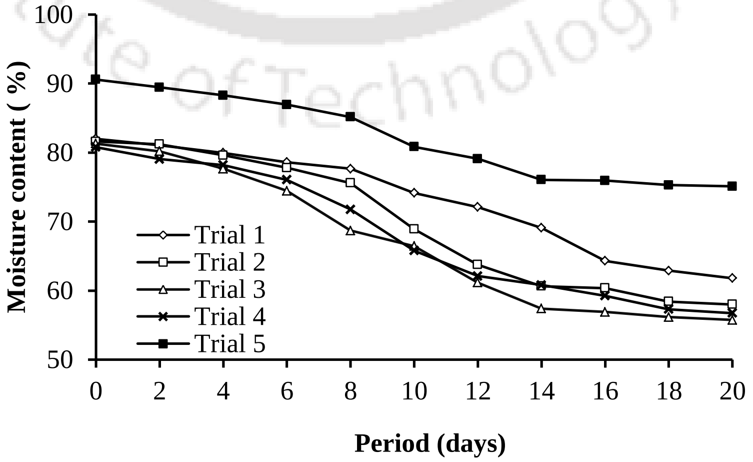

Fig. 5.3.2c. Variation of MC during drum composting of *Salvinia natans*

The temperature profile of the trials was also corroborated with the VS loss during the process (Fig. 5.3.2d). The descending order of VS loss after drum composting of *Salvinia natans* was trial 3 (32.9%, $K_b = 0.67$) > trial 4 (30.8%, $K_b = 0.64$) > trial 2 (29.8%, $K_b = 0.63$) > trial 1 (24.8%, $K_b = 0.58$) > trial 5 (14.7%, $K_b = 0.41$). The K_b of rotary drum composting was higher than the K_b of pile composting. ANOVA analysis indicated significant variation of VS among the trials during the process ($P < 0.05$).

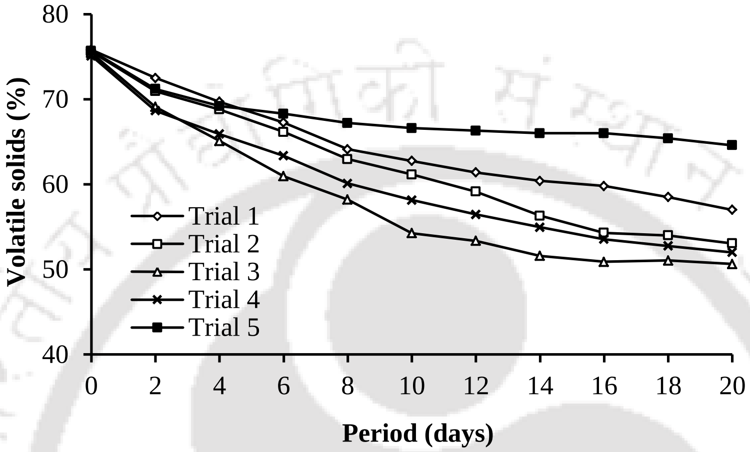

Fig. 5.3.2d. Variation of VS during drum composting of *S. natans*

The soluble BOD of all trials (Fig. 5.3.2e) decreased due to degradation of easily degradable WS compounds. Trial 3 recorded highest reduction of soluble BOD (82.4%) followed by trial 4 (77.0%) after 20 days. There were no significant changes in soluble BOD concentrations of the composts of trial 3 and 4 after day 18. The reduction of soluble BOD was significant for all trials during the composting process ($P < 0.05$).

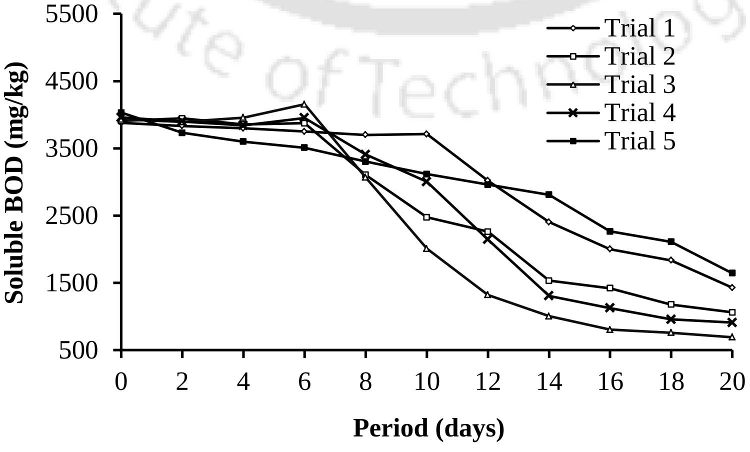

Fig. 5.3.2e. Variation of soluble BOD during drum composting of *S. natans*

The CO_2 evolution rate of trial 3 and 4 decreased significantly from day 6 during the rotary drum composting of *Salvinia natans* (Fig. 5.3.2f). On day 20, the CO_2 evolution rate of trial 3 and 4 decreased from 6.9 and 6.7 to 1.0 and 1.2 mg/g VS/day, respectively. The OUR showed temporal decrease after day 6 in trial 2, 3 and 4 (Fig.5.3.2g). OUR of trial 3 and 4 indicated that the respiration rate was reduced with no significant variation by 18th day. The reduction of soluble BOD concentration, CO_2 evolution rate and OUR of trial 3 and 4 indicated that the respiration rate was reduced with no significant variation after 16 days due to decrease in soluble BOD concentration. From the results of CO_2 evolution rate and OUR, the *Salvinia natans* composts of trial 3 and 4 containing higher proportions of cattle manure were stable (TMECC, 2002).

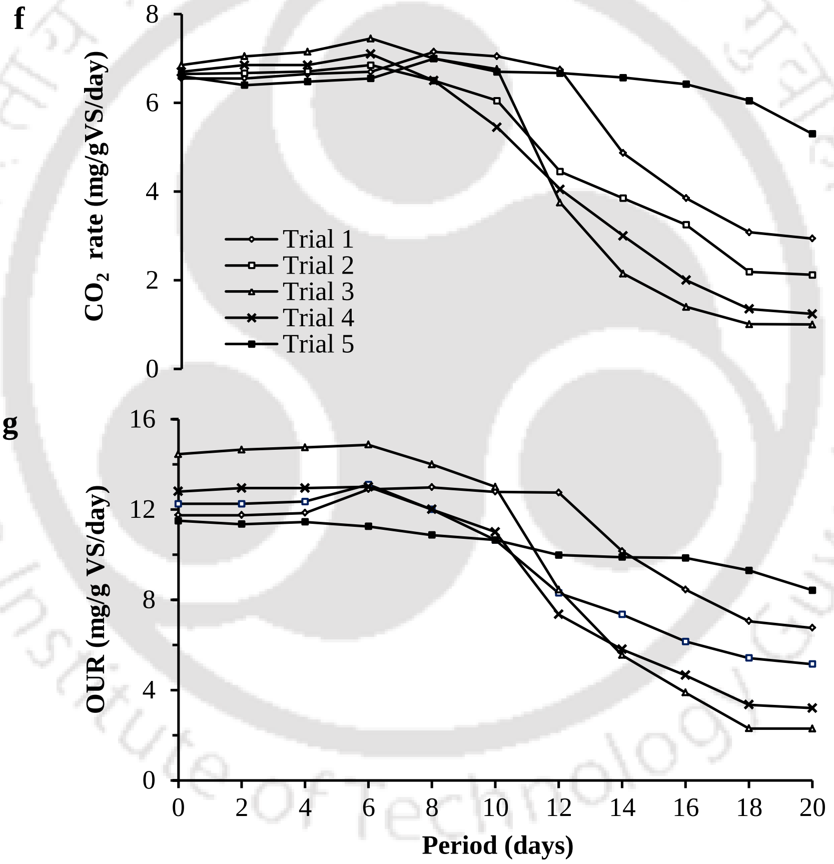

Fig. 5.3.2 f. Variation of CO_2 evolution rate during drum composting of *Salvinia natans*
g. Variation of OUR during drum composting of *Salvinia natans*

5.3.3 NUTRIENTS

Trial 3 showed the highest increase in the concentration of TKN (34.1%) followed by trial 4 (33.0%) due to the higher loss of dry mass (Fig. 5.3.3a). The variation of TKN concentration among all the *Salvinia natans* trials during the composting period was significant ($P < 0.05$). The NH_4–N decreased from day 6 and the lowest value (190 mg/Kg) was indicated in trial 3 on day 20. The concentration of TP during the drum composting of *Salvinia natans* gradually increased also due to net loss in dry mass (Fig. 5.3.3b). The highest increase of TP was indicated in trial 3 (76.2%) which was higher than the highest increase during pile composting of *Salvinia natans* due to higher loss in dry mass. The AP increased prominently in the composts of trial 1, 2, 3 and 4 and the highest increase was indicated in trial 3 (37.6%). However, the highest increase of AP was lower than the highest increase of AP indicated after pile composting of *Salvinia natans* in trial 3 (51.4%). Differences in composting processes and materials influenced the amounts and relative distribution of P fractions in composts (Sharpley and Moyer, 2000).

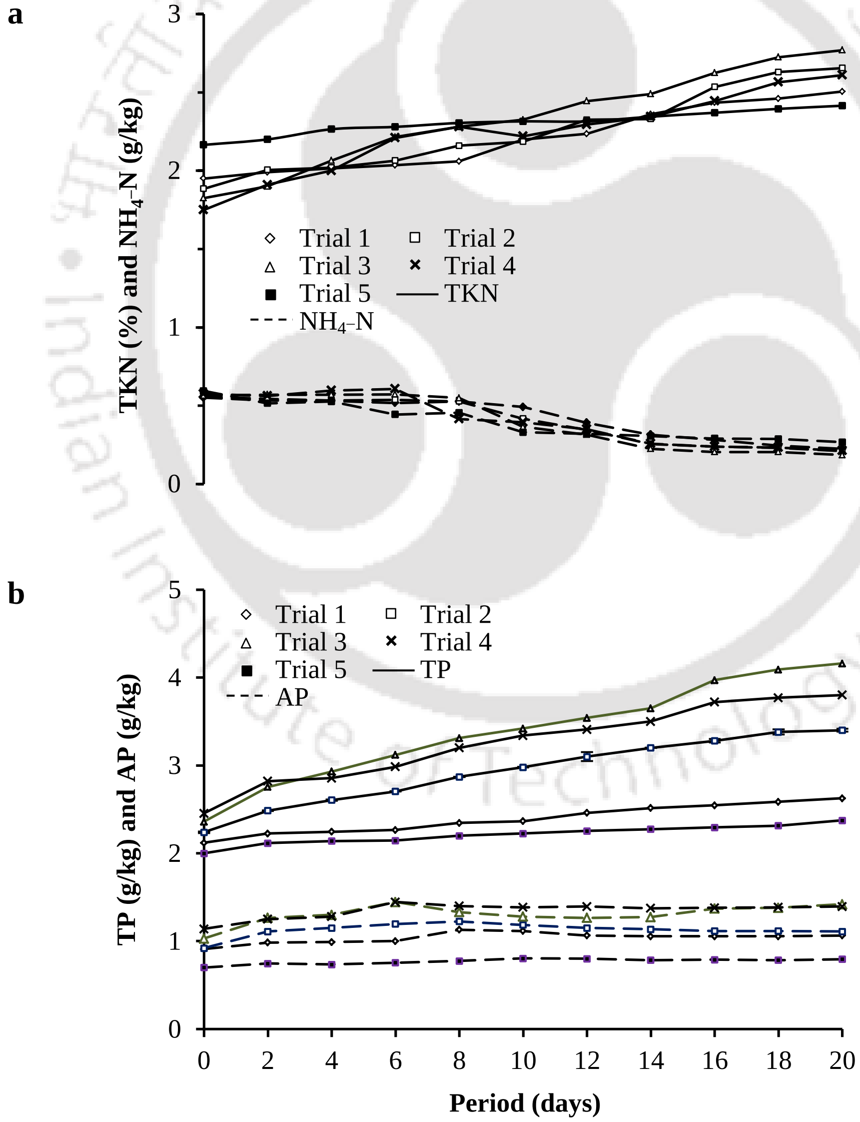

Fig. 5.3.3 a. Variation of TKN and NH_4–N during drum composting of *Salvinia natans*
b. Variation of TP and AP during drum composting of *Salvinia natans*

Table 5.3.1 illustrates the variation of the total concentration of Na, K, Ca and Mg of the trials during the rotary drum composting of *Salvinia natans*. The total concentration of the nutrients gradually increased during the drum composting process. The total concentration of the nutrients of the *Salvinia natans* composts after drum composting increased in the range 16.5–63.0% for Na, 18.7–46.7% for K, 20.7–62.0% for Ca and 10.0–36.7% for Mg. The highest increase of the total concentration of the nutrients was in trial 3 which also indicated the highest reduction of VS. Similar to drum composting of phumdi biomass, the increase of the total concentration of the nutrients was higher than the highest increase after pile composting of *Salvinia natans*. The final concentrations of the nutrients of the final composts of all trials were also near the limits (Barker, 1997; Bord na More, 2003; ALCL, 2004). The order of the concentration of total nutrients of the final composts was K > Ca > Mg > Na. The variation of the total concentration of the nutrients was statistically significant for all trials ($P < 0.05$).

Table 5.3.1. Variation of total Na, K, Ca and Mg during drum composting of *S. natans*

Days	Total nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	6078 ± 11	5648 ± 15	5219 ± 12	4789 ± 12	6995 ± 15
4	6495 ± 14	5887 ± 12	5569 ± 14	5839 ± 14	7125 ± 11
8	6855 ± 12	6828 ± 16	6199 ± 16	6709 ± 15	7265 ± 14
12	6894 ± 11	7032 ± 14	8342 ± 17	6775 ± 12	7668 ± 12
16	7135 ± 12	7959 ± 12	8414 ± 18	7495 ± 16	7939 ± 12
20	7487 ± 14	8015 ± 16	8508 ± 11	7609 ± 17	8149 ± 18
	K				
0	16132 ± 24	14339 ± 22	12546 ± 21	10753 ± 22	18920 ± 19
4	16745 ± 26	14467 ± 21	13913 ± 20	11837 ± 24	19002 ± 18
8	16975 ± 24	14686 ± 24	15486 ± 19	12322 ± 26	18878 ± 28
12	17852 ± 21	17234 ± 26	17989 ± 21	14879 ± 27	19895 ± 29
16	18789 ± 28	18905 ± 27	18101 ± 18	15172 ± 28	20126 ± 24
20	19456 ± 24	19234 ± 29	18401 ± 21	15471 ± 21	22456 ± 21
	Ca				
0	8477 ± 14	8162 ± 14	7848 ± 16	7533 ± 17	9337 ± 15
4	8999 ± 12	9195 ± 16	10088 ± 24	8811 ± 18	9954 ± 16
8	9815 ± 21	10027 ± 27	11258 ± 25	10007 ± 26	10469 ± 27
12	10068 ± 25	10199 ± 28	11935 ± 24	10501 ± 29	10845 ± 28
16	10206 ± 26	10740 ± 32	12482 ± 23	10937 ± 21	10921 ± 29
20	11238 ± 21	11528 ± 22	12714 ± 21	11176 ± 24	11266 ± 24
	Mg				
0	6427 ± 11	6190 ± 17	5983 ± 12	5776 ± 19	7227 ± 18
4	6922 ± 12	6722 ± 15	7196 ± 11	6404 ± 21	7522 ± 19
8	7174 ± 14	7073 ± 12	7689 ± 15	6957 ± 12	7670 ± 15
12	7294 ± 16	7152 ± 16	7780 ± 16	7473 ± 14	7712 ± 17
16	7358 ± 14	7212 ± 18	8055 ± 17	7679 ± 16	7889 ± 18
20	7566 ± 15	7552 ± 19	8180 ± 18	7840 ± 18	7951 ± 14

*Mean ± SD, n = 3, $P < 0.05$

Similar to rotary drum composting of phumdi biomass, the concentration of the WS forms of the nutrients increased due to net loss in dry mass (Table 5.3.2). The WS nutrients increased in the range 11.4–67.6% for Na, 6.4–56.2% for K, 10.5–38.6% for Ca and 10.3–40.7% for Mg. As discussed before, these alkali earth metals having single or double positive charges (i.e. Na^+, K^+, Ca^{2+}, Mg^{2+}) are held weakly by exchangeable hydrated ions, or by electrostatic forces on charge humus carboxyl groups (Tan, 2010). The range of pH observed during *Salvinia natans* composting were in the range for the alkaline earth metals to exist mainly in soluble forms. Similar to pile composting of *Salvinia natans*, the highest increase of WS Ca after the drum composting of *Salvinia natans* was indicated in trial 2. The concentration of the WS nutrients is regulated by the net loss in dry mass and the formation of insoluble complexes. ANOVA showed significant differences in nutrients were observed between the trials ($P < 0.05$). The order of the concentration of WS nutrients of all trials was Ca > K > Mg > Na.

Table 5.3.2. Variation of WS Na, K, Ca and Mg during drum composting of *S. natans*

Days	WS nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	1361 ± 4	1276 ± 8	1192 ± 8	1108 ± 4	1545 ± 5
4	1432 ± 5	1371 ± 6	1402 ± 7	1176 ± 5	1565 ± 4
8	1435 ± 6	1405 ± 8	1784 ± 6	1490 ± 6	1585 ± 6
12	1448 ± 7	1508 ± 9	1769 ± 9	1487 ± 7	1646 ± 3
16	1578 ± 5	1587 ± 4	1892 ± 5	1519 ± 8	1707 ± 7
20	1605 ± 7	1679 ± 5	1998 ± 9	1580 ± 6	1721 ± 4
	K				
0	2750 ± 8	2444 ± 11	2137 ± 9	1831 ± 11	3352 ± 9
4	3000 ± 9	2543 ± 4	2457 ± 6	1878 ± 10	3502 ± 8
8	3101 ± 10	2594 ± 8	2873 ± 8	2243 ± 8	3505 ± 9
12	3033 ± 11	2954 ± 9	2987 ± 7	2231 ± 9	3536 ± 8
16	3130 ± 8	3106 ± 11	3235 ± 5	2412 ± 10	3584 ± 6
20	3169 ± 7	3243 ± 10	3338 ± 9	2514 ± 12	3567 ± 11
	Ca				
0	2993 ± 7	2916 ± 12	2840 ± 11	2764 ± 12	3255 ± 11
4	3112 ± 8	3012 ± 14	3450 ± 10	3219 ± 11	3471 ± 9
8	3177 ± 9	3890 ± 10	3810 ± 11	3318 ± 10	3478 ± 8
12	3679 ± 8	3850 ± 9	3980 ± 10	3567 ± 11	3475 ± 9
16	3723 ± 10	3973 ± 8	3780 ± 9	3467 ± 9	3501 ± 10
20	3879 ± 11	4042 ± 9	3789 ± 8	3398 ± 9	3598 ± 11
	Mg				
0	1808 ± 2	1697 ± 2	1587 ± 4	1476 ± 3	2056 ± 4
4	1875 ± 4	1820 ± 2	1901 ± 5	1659 ± 4	2119 ± 4
8	1914 ± 2	2069 ± 4	2127 ± 6	1988 ± 5	2117 ± 5
12	1989 ± 5	1989 ± 3	2081 ± 4	1812 ± 3	2049 ± 6
16	2014 ± 2	2120 ± 4	2189 ± 3	1810 ± 4	2125 ± 4
20	2124 ± 6	2234 ± 6	2232 ± 4	1890 ± 2	2268 ± 2

*Mean ± SD, n = 3, $P < 0.05$

5.3.4 TOTAL HEAVY METALS

Table 5.3.3 illustrates the variation of total concentration of Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr in all trials during the drum composting of *Salvinia natans*. Since no leaching or runoff took place, the heavy metals were concentrated during the composting process, due to net loss of dry mass (Ciavatta et al., 1993; Hsu and Lo, 2001). The highest increase in the total concentration of all heavy metals was also in trial 3. The order of concentration of the total heavy metals of the *Salvinia natans* compost was Fe > Mn > Pb > Ni > Zn > Cr > Cu > Cd indicating no change in the order of the concentration of the heavy metals when compared with pile composting of the same *Salvinia natans*. The increase in total concentration of heavy metals was higher after drum composting due to higher loss in dry mass. ANOVA analysis indicated that the variation amongst the trials was statistically significant ($P < 0.05$).

5.3.5 BIOAVAILABLE HEAVY METALS

5.3.5.1 WS heavy metals

The WS concentrations of heavy metals decreased in all trials after drum composting of *Salvinia natans* in the following order:

Zn: T4 (25.8%) > T3 (24.9%) > T5 (21.0%) > T2 (17.8%) > T1 (17.0%)
Cu: T4 (33.6%) > T3 (33.1%) > T2 (26.9%) > T1 (23.0%) > T5 (15.7%)
Mn: T3 (38.7%) > T4 (31.3%) > T2 (29.8%) > T1 (21.1%) > T5 (20.6%)
Fe: T3 (42.0%) > T2 (38.9%) > T4 (38.5%) > T1 (38.4%) > T5 (23.5%)
Pb: T3 (66.4%) > T4 (50.5%) > T2 (47.1%) > T1 (26.8%) > T5 (15.8%)
Cr: T3 (50.7%) > T4 (41.5%) > T2 (32.9%) > T1 (24.2%) > T5 (19.9%)

(Note: T–trial)

Metallic Cr has low water solubility and therefore, only a small portion of total Cr is bioavailable (Alloway, 1990; Harouna et al., 2009). The trivalent Cr(III) and hexavalent Cr(VI) forms of Cr exhibit amphotericity. Cr(III) forms insoluble oxides and hydroxides at neutral or basic pH (Ciavatta et al., 1993). The decrease of WS Fe in all five trials was due to the formation of insoluble organo-metallic complexes (Wong and Fang 2000). In water, $-COOH$ groups of humic and fulvic acids dissociate to form $-COO^-$ and H^+ with the organic molecule stretching out due to repulsion of the negative charges. When metal ions are then introduced into the system, humic and fulvic salts are formed and the negative charges become satisfied. The organic molecule then collapses on itself and may become insoluble (Talbot, 2006).

Table 5.3.3. Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *S. natans*

Days	Total heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	197 ± 1.5	190 ± 1.8	188 ± 1.9	183 ± 1.8	210 ± 1.9	252 ± 4.5	250 ± 4.5	248 ± 4.5	246 ± 4.5	266 ± 4.5
6	206 ± 1.7	202 ± 1.9	198 ± 1.8	190 ± 1.7	216 ± 1.9	265 ± 4.5	265 ± 3.0	269 ± 2.5	272 ± 4.5	278 ± 2.3
12	211 ± 1.9	208 ± 1.7	212 ± 1.7	210 ± 1.7	223 ± 1.8	282 ± 3.5	280 ± 1.5	278 ± 2.5	279 ± 3.5	304 ± 5.3
18	216 ± 1.7	220 ± 1.6	233 ± 1.8	228 ± 1.6	229 ± 1.5	292 ± 2.0	289 ± 1.5	290 ± 2.5	291 ± 3.5	308 ± 3.0
24	222 ± 1.9	227 ± 1.8	254 ± 1.9	232 ± 1.5	233 ± 1.7	307 ± 2.5	301 ± 3.0	323 ± 4.5	307 ± 2.0	316 ± 1.0
30	234 ± 1.7	238 ± 1.7	264 ± 1.8	245 ± 1.9	239 ± 1.6	316 ± 3.0	318 ± 3.0	332 ± 2.5	320 ± 2.5	319 ± 2.0
	Cu					**Pb**				
0	50.5 ± 0.5	50.0 ± 0.5	49.5 ± 0.4	48.9 ± 0.4	53.8 ± 0.3	627 ± 2	568 ± 3	508 ± 2	449 ± 3	756 ± 2
6	59.8 ± 0.3	51.8 ± 0.6	58.8 ± 0.4	53.0 ± 0.6	55.9 ± 0.4	644 ± 2	580 ± 7	549 ± 11	498 ± 4	771 ± 12
12	64.3 ± 0.3	57.9 ± 0.9	63.1 ± 0.3	62.0 ± 0.6	58.2 ± 0.3	682 ± 3	633 ± 8	606 ± 5	520 ± 6	791 ± 10
18	67.8 ± 0.8	71.1 ± 0.1	71.1 ± 0.6	73.0 ± 0.5	65.0 ± 0.5	700 ± 3	664 ± 8	618 ± 4	528 ± 4	840 ± 6
24	68.5 ± 0.5	77.0 ± 0.1	77.4 ± 0.4	75.2 ± 0.3	67.5 ± 0.4	719 ± 2	675 ± 4	639 ± 3	551 ± 4	845 ± 11
30	70.0 ± 0.5	78.9 ± 0.5	79.5 ± 0.5	78.0 ± 1.0	68.2 ± 0.4	738 ± 7	699 ± 8	681 ± 11	570 ± 8	862 ± 4
	Mn					**Cd**				
0	865 ± 10	818 ± 11	771 ± 11	724 ± 11	998 ± 11	55 ± 0.8	54 ± 0.5	53 ± 0.6	54 ± 0.5	54 ± 0.8
6	939 ± 5	927 ± 6	975 ± 5	800 ± 6	1106 ± 11	59 ± 0.7	68 ± 0.5	64 ± 0.2	61 ± 0.5	56 ± 0.6
12	996 ± 3	972 ± 7	1052 ± 7	844 ± 10	1132 ± 8	67 ± 0.3	70 ± 0.5	67 ± 0.9	63 ± 0.5	57 ± 0.3
18	1019 ± 5	1004 ± 6	1093 ± 6	873 ± 6	1173 ± 6	69 ± 0.7	72 ± 0.8	72 ± 0.5	67 ± 0.4	58 ± 0.3
24	1055 ± 11	1020 ± 5	1120 ± 4	941 ± 7	1218 ± 5	71 ± 0.2	75 ± 1.1	74 ± 0.3	71 ± 0.3	61 ± 0.5
30	1101 ± 10	1102 ± 4	1150 ± 5	982 ± 6	1226 ± 5	72 ± 0.3	77 ± 1.0	76 ± 0.3	73 ± 0.5	64 ± 0.9
	Fe					**Cr**				
0	5925 ± 50	5436 ± 50	4946 ± 50	4457 ± 50	6755 ± 50	128 ± 2.2	126 ± 2.3	124 ± 1.9	123 ± 2.5	143 ± 2.4
6	6162 ± 39	5755 ± 46	5811 ± 13	5036 ± 28	6995 ± 17	133 ± 3.1	132 ± 2.4	130 ± 1.8	131 ± 2.6	150 ± 2.1
12	6594 ± 51	6132 ± 14	6277 ± 32	5240 ± 6	7225 ± 10	139 ± 3.2	151 ± 1.9	153 ± 2.1	149 ± 3.5	155 ± 2.1
18	6832 ± 48	6675 ± 41	6761 ± 38	5740 ± 6	7410 ± 12	154 ± 3.4	163 ± 1.9	181 ± 1.5	164 ± 3.5	161 ± 2.4
24	6900 ± 25	7001 ± 12	6870 ± 25	5839 ± 35	7635 ± 11	166 ± 2.1	177 ± 2.2	187 ± 2.4	179 ± 2.2	179 ± 1.9
30	7120 ± 95	7085 ± 25	6897 ± 18	5872 ± 18	7803 ± 18	180 ± 2.3	190 ± 2.4	199 ± 1.5	187 ± 3.4	189 ± 2.4

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Table 5.3.4. Variation of WS fraction of Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *S. natans*

Days	WS heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	13.0 ± 0.3	12.1 ± 0.1	11.3 ± 0.3	10.5 ± 0.1	14.8 ± 0.4	–	–	–	–	–
6	12.7 ± 0.3	12.0 ± 0.1	10.7 ± 0.2	10.2 ± 0.2	14.4 ± 0.4	–	–	–	–	–
12	12.0 ± 0.2	12.0 ± 0.1	11.7 ± 0.1	10.7 ± 0.1	13.0 ± 0.1	–	–	–	–	–
18	11.1 ± 0.1	11.3 ± 0.1	10.1 ± 0.1	10.3 ± 0.1	13.3 ± 0.1	–	–	–	–	–
24	10.9 ± 0.1	9.8 ± 0.2	9.2 ± 0.2	8.2 ± 0.2	12.0 ± 0.1	–	–	–	–	–
30	10.8 ± 0.1	9.9 ± 0.1	8.5 ± 0.1	7.8 ± 0	11.7 ± 0.2	–	–	–	–	–
	Cu					**Pb**				
0	7.0 ± 0.15	6.6 ± 0.15	6.2 ± 0.10	5.8 ± 0.10	8.0 ± 0.15	7.9 ± 0.07	6.9 ± 0.07	5.9 ± 0.08	5 ± 0.05	9.9 ± 0.09
6	6.8 ± 0.10	6.5 ± 0.15	6.6 ± 0.15	6.0 ± 0.05	8.0 ± 0.15	7.8 ± 0.08	6.8 ± 0.1	6.1 ± 0.05	5.1 ± 0.05	9.7 ± 0.09
12	5.9 ± 0.05	5.8 ± 0.05	6.3 ± 0.05	6.0 ± 0.05	7.5 ± 0.10	7.6 ± 0.09	6.5 ± 0.09	5.9 ± 0.05	5.3 ± 0.10	9.7 ± 0.05
18	5.7 ± 0.05	5.3 ± 0.10	6.0 ± 0.05	4.8 ± 0.05	7.1 ± 0.10	7.0 ± 0.08	6.0 ± 0.09	3.0 ± 0.08	4.2 ± 0.07	9.4 ± 0.05
24	5.5 ± 0.05	5.1 ± 0.05	5.7 ± 0.05	4.2 ± 0.05	7.0 ± 0.05	6.1 ± 0.09	4.5 ± 0.08	2.1 ± 0.06	3.0 ± 0.09	8.9 ± 0.05
30	5.4 ± 0.05	4.8 ± 0.11	4.2 ± 0.05	3.9 ± 0.05	6.7 ± 0.10	5.8 ± 0.08	3.7 ± 0.04	2.0 ± 0.08	2.5 ± 0.08	8.3 ± 0.10
	Mn					**Cd**				
0	48.8 ± 1.0	45.4 ± 1.1	42.0 ± 0.5	38.6 ± 1.1	55.5 ± 0.1	–	–	–	–	–
6	45.5 ± 0.5	41.0 ± 1.3	36.5 ± 0.5	35.5 ± 0.5	54.7 ± 0.4	–	–	–	–	–
12	43.5 ± 0.5	40.0 ± 1.3	36.5 ± 0.5	38.5 ± 0.5	51.8 ± 0.4	–	–	–	–	–
18	41.5 ± 0.5	38.5 ± 3.5	31.5 ± 0.5	30.5 ± 0.5	50.6 ± 0.6	–	–	–	–	–
24	39.5 ± 0.5	33.5 ± 0.5	26.5 ± 0.5	27.5 ± 0.5	48.3 ± 0.6	–	–	–	–	–
30	38.5 ± 0.5	31.9 ± 0.4	25.7 ± 0.5	26.5 ± 0.5	44.1 ± 0.2	–	–	–	–	–
	Fe					**Cr**				
0	241 ± 4.5	228 ± 4.5	215 ± 4.5	202 ± 4.5	269 ± 4.5	28.3 ± 0.4	25.4 ± 0.1	23.4 ± 0.4	20.4 ± 0.5	34.4 ± 0.4
6	223 ± 5.5	212 ± 3.5	188 ± 3.4	193 ± 5.5	264 ± 6.0	27.3 ± 0.3	26.9 ± 0.1	25.3 ± 0.1	21.9 ± 0.3	33.7 ± 0.1
12	212 ± 2.9	203 ± 4.0	182 ± 4.5	203 ± 4.0	253 ± 3.0	24.9 ± 0.1	26.7 ± 0.4	24.4 ± 0.2	20.6 ± 0.2	32.4 ± 0.3
18	195 ± 3.0	193 ± 5.5	158 ± 2.6	184 ± 5.5	241 ± 2.0	23.3 ± 0.1	23.6 ± 0.2	18.0 ± 0.6	15.1 ± 0.5	31.5 ± 0.3
24	173 ± 4.6	141 ± 4.2	132 ± 3.0	145 ± 4.6	223 ± 3.0	22.5 ± 0.3	17.7 ± 0.3	12.0 ± 0.5	12.4 ± 0.4	30.0 ± 0.1
30	148 ± 3.2	139 ± 4.5	124 ± 4.0	124 ± 4.2	206 ± 4.5	21.4 ± 0.4	17.1 ± 0.2	11.5 ± 0.6	11.9 ± 0.5	27.5 ± 0.3

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Composting modified and substantially reduced the solubility of Pb with a consequent redistribution of its WS fraction into more stable fractions by binding with the organic substance (Castaldi et al., 2006). WS Ni and Cd contents were not detected at all in the *Salvinia natans* biomass. WS Ni and Cd were also not detected during composting of water hyacinth (Singh and Kalamdhad, 2013). Castaldi et al. (2006) reported presence of WS Pb and Cd (0.89 and 0.005 mg/kg dry matter, respectively) in the mature compost of municipal solid waste. Sims and Kline (1991) also reported WS Ni (7.2% of total Ni) during sewage sludge composting. The order of WS metal concentration in the composted *Salvinia natans* biomass was Fe > Mn > Cr > Zn > Pb > Cu. The variation in the concentration of WS Zn, Cu, Fe, Cr, Mn and Pb among all trials was statistically significant ($P < 0.05$).

5.3.5.2 DTPA extractable heavy metals

The DTPA fraction of heavy metals showed steady decrease during the drum composting of *Salvinia natans* (Table 5.3.5). The DTPA fraction of heavy metals reduced in the following order:

Zn: T3 (26.6%) > T4 (26.0%) > T2 (19.9%) > T1 (19.0%) > T5 (12.0%)
Cu: T3 (45.0%) > T4 (40.5%) > T2 (38.7%) > T1 (31.3%) > T5 (16.4%)
Mn: T3 (26.0%) > T4 (23.3%) > T2 (21.1%) > T1 (19.4%) > T5 (14.7%)
Fe: T3 (39.7%) > T2 (32.8%) > T3 (32.4%) > T1 (31.3%) > T5 (26.6%)
Ni: T3 (54.7%) > T4 (35.9%) > T2 (30.8%) > T1 (24.4%) > T5 (14.0%)
Pb: T3 (67.2%) > T4 (42.2%) > T2 (41.6%) > T1 (28.6%) > T5 (17.8%)
Cr: T3 (56.7%) > T4 (53.4%) > T2 (49.2%) > T1 (24.3%) > T5 (20.1%)

(Note: T–trial)

Dissolution of the organic compounds, cation exchange and complexation by organic ligands controls Zn mobility regulating the concentration of DTPA fraction of Zn (Kumpiene et al., 2008). The DTPA fraction of Cu also decreased due to humic acid forming complexes with Cu. The stability constant of metal-humic complexes depend on the nature of organics, metal, as well as other factors such as ion strength and pH of the environment (Liu et al., 2008). Changes in pH alter the extent to which the –COOH groups dissociate and also effects hydrolysis of metal ions with increasing pH leads to increasing hydrolysis (Talbot, 2006). Lesser reduction of DTPA metals in trial 5 can also be explained as complexation capacity of a humic acid is low if salinity is high (Talbot, 2006). The order of plant available metal content in the composted phumdi biomass was

Table 5.3.5. Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *S. natans*

Days	DTPA extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	85.1 ± 0.7	79.8 ± 0.9	74.6 ± 0.5	69.2 ± 0.4	96.6 ± 0.4	14.6 ± 0.05	13.7 ± 0.05	12.6 ± 0.05	11.6 ± 0.01	17.6 ± 0.15
6	81.9 ± 0.5	77.7 ± 0.3	71.6 ± 0.5	66.9 ± 0.1	96.2 ± 0.2	14.4 ± 0.05	13.5 ± 0.05	12.2 ± 0.05	11.4 ± 0.02	17.4 ± 0.03
12	76.2 ± 0.2	71.9 ± 0.1	67.1 ± 0.3	60.2 ± 0.2	94.8 ± 0.3	14.2 ± 0.05	12.7 ± 0.05	11.5 ± 0.05	10.9 ± 0.01	17 ± 0.05
18	77.6 ± 0.4	72.7 ± 0.3	68.2 ± 0.2	61.8 ± 0.3	90.6 ± 0.4	13.4 ± 0.05	12.1 ± 0.05	10.3 ± 0.05	10 ± 0.06	16.5 ± 0.05
24	71.9 ± 0.1	67.8 ± 0.4	64.5 ± 0.5	55.2 ± 0.4	86.7 ± 0.3	12.7 ± 0.05	10.1 ± 0.05	6.1 ± 0.02	8.1 ± 0.01	16.2 ± 0.06
30	68.9 ± 0.1	63.9 ± 0.1	54.7 ± 0.3	50.9 ± 0.4	85.1 ± 0.5	11.0 ± 0.15	9.5 ± 0.05	5.7 ± 0.05	7.4 ± 0.03	15.1 ± 0.1
	Cu					**Pb**				
0	9.1 ± 0.10	8.9 ± 0.05	8.6 ± 0.05	8.3 ± 0.15	9.8 ± 0.15	25.2 ± 0.45	22.1 ± 0.45	18.9 ± 0.15	15.8 ± 0.25	31.5 ± 0.24
6	8.5 ± 0.10	8.3 ± 0.10	9.8 ± 0.45	7.3 ± 0.10	9.3 ± 0.10	23.1 ± 0.15	21.3 ± 0.10	19.3 ± 0.15	16.2 ± 0.15	29.3 ± 0.10
12	9.0 ± 0.05	8.4 ± 0.05	7.0 ± 0.17	7.8 ± 0.15	8.5 ± 0.10	22.0 ± 0.1	19.0 ± 0.10	15.9 ± 0.15	13.1 ± 0.20	30.2 ± 0.20
18	8.0 ± 0.10	7.3 ± 0.10	5.3 ± 0.32	6.4 ± 0.05	8.8 ± 0.10	20.2 ± 0.25	16.1 ± 0.10	7.9 ± 0.10	11.5 ± 0.10	27.5 ± 0.10
24	6.8 ± 0.20	6.2 ± 0.05	5.6 ± 0.20	5.5 ± 0.05	8.5 ± 0.05	18.9 ± 0.15	14 ± 0.05	7 ± 0.05	10.2 ± 0.05	26.9 ± 0.05
30	6.3 ± 0.15	5.4 ± 0.02	4.7 ± 0.10	4.9 ± 0.09	8.2 ± 0.05	18 ± 0.05	12.9 ± 0.05	6.2 ± 0.05	9.1 ± 0.05	25.9 ± 0.15
	Mn					**Cd**				
0	209 ± 3.5	208 ± 3.5	208 ± 1.5	204 ± 4	221 ± 3.5	–	–	–	–	–
6	210 ± 2	205 ± 5	199 ± 0.5	198 ± 0.5	218 ± 2.5	–	–	–	–	–
12	199 ± 1.5	209 ± 2	202 ± 2	204 ± 2.5	205 ± 3.5	–	–	–	–	–
18	187 ± 2.5	197 ± 2	172 ± 4.5	182 ± 3.5	202 ± 2	–	–	–	–	–
24	172 ± 2	171 ± 3	160 ± 0.5	170 ± 0.5	195 ± 2.5	–	–	–	–	–
30	168 ± 4	164 ± 4.15	154 ± 4.5	157 ± 4.5	188 ± 3	–	–	–	–	–
	Fe					**Cr**				
0	311 ± 4.5	315 ± 4.5	324 ± 0.5	323 ± 4.0	315 ± 4.5	41.6 ± 1.1	37.8 ± 1.1	34.5 ± 0.5	30.3 ± 0.8	50.3 ± 1.1
6	246 ± 5	241 ± 0.3	264 ± 2.0	283 ± 4.0	295 ± 6.0	40.2 ± 0.8	39.5 ± 0.5	35.4 ± 0.4	31.0 ± 1.0	49.2 ± 0.8
12	248 ± 4.1	245 ± 4.6	270 ± 2.9	294 ± 3.5	289 ± 2.0	39.5 ± 0.5	40.0 ± 1.0	30.5 ± 0.5	29.9 ± 0.1	46.6 ± 0.4
18	234 ± 9.9	225 ± 3.5	225 ± 5.1	260 ± 4.0	260 ± 1.0	37.5 ± 0.5	27.5 ± 0.5	25.5 ± 0.5	18.7 ± 0.7	45.2 ± 0.2
24	227 ± 4.3	220 ± 0.5	201 ± 3.0	227 ± 2.9	240 ± 1.0	35.5 ± 0.5	21.2 ± 0.2	16.0 ± 0.4	15.4 ± 0.2	41.8 ± 0.3
30	216 ± 4.7	212 ± 2.5	195 ± 1.0	219 ± 4.5	231 ± 3.0	31.5 ± 0.5	19.2 ± 0.2	15.0 ± 0.3	14.1 ± 0.1	40.2 ± 0.2

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Fe > Mn > Zn > Cr > Pb > Ni > Cu of the composts. ANOVA analysis showed that the variation of DTPA extractable Zn, Cu, Mn, Fe, Ni and Cr were statistically significant ($P < 0.05$) for all trials.

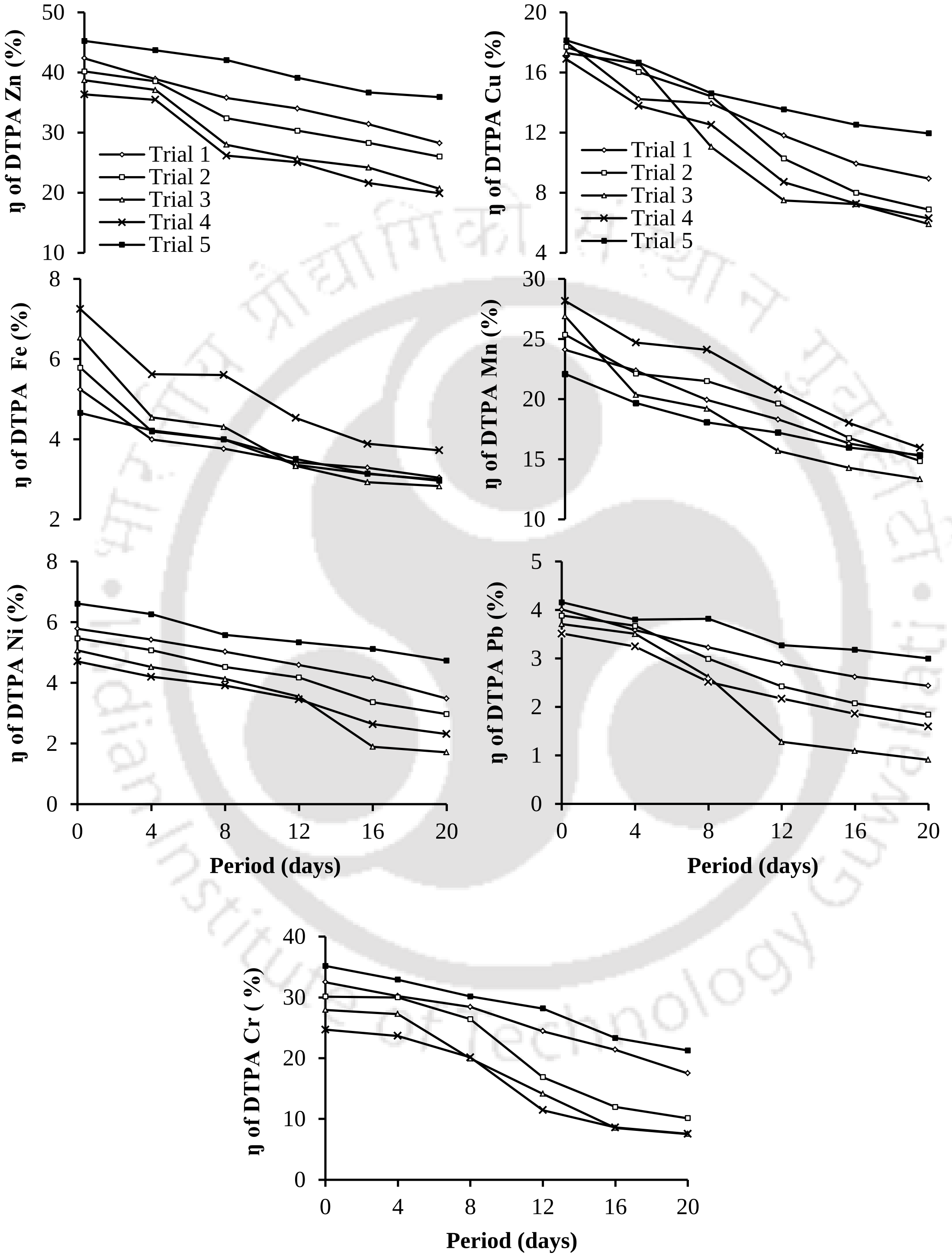

Fig. 5.3.5. Variation of “ŋ” of DTPA extractable heavy metals during drum composting of *Salvinia natans*.

The final “ŋ” of the DTPA extractable heavy metals of *Salvinia natans* composts after drum composting were in the range 20.7–35.6% for Zn, 6.0–12.0% for Cu,

Table 5.3.6. Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during drum composting of *S. natans*

Days	TCLP extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	112.4 ± 1.3	104.5 ± 0.5	97.0 ± 1.0	89.3 ± 0.3	129.2 ± 0.8	165 ± 1.5	144 ± 2.5	124 ± 2.5	104 ± 2.5	206 ± 4.5
6	104.0 ± 0.3	101.4 ± 1.0	97.4 ± 0.6	90.9 ± 0.5	126.5 ± 0.5	161 ± 1.0	133 ± 1.5	118 ± 0.5	95 ± 1.0	197 ± 1.0
12	99.9 ± 0.1	99.4 ± 0.4	90.7 ± 0.5	92.1 ± 0.3	119.8 ± 0.3	158 ± 1.0	119 ± 1.5	103 ± 1.0	92 ± 1.0	185 ± 2.5
18	96.9 ± 0.5	90.8 ± 0.3	88.7 ± 0.5	87.3 ± 0.6	121.5 ± 0.5	151 ± 1.0	114 ± 1.0	96 ± 1.5	89 ± 0.5	180 ± 1.0
24	93.7 ± 0.4	87.0 ± 0.5	76.2 ± 0.3	73.9 ± 0.4	117.8 ± 0.2	143 ± 1.5	105 ± 0.5	88 ± 1.0	79 ± 1.0	177 ± 0.5
30	92.5 ± 0.5	86.2 ± 0.3	71.8 ± 0.6	70.9 ± 0.5	115.5 ± 0.5	135 ± 0.5	102 ± 0.5	85 ± 0.5	75 ± 1.0	172 ± 2.0
	Cu					**Pb**				
0	20.1 ± 0.2	18.7 ± 0.2	17.3 ± 0.1	15.8 ± 0.2	23.1 ± 0.2	53.2 ± 0.4	46.5 ± 0.6	40.2 ± 0.3	34.2 ± 0.3	65.1 ± 0.5
6	19.3 ± 0.2	15.9 ± 0.2	13.5 ± 0.5	14.8 ± 0.2	22.0 ± 0.5	50.1 ± 0.4	49.3 ± 0.5	41.1 ± 0.3	36.3 ± 0.3	57.4 ± 0.8
12	18.8 ± 0.1	16.7 ± 0.3	13.6 ± 0.2	15.3 ± 0.1	20.0 ± 0.2	48.2 ± 0.6	44.2 ± 0.6	35.3 ± 1.0	35.6 ± 0.5	53.6 ± 0.7
18	16.9 ± 0.5	14.9 ± 0.1	11.6 ± 0.1	14.4 ± 0.3	21.3 ± 0.4	46.1 ± 0.4	44.4 ± 0.5	31.1 ± 0.4	29.2 ± 0.1	52.7 ± 0.5
24	15.3 ± 0.5	14.0 ± 0.1	10.8 ± 0.5	12.8 ± 0.1	19.7 ± 0.4	42.1 ± 0.3	38.2 ± 0.4	23.4 ± 0.1	24.4 ± 0.1	49.2 ± 0.5
30	15.0 ± 0.4	13.3 ± 0.2	11.0 ± 0.5	11.2 ± 0.5	18.6 ± 0.2	40.4 ± 0.3	33.4 ± 0.5	23.1 ± 0.2	23.1 ± 0.1	53.1 ± 0.3
	Mn					**Cd**				
0	294 ± 5.0	310 ± 5.0	326 ± 5.0	344 ± 3.5	290 ± 5.0	2.4 ± 0.01	2.2 ± 0.02	2.1 ± 0.04	2.0 ± 0.03	2.4 ± 0.02
6	283 ± 4.5	300 ± 2.5	299 ± 1.5	332 ± 7.5	288 ± 6.0	2.4 ± 0.01	2.2 ± 0.03	2.1 ± 0.02	2.0 ± 0.03	2.4 ± 0.02
12	260 ± 5.5	283 ± 4.5	281 ± 6.5	338 ± 4.0	283 ± 4.5	2.2 ± 0.04	1.7 ± 0.02	1.6 ± 0.05	1.6 ± 0.05	2.4 ± 0.01
18	241 ± 4.5	261 ± 4.5	261 ± 4.5	308 ± 2.5	300 ± 1.0	2.1 ± 0.05	1.6 ± 0.01	1.2 ± 0.01	1.4 ± 0.02	2.3 ± 0.01
24	228 ± 3.0	243 ± 2.5	241 ± 1.5	258 ± 4.0	260 ± 5.5	1.9 ± 0.01	1.4 ± 0.01	1.0 ± 0.03	1.1 ± 0.02	2.0 ± 0.01
30	226 ± 3.5	232 ± 4.0	228 ± 5.0	248 ± 3.5	240 ± 5.0	1.8 ± 0.01	1.4 ± 0.01	1.0 ± 0.01	1.1 ± 0.01	1.8 ± 0.02
	Fe					**Cr**				
0	426 ± 4.5	411 ± 4.5	396 ± 4.5	381 ± 4.5	475 ± 4.5	55.0 ± 1.0	49.3 ± 0.8	44.5 ± 0.5	39.1 ± 0.4	66.5 ± 1.1
6	354 ± 5.0	394 ± 4.0	385 ± 2.5	360 ± 6.0	423 ± 6.5	54.5 ± 0.5	48.4 ± 0.6	46.5 ± 0.5	42.0 ± 0.6	63.8 ± 0.5
12	357 ± 5.5	382 ± 5.5	390 ± 2.2	370 ± 1.5	404 ± 6.0	52.0 ± 1.0	40.6 ± 0.6	40.7 ± 0.7	39.1 ± 0.4	64.4 ± 0.3
18	339 ± 1.5	337 ± 4.5	341 ± 4.5	330 ± 6.0	400 ± 1.0	47.5 ± 0.5	35.2 ± 0.4	31.7 ± 0.7	35.3 ± 0.9	59.6 ± 0.4
24	327 ± 2.5	310 ± 2.5	281 ± 6.0	270 ± 4.5	396 ± 2.0	42.5 ± 0.5	33.1 ± 0.3	28.0 ± 0.2	30.6 ± 0.6	54.6 ± 0.4
30	317 ± 4.5	283 ± 4.5	262 ± 5.5	241 ± 6.5	382 ± 2.5	39.5 ± 0.5	30.6 ± 0.7	25.2 ± 0.4	25.5 ± 0.5	51.8 ± 0.6

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

13.4–16.0% for Mn, 2.8–3.7% for Fe, 1.7–4.7% for Ni, 0.9–3.1% for Pb and 7.5–21.3% for Cr. The intermittent increase of “ŋ” indicated during drum composting of phumdi biomass was not indicated during the drum composting of *Salvinia natans*. The differences of “ŋ” after the drum composting and pile composting of *Salvinia natans* for all heavy metals were not significant ($P > 0.05$).

5.3.5.3 TCLP extractable heavy metals

Table 5.3.6 illustrates the changes in leachable Zn, Cu, Mn, Fe, Ni, Cd, Pb and Cr concentration during the drum composting period of *Salvinia natans*. The concentrations of TCLP extractable forms of heavy metals decreased after the drum composting process in the following order:

Zn: T3 (25.9%) > T4 (20.6%) > T1 (17.7%) > T2 (17.6%) > T5 (10.6%)

Cu: T3 (36.5%) > T4 (29.2%) > T2 (29.0%) > T1 (25.2%) > T5 (19.5%)

Mn: T3 (30.1%) > T4 (27.9%) > T2 (25.2%) > T1 (23.3%) > T5 (17.2%)

Fe: T4 (36.8%) > T3 (33.9%) > T2 (31.2%) > T1 (25.6%) > T5 (19.6%)

Ni: T3 (31.6%) > T2 (29.3%) > T4 (27.5%) > T1 (18.2%) > T5 (16.3%)

Pb: T3 (43.3%) > T4 (32.1%) > T2 (30.0%) > T1 (23.4%) > T5 (18.3%)

Cd: T3 (53.7%) > T4 (42.2%) > T2 (35.2%) > T1 (25.5%) > T5 (23.0%)

Cr: T3 (43.3%) > T2 (38.0%) > T2 (34.7%) > T1 (28.2%) > T5 (22.1%)

(Note: T–trial)

Cu, Mn and Zn complexed with OM or humic substances of compost. During the first phase, the low pH values caused weak adsorption onto OM of Cu and Zn and leached out with the TCLP extract (Lazzari et al., 2000). This explains the initial increase in the leachable fraction of the metals in some of the trials during the drum composting of *Salvinia natans*. The reduction of leachable fraction of Zn and Cu during composting process was consistent with other finding (Chiang et al., 2007). In general the organo-metallic complexes follow the Irwing William series: Cu > Pb > Zn > Cd > Fe (Nomeda et al., 2008). Cr(III) has an electron configuration closest to a noble gas with a high spherical symmetry and low polarization capacity. It has a valency of three and therefore it has a stronger electrostatic affinity for the sorption sites than divalent cations. Consequently it forms the most stable complex with humic substances (Qiao and Ho, 1997). The influence of pH on trace element solubility is well known. Either through solubility equilibria, or due to complexation by soluble and surface ligands, increasing pH, within an ordinary range, decreases solubility and bioavailability of divalent trace metals (Cambier and Charlatchka, 1999). Chiang et al. (2007) also reported reduction of Ni with increase in composting time. The pH of *Salvinia natans* compost also affected the solubility of the metal hydroxides and carbonates, and the lower pH values increased the solubility of heavy metals resulting enhanced leachability of metals (Qiao and Ho, 1997). Pb is the least mobile heavy metal under reducing and non-acidic condition (Lazzari et al., 2000). Leachable Pb, Cd and Cr were also detected during the composting of water hyacinth in the range of 1.0–6.8% of total Pb, 1.4–23.6% of total Cd and 7.5–23.7% of total Cr, respectively (Singh and Kalamdhad, 2013a). On analyzing the results by ANOVA, significant differences in leachable fraction of Mn, Fe, Zn, Cu, Cd, Pb, Ni and Cr were observed between all the trials ($P < 0.05$).

5.4 VERMICOMPOSTING OF *SALVINIA NATANS*

5.4.1 EARTHWORM BIOMASS

The variation of the number of earthworms, hatchings, cocoons and total earthworm biomass during the vermicomposting of *Salvinia natans* with earthworm *Eisenia fetida* are shown at Fig. 5.4.1. The total number of earthworms (clitellated and young non-clitellated) initially decreased in all trials. The number of earthworms were found increased on day 45 in trial 2 (206±1), trial 3 (235±2) and trial 4 (242±4) and no mortality was indicated in trial 3 and trial 4 during the process. Trial 4 substrate had the highest proportion of cattle manure containing easily metabolizable OM and non-assimilated carbohydrates essential for the growth and reproduction of earthworms (Gupta et al. 2007). The growth of the earthworms is also related to the palatability, nutrient pool and microbial populations of the feed (Fleggel and Schredder, 2000; Suther, 2008). The high mortality in trial 5 indicates that *Salvinia natans* without proper amendments is not suitable for vermicomposting. The cocoon population was seen during the monitoring of the reactors on day 15. The highest number of cocoons was also observed on day 30 in trial 4 (105±5) followed by trial 3 (90±1). The decrease in the total number of cocoons on day 45 in trial 2, 3 and 4 was due to the hatching of the cocoons. The production of cocoons in different feed mixtures is also related to the biochemical quality of the feed and the microbial mass and decomposition activities (Flack and Hartenstein, 1984; Suther, 2007). Few new hatchings were first observed during monitoring on day 30 in all trials and the highest number of hatchings was in trial 4 (203±5) followed by trial 3 (173±6) on day 45. The highest increase of total biomass was in trial 4 (302.2 g) followed by trial 3 (232.0 g) on day 45. In trial 4, the highest total biomass growth rate was from day 30 to 45 (7.4 g/day) similar to vermicomposting of phumdi biomass. The total biomass growth rate was comparatively lower from day 0 to 30 (6.8 g/day) due to the energy consumed by the adult earthworms for production of cocoons which otherwise would have been utilized for tissue growth (Chaudhari and Bhattacharjee, 2002; Kale et al., 1982). The highest net total biomass growth rate from day 0 to 45 was in trial 4 (4.5 g/day) followed by trial 3 (2.9 g/day). Therefore, the growth and fecundity was dependent on the cattle manure proportions of the substrates. The rate of growth of the earthworms, their increase in population as well as fecundity is an indicator of the suitability for vermicomposting of the substrates (Chaudhari and Bhattacharjee, 2002). ANOVA analysis indicated that the variation of the number of earthworms, cocoons and hatchings and the total earthworm biomass of all trials were significant ($P < 0.05$).

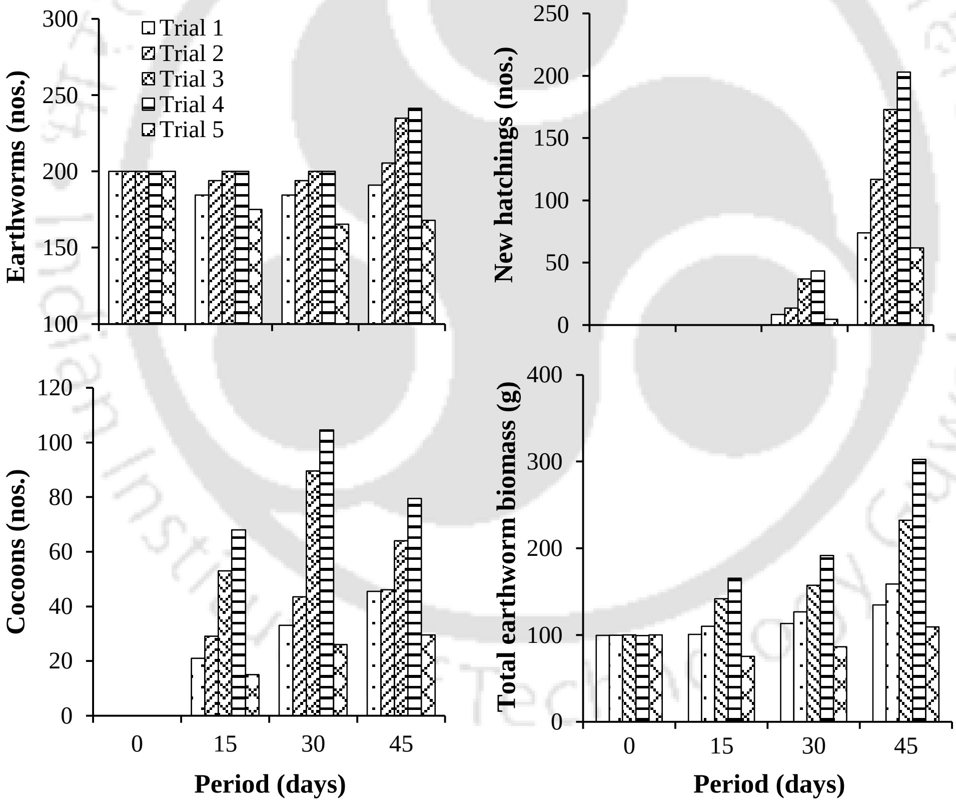

Fig. 5.4.1. Variations in the no. of earthworms, cocoons, hatchings and earthworm biomass during vermicomposting of *Salvinia natans*

5.4.2 PHYSICO-CHEMICAL AND BIO-CHEMICAL PARAMETERS

Similar to phumdi biomass vermicomposting, the pH increased in all trials after the vermicomposting process (Fig. 5.4.2a). On day 45, the highest pH was in trial 4 (7.61) followed by trial 3 (7.43). There was initial decrease in pH in some of the trials which could be attributed to the production of CO_2, ammonia, NO_3^- and organic acid by the associated microbial decomposition during vermicomposting process, which lower the pH (Suther, 2007). ANOVA test showed that the variation of pH among the trials was significant ($P < 0.05$).

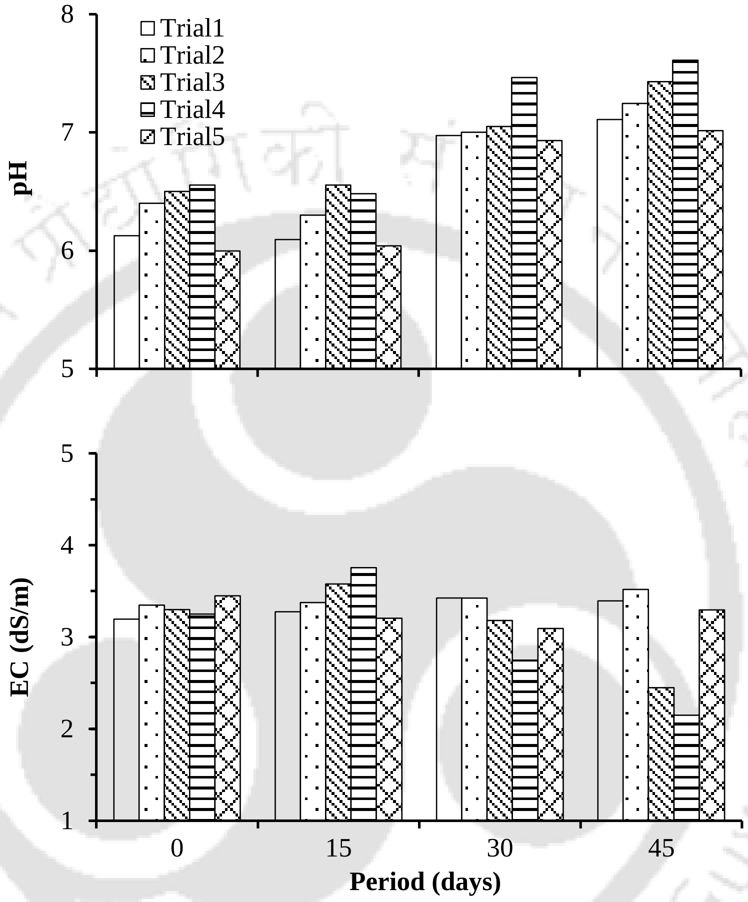

Fig. 5.4.2 a. Variation of pH during vermicomposting of *Salvinia natans*
b. Variation of EC during vermicomposting of *Salvinia natans*

The EC of trial 1 and 2 increased from 3.2 and 3.35 to 3.44 and 3.52 dS/m on day 45, respectively (Fig. 5.4.2b). The increase of EC was due to loss of OM and release of different mineral salts in available forms such as phosphate, ammonium, potassium, etc. (Garg et al., 2006). The EC of trial 5 decreased from 3.45 dS/m to 3.30 dS/m during the process indicating the slow mineralization process of the trial 5 feedstock. The EC of trial 3 and 4 after an initial increase from 3.30 and 3.25 dS/m to 3.58 and 3.76 dS/m decreased to 2.45 and 2.15 dS/m, respectively. The precipitation of mineral salts could be the reason for the final decrease in EC and that corroborated with the increased pH. The increase of pH was also reported by Vig et al. (2011). The change in the availability of cations or anions with pH may also affect metal mobility and availability through competitive sorption and complexation reactions (Sizmur and Hodson, 2009). ANOVA test indicated significant difference in the variation of pH and EC among all trials ($P <$ 0.05).

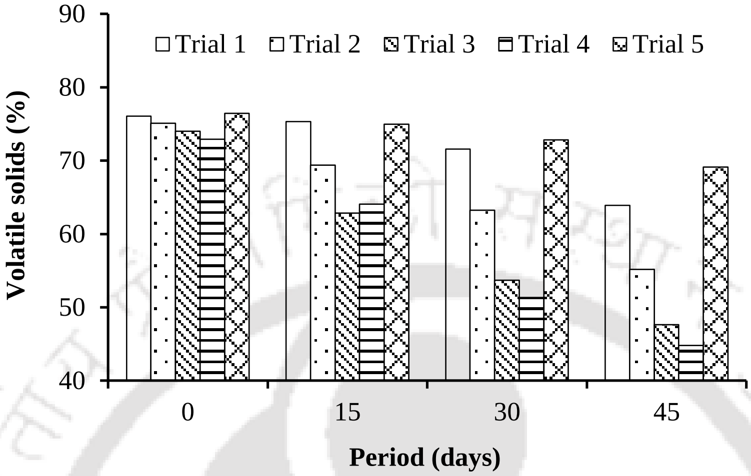

Fig. 5.4.2c. Variation of VS during vermicomposting of *Salvinia natans*

The VS concentration decreased during the vermicomposting process (Fig. 5.4.2c). The loss of VS after the process was in the order trial 4 (38.6%) > trial 3 (35.6%) > trial 2 (26.5%) > trial 1 (16.0%) > trial 5 (9.5%). Trial 4 had the highest proportion of cattle manure containing fungal stains and greater population of other microbes, such as bacteria, protozoa, nematodes, fungi, actinomycetes, etc. that played an important role in OM decomposition by providing extracellular enzymes in the reactors (Suther et al., 2012). The results were consistent with the findings during vermicomposting of water hyacinth (Singh and Kalamdhad, 2013a). The reduction trend of VS was also in agreement with the growth profile of the *Eisenia fetida* (Fig. 5.4.1). The difference in variation of VS among all trials was statistically significant ($P < 0.05$).

The variation of soluble BOD during the vermicomposting process of *Salvinia natans* is shown at Fig. 5.4.2d. The soluble BOD decreased after the vermicomposting process of *Salvinia natans* in all trials in the following order: Trial 4 (82.3%) > Trial 3 (79.1%) > Trial 2 (76.1%) > Trial 1 (72.7%) > Trial 5 (50.4%). The trend of reduction of soluble BOD was also in agreement with the highest earthworm biomass in trial 4. ANOVA analysis indicated that the variation of soluble BOD concentration during the vermicomposting of *Salvinia natans* was statistically significant among all the trials ($P >$ 0.05).

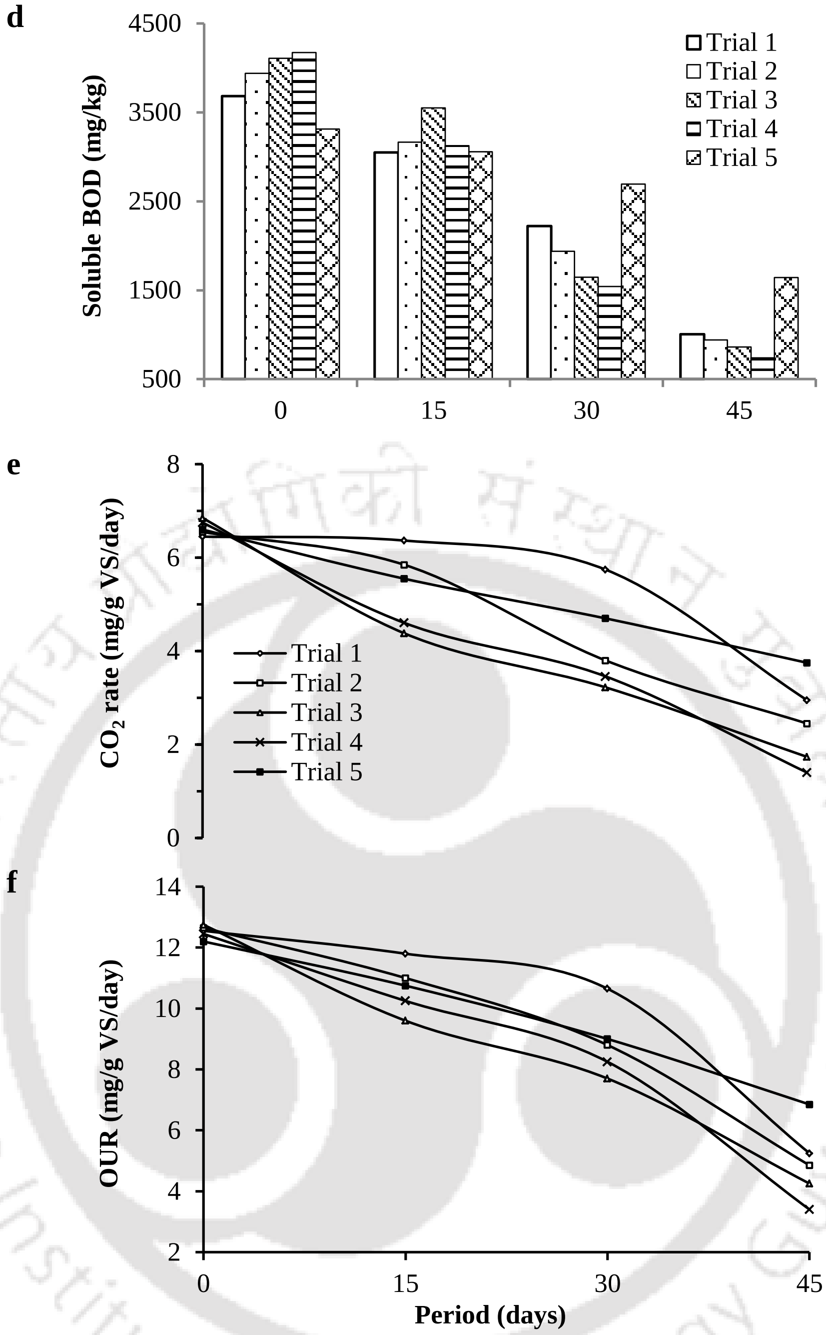

Fig. 5.4.2 d. Variation of soluble BOD during vermicomposting of *Salvinia natans*
e. Variation of CO_2 evolution rate during vermicomposting of *Salvinia natans*
f. Variation of OUR during vermicomposting of *Salvinia natans*

5.4.3 NUTRIENTS

The TKN increased in all trials after the vermicomposting process from 1.95, 1.88, 1.81, 1.74 and 2.20% to 2.41, 2.43, 2.49, 2.63 and 2.66% in trial 1, 2, 3, 4 and 5, respectively (Fig. 5.4.3a). The highest increase was in trial 4 (51.0%) followed by trial 3 (37.3%). The result was consistent with the vermicomposting of phumdi biomass. The NH_4–N also decreased during vermicomposting of *Salvinia natans*. The NH_4–N contents of the composts of all trials were low (≤ 400 mg/Kg) and there was no risk of phytotoxicity (Bernal et al., 1998). The variation of NH_4–N concentration for the 5 trials was statistically significant ($P < 0.05$).

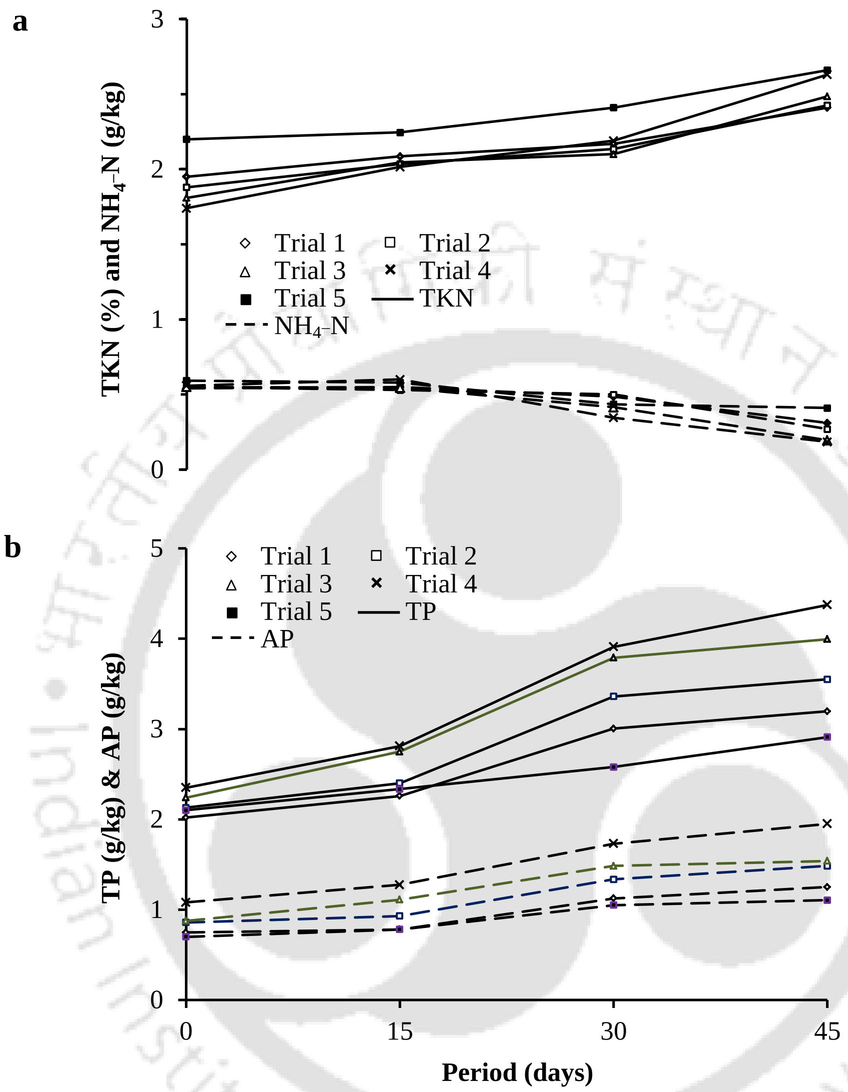

Fig. 5.4.3 a. Variation of TKN and NH_4–N during vermicomposting of *Salvinia natans*
b. Variation of TP and AP during vermicomposting of *Salvinia natans*

The concentration of TP gradually increased due to the mineralization and mobilization of phosphorous by bacterial and faecal phosphatase activity of the earthworms (Khwairakpam and Bhargava, 2009). TP of trial 1, 2, 3, 4 and 5 increased from 2.02, 2.13, 2.24, 2.35 and 2.10 g/kg to 3.20, 3.55, 4.00, 4.38 and 2.91 g/kg and the highest increase was in trial 4 (86.2%) followed by trial 3 (78.3%). The AP of trial 1, 2, 3, 4 and 5 also increased from 0.75, 0.86, 0.88, 1.08 and 0.70 g/kg to 1.25, 1.49, 1.54, 1.95 and 1.11 g/kg. The highest increase was in trial 4 (80.3%) followed by trial 3

(75.9%). When the organic materials passed through the gut of the earthworm some of the phosphorous were converted to bioavailable forms mediated by phosphatase (Lee, 1992; Ghosh et al., 1999). The phosphorous solubilizing microorganisms present in the substrate and the cast facilitated further release of phosphorous.

Table 5.4.1. Variation of total Na, K, Ca and Mg during vermicomposting of *S. natans*

Days	Total nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	5915 ± 65	5325 ± 35	5185 ± 55	4728 ± 15	6995 ± 20
15	6371 ± 31	5974 ± 44	6712 ± 28	6775 ± 41	7343 ± 45
30	7194 ± 30	6895 ± 28	7524 ± 20	7874 ± 30	7902 ± 21
45	8204 ± 48	7977 ± 29	8018 ± 46	8730 ± 28	8466 ± 29
	K				
0	15305 ± 115	13511 ± 114	11681 ± 112	9925 ± 101	18920 ± 101
15	16001 ± 112	14281 ± 110	13518 ± 110	11556 ± 114	19422 ± 103
30	16995 ± 102	15640 ± 103	15021 ± 102	14010 ± 112	20848 ± 110
45	19302 ± 101	18190 ± 102	16456 ± 101	14778 ± 108	22314 ± 108
	Ca				
0	8301 ± 55	7956 ± 78	7609 ± 87	7267 ± 68	9337 ± 98
15	8469 ± 45	8703 ± 67	8225 ± 65	8634 ± 56	9750 ± 68
30	9096 ± 87	9299 ± 86	9058 ± 78	11028 ± 87	10135 ± 98
45	10140 ± 87	10045 ± 98	10882 ± 106	12020 ± 110	10474 ± 102
	Mg				
0	6819 ± 20	6787 ± 25	6756 ± 35	6723 ± 20	7277 ± 36
15	7414 ± 17	6927 ± 27	7121 ± 55	7832 ± 48	7608 ± 15
30	7898 ± 26	7387 ± 43	8687 ± 35	8539 ± 93	8199 ± 34
45	8177 ± 73	8769 ± 45	8844 ± 57	9025 ± 36	8775 ± 69

*Mean ± SD, n = 3, $P < 0.05$

Similar to phumdi biomass vermicomposting, the nutrients Na, K, Ca and Mg increased in all trials after the vermicomposting process of *Salvinia natans* in the range 21.0–84.6% for Na, 17.9–48.9% for K, 12.2–65.4% for Ca and 19.9–34.2% for Mg with all highest increases in trial 4 (Table 5.4.1). The result was in agreement with the highest reduction of VS in trial 4. The order of the concentration of nutrients in the final vermicompost was K > Ca > Mg > Na. The concentrations of the nutrients were near the prescribed limits (Barker, 1997; Bord na More, 2003; ALCL, 2004). The WS nutrients increased in the range of 22.8–77.5% for Na, 12.9–66.8% for K, 16.2–64.0% for Ca and 34.6–72.7% for Mg with highest increase all in trial 4 (Table 5.4.2). The order of the concentrations of the WS nutrients of the final vermicompost was Ca > K > Mg > Na. ANOVA analysis indicated that the variation of the nutrients (both total and WS) forms during the process amongst all trials was significant ($P < 0.05$). Vermicomposting caused considerable increase in total as well as WS K, Na, Ca and Mg contents relative to the compost material (Hait and Tare, 2012). The results once again affirmed that bioavailability of nutrients can be improved considerably through vermicomposting due to increased activity of different microorganisms in the earthworm intestine (Edwards and Lofty, 1972).

Table 5.4.2. Variation of WS Na, K, Ca and Mg during vermicomposting of *S. natans*

Days	WS nutrients (mg/kg dry mass)				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Na				
0	1342 ± 21	1251 ± 22	1168 ± 32	1083 ± 34	1545 ± 28
15	1366 ± 19	1311 ± 27	1294 ± 29	1184 ± 19	1607 ± 24
30	1544 ± 25	1483 ± 24	1687 ± 28	1561 ± 37	1718 ± 32
45	1745 ± 27	1789 ± 26	1834 ± 32	1922 ± 34	1898 ± 37
	K				
0	2874 ± 42	2550 ± 44	2226 ± 38	1902 ± 46	3532 ± 47
15	2991 ± 41	2830 ± 43	2546 ± 39	2264 ± 43	3643 ± 46
30	3402 ± 43	3187 ± 58	2789 ± 41	2879 ± 42	3737 ± 45
45	3587 ± 47	3348 ± 49	3182 ± 48	3172 ± 41	3989 ± 42
	Ca				
0	3103 ± 24	2950 ± 26	2801 ± 25	2616 ± 19	3221 ± 25
15	3346 ± 21	3457 ± 34	3398 ± 42	3146 ± 34	3262 ± 27
30	3403 ± 25	3750 ± 32	3501 ± 40	3819 ± 32	3523 ± 28
45	3736 ± 32	3959 ± 31	4134 ± 38	4290 ± 31	3742 ± 42
	Mg				
0	1824 ± 31	1713 ± 34	1603 ± 41	1493 ± 31	2041 ± 36
15	2164 ± 32	2045 ± 32	2125 ± 40	1930 ± 36	2127 ± 43
30	2335 ± 34	2318 ± 36	2374 ± 36	2324 ± 32	2607 ± 44
45	2501 ± 37	2657 ± 47	2482 ± 49	2578 ± 58	2746 ± 56

*Mean ± SD, $n = 3$, $P < 0.05$

5.4.4 TOTAL HEAVY METALS

The variations of total concentration of Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during the vermicomposting of *Salvinia natans* are shown at Table 5.4.3. Similar to vermicomposting of phumdi biomass, the total concentration of the heavy metals after vermicomposting of *Salvinia natans* increased in all the trials in the range 14.9–19.7% for Zn, 8.7–19.7% for Cu, 14.8–23.2% for Mn, 11.5–21.9% for Fe, 15.9–31.3% for Cr, 10.5–19.2% for Ni, 2.1–22.9% for Pb and 3.4–13.7% for Cd due to reduction in the weight and volume of the *Salvinia natans* biomass (Vig et al. 2011). Increase in heavy metals concentration in the vermicompost of different wastes was also reported by Kaushik and Garg (2003). The order of the concentration of total heavy metals of the vermicompost was Fe > Mn > Pb > Ni > Zn > Cr > Cd > Cu. The variation in Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr concentrations in different trials were significant ($P < 0.05$).

Table 5.4.3. Variation of total Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of *S. natans*

Days	Total heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	195 ± 1.5	190 ± 1.5	185 ± 1.3	180 ± 1.5	210 ± 1.5	264 ± 2.0	260 ± 2.8	257 ± 1.8	253 ± 2.3	265 ± 2.5
15	197 ± 0.9	198 ± 1.0	189 ± 0.5	180 ± 2.9	211 ± 1.1	273 ± 1.5	272 ± 6.8	260 ± 1.4	263 ± 1.7	280 ± 3.5
30	222 ± 0.3	225 ± 0.8	211 ± 1.5	204 ± 1.1	227 ± 1.2	308 ± 1.0	310 ± 5.3	308 ± 1.5	300 ± 2.3	303 ± 3.3
45	226 ± 1.7	227 ± 1.1	216 ± 1.0	206 ± 1.0	242 ± 1.1	309 ± 1.1	297 ± 3.5	285 ± 1.2	279 ± 1.1	316 ± 5.8
	Cu					**Pb**				
0	49.6 ± 0.10	49.1 ± 0.05	48.5 ± 0.10	47.9 ± 0.04	53.5 ± 0.10	756 ± 2.0	756 ± 2.5	755 ± 2.0	754 ± 2.5	756 ± 3.0
15	51.3 ± 0.40	50.6 ± 0.40	48.8 ± 0.13	47.4 ± 0.15	54.2 ± 0.40	789 ± 3.0	771 ± 1.6	769 ± 1.6	767 ± 2.6	798 ± 4.3
30	58.1 ± 0.38	56.9 ± 0.11	55.1 ± 0.08	54.2 ± 0.22	59.5 ± 0.35	896 ± 8.3	830 ± 8.5	803 ± 3.4	804 ± 2.5	856 ± 2.3
45	59.4 ± 0.15	58.2 ± 0.11	54.0 ± 0.07	52.1 ± 0.13	61.3 ± 0.35	929 ± 6.5	807 ± 4.9	771 ± 1.5	771 ± 1.2	870 ± 2.8
	Mn					**Cd**				
0	866 ± 2.4	819 ± 6.8	772 ± 4.8	725 ± 4.6	999 ± 7.4	56.5 ± 0.5	52.5 ± 0.5	52.0 ± 0.5	51.9 ± 0.5	58.3 ± 0.3
15	997 ± 2.5	824 ± 3.0	748 ± 4.0	736 ± 7.5	1090 ± 5.6	59.0 ± 0.5	54.0 ± 0.5	52.1 ± 0.3	51.9 ± 0.9	59.5 ± 0.8
30	1008 ± 3.4	944 ± 3.2	891 ± 4.8	790 ± 8.2	1131 ± 3.8	56.8 ± 0.3	57.8 ± 0.3	59.0 ± 0.5	61.2 ± 0.6	62.3 ± 1.0
45	1010 ± 6.9	973 ± 7.5	906 ± 4.8	893 ± 7.5	1147 ± 4.5	64.3 ± 1.3	56.6 ± 0.5	53.9 ± 0.4	53.7 ± 0.8	66.3 ± 0.8
	Fe					**Cr**				
0	5867 ± 3.5	5377 ± 3.8	4891 ± 6.8	4399 ± 10.5	6762 ± 13.5	135 ± 1.5	133 ± 1.0	131 ± 1.5	129 ± 1.0	143 ± 1.5
15	6101 ± 5.0	5422 ± 10.0	5082 ± 16.5	4413 ± 12.0	6962 ± 14.8	134 ± 1.6	139 ± 1.9	136 ± 1.5	133 ± 1.2	149 ± 2.5
30	6740 ± 6.5	5999 ± 9.5	5688 ± 20.0	5218 ± 10.0	7151 ± 24.0	163 ± 2.5	165 ± 1.9	168 ± 3.2	170 ± 2.8	169 ± 2.5
45	7152 ± 12.5	6140 ± 24.5	5575 ± 10.5	4903 ± 12.5	7557 ± 18.5	177 ± 1.2	157 ± 1.1	152 ± 1.8	150 ± 1.6	172 ± 2.0

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

Table 5.4.4. Variation of WS fraction of Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of *S. natans*

Days	Total heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	13.8 ± 0.05	13.3 ± 0.05	11.9 ± 0.20	11.0 ± 0.05	14.4 ± 0.10	–	–	–	–	–
15	12.9 ± 0.10	12.3 ± 0.05	11.3 ± 0.05	10.5 ± 0.05	13.7 ± 0.10	–	–	–	–	–
30	12.7 ± 0.05	11.2 ± 0.10	10.3 ± 0.05	9.0 ± 0.05	13.2 ± 0.15	–	–	–	–	–
45	11.8 ± 0.05	11.0 ± 0.10	9.5 ± 0.05	7.9 ± 0.05	12.5 ± 0.15	–	–	–	–	–
	Cu					**Pb**				
0	6.9 ± 0.05	6.5 ± 0.10	6.0 ± 0.05	5.6 ± 0.01	8.0 ± 0.05	7.92 ± 0.01	6.93 ± 0.05	5.94 ± 0.01	4.95 ± 0.02	9.90 ± 0.01
15	6.4 ± 0.02	5.4 ± 0.04	5.1 ± 0.02	4.7 ± 0.04	7.7 ± 0.05	7.69 ± 0.62	5.18 ± 0.08	4.76 ± 0.45	2.55 ± 0.46	9.07 ± 0.28
30	5.5 ± 0.02	4.8 ± 0.04	4.6 ± 0.04	4.1 ± 0.02	7.6 ± 0.06	4.99 ± 0.38	3.88 ± 0.10	3.04 ± 0.11	1.40 ± 0.61	8.05 ± 0.20
45	5.1 ± 0.01	4.5 ± 0.03	4.2 ± 0.05	3.6 ± 0.05	7.5 ± 0.02	2.93 ± 0.26	2.01 ± 0.03	1.25 ± 0.05	0.99 ± 0.00	7.56 ± 0.33
	Mn					**Cd**				
0	47.1 ± 0.10	43.7 ± 0.15	40.2 ± 0.12	36.8 ± 0.15	55.5 ± 0.10	–	–	–	–	–
15	41.4 ± 0.18	40.3 ± 0.15	37.9 ± 0.10	29.4 ± 0.18	52.7 ± 0.17	–	–	–	–	–
30	43.6 ± 0.15	34.5 ± 0.81	27.7 ± 1.26	27.6 ± 0.16	53.6 ± 0.15	–	–	–	–	–
45	39.6 ± 0.15	32.3 ± 0.28	25.7 ± 1.08	23.5 ± 0.19	50.1 ± 0.10	–	–	–	–	–
	Fe					**Cr**				
0	241 ± 2.0	226 ± 1.2	215 ± 2.5	202 ± 2.0	268 ± 2.5	28.5 ± 0.1	25.6 ± 0.1	22.8 ± 0.2	20.0 ± 0.1	34.5 ± 0.2
15	228 ± 1.4	187 ± 0.3	206 ± 1.1	184 ± 0.9	265 ± 1.3	23.2 ± 0.1	20.4 ± 0.6	16.4 ± 0.2	14.6 ± 0.3	28.3 ± 0.3
30	195 ± 0.2	172 ± 1.3	153 ± 1.7	136 ± 1.7	261 ± 2.5	20.2 ± 0.1	17.8 ± 0.1	14.1 ± 0.3	11.0 ± 0.2	27.7 ± 0.4
45	189 ± 0.1	151 ± 1.5	138 ± 1.3	126 ± 1.4	259 ± 1.9	18.4 ± 0.8	16.7 ± 0.1	13.1 ± 0.2	9.9 ± 0.3	26.5 ± 0.8

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

5.4.5 BIOAVAILABILITY OF HEAVY METALS

5.4.5.1 WS heavy metals

WS fraction of the heavy metals decreased after the vermicomposting of *Salvinia natans* (Table 5.4.4) in all trials in the following order:

Zn: T4 (27.5%) > T3 (20.6%) > T2 (17.0%) > T1 (14.6%) > T5 (13.5%)
Cu: T4 (35.1%) > T2 (30.6%) > T3 (30.5%) > T1 (25.9%) > T5 (6.6%)
Mn: T4 (36.3%) > T3 (36.1%) > T2 (26.1%) > T1 (15.9%) > T5 (9.7%)
Fe: T4 (37.8%) > T3 (35.8%) > T2 (33.1%) > T1 (21.4%) > T5 (3.3%)
Pb: T4 (80.0%) > T3 (79.0%) > T2 (71.0%) > T1 (63.1%) > T5 (23.6%)
Cr: T4 (50.7%) > T3 (42.8%) > T1 (35.2%) > T2 (35.3%) > T5 (23.2%)

(Note: T–trial)

WS concentrations of Ni and Cd were not detected during the vermicomposting of *Salvinia natans*. The decrease of WS heavy metals was statistically significant ($P < 0.05$) in all the trials.

5.4.5.2 DTPA extractable heavy metals

The DTPA extractable forms of metals were reduced after the vermicomposting process of *Salvinia natans* in all trials (Table 5.4.5) in the following order:

Zn: T4 (31.0%) > T3 (27.1%) > T2 (17.9%) > T1 (11.5%) > T5 (8.3%)
Cu: T4 (39.2%) > T3 (32.6%) > T2 (22.5%) > T1 (21.2%) > T5 (11.8%)
Mn: T5 (18.2%) > T1 (11.2%) > T2 (8.1%) > T3 (7.9%) > T4 (7.0%)
Fe: T4 (37.2%) > T3 (33.2%) > T2 (24.1%) > T1 (23.1%) > T5 (18.4%)
Ni: T3 (78.9%) > T2 (73.9%) > T4 (73.5%) > T1 (58.1%) > T5 (43.0%)
Pb: T4 (82.7%) > T3 (79.3%) > T2 (66.4%) > T1 (60.7%) > T5 (35.9%)
Cr: T4 (62.0%) > T3 (41.8%) > T2 (32.0%) > T1 (23.1%) > T5 (17.4%)

(Note T–trial)

The DTPA extractable concentration of Cd was not detected during the vermicomposting process of *Salvinia natans*. The variation of the DTPA extractable heavy metals were found statistically different ($P < 0.05$) in all the trials during the vermicomposting process. The order of the concentrations of DTPA extractable heavy metals of the final vermicomposts of *Salvinia natans* was Fe > Mn > Zn > Cr > Pb > Ni > Cu. The “ŋ” of DTPA extractable heavy metals of *Salvinia natans* vermicompost were also reduced and the final values were in the range 26.3–35.9% for Zn,

Table 5.4.5. Variation of DTPA extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of *S. natans*

Days	DTPA extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	91.1 ± 0.02	89.6 ± 0.34	78.9 ± 0.08	78.7 ± 0.08	94.6 ± 0.08	14.3 ± 0.05	13.4 ± 0.05	12.3 ± 0.05	11.3 ± 0.05	17.6 ± 0.08
15	87.8 ± 0.11	88.2 ± 0.05	74.3 ± 0	74.6 ± 0.27	92.2 ± 0.01	13.4 ± 0.05	12.5 ± 0.05	11.4 ± 0.05	10.4 ± 0.07	16.7 ± 0.07
30	83.2 ± 0.04	83.2 ± 0.13	69.4 ± 0.48	73.8 ± 0.08	91.8 ± 0.04	13.0 ± 0.05	10.1 ± 0.07	9.4 ± 0.06	9.4 ± 0.06	16.5 ± 0.08
45	80.6 ± 0.59	73.5 ± 2.26	57.5 ± 1.37	54.3 ± 2.17	86.7 ± 0.48	6.0 ± 0.05	3.5 ± 0.08	2.6 ± 0.07	3.0 ± 0.04	10.0 ± 0.05
	Cu					**Pb**				
0	8.7 ± 0.02	8.4 ± 0.02	8.1 ± 0.01	7.8 ± 0.04	9.8 ± 0.05	25.1 ± 0.05	21.9 ± 0.06	18.8 ± 0.06	15.7 ± 0.06	31.4 ± 0.05
15	8.5 ± 0.04	7.8 ± 0.02	7.3 ± 0.06	7.1 ± 0.04	9.4 ± 0.01	21.5 ± 0.08	17.4 ± 0.08	14.4 ± 0.06	11.3 ± 0.06	28.6 ± 0.09
30	7.1 ± 0.03	7.3 ± 0.02	6.7 ± 0.04	6.6 ± 0.04	9.0 ± 0.04	20.3 ± 0.06	17.0 ± 0.05	13.6 ± 0.05	8.2 ± 0.05	27.2 ± 0.04
45	6.9 ± 0.04	6.5 ± 0.09	5.5 ± 0.02	4.7 ± 0.05	8.6 ± 0.05	9.9 ± 0.09	7.4 ± 0.06	3.9 ± 0.05	2.7 ± 0.05	20.1 ± 0.05
	Mn					**Cd**				
0	203 ± 1.5	203 ± 1.1	204 ± 1.0	204 ± 0.5	220 ± 1.0	–	–	–	–	–
15	180 ± 1.3	205 ± 1.2	209 ± 1.5	210 ± 0.6	216 ± 0.5	–	–	–	–	–
30	181 ± 1.5	200 ± 1.4	189 ± 1.5	195 ± 1.0	209 ± 0.7	–	–	–	–	–
45	183 ± 1.6	202 ± 1.6	200 ± 1.0	203 ± 1.0	180 ± 0.5	–	–	–	–	–
	Fe					**Cr**				
0	241 ± 2.0	226 ± 1.2	215 ± 2.5	202 ± 2.0	268 ± 2.5	41.2 ± 0.2	37.5 ± 1.1	33.4 ± 0.4	30.0 ± 1.1	50.5 ± 0.5
15	228 ± 1.4	187 ± 0.3	206 ± 1.1	184 ± 0.9	265 ± 1.3	39.4 ± 0.8	35.1 ± 0.8	27.0 ± 0.1	28.9 ± 1.5	48.5 ± 0.7
30	195 ± 0.2	172 ± 1.3	153 ± 1.7	136 ± 1.7	261 ± 2.5	36.4 ± 1.5	30.0 ± 0.9	21.5 ± 0.8	16.9 ± 0.5	44.3 ± 0.9
45	189 ± 0.1	151 ± 1.5	138 ± 1.3	126 ± 1.4	259 ± 1.9	31.7 ± 1.9	25.5 ± 1.7	19.4 ± 0.8	11.4 ± 0.8	41.7 ± 0.1

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

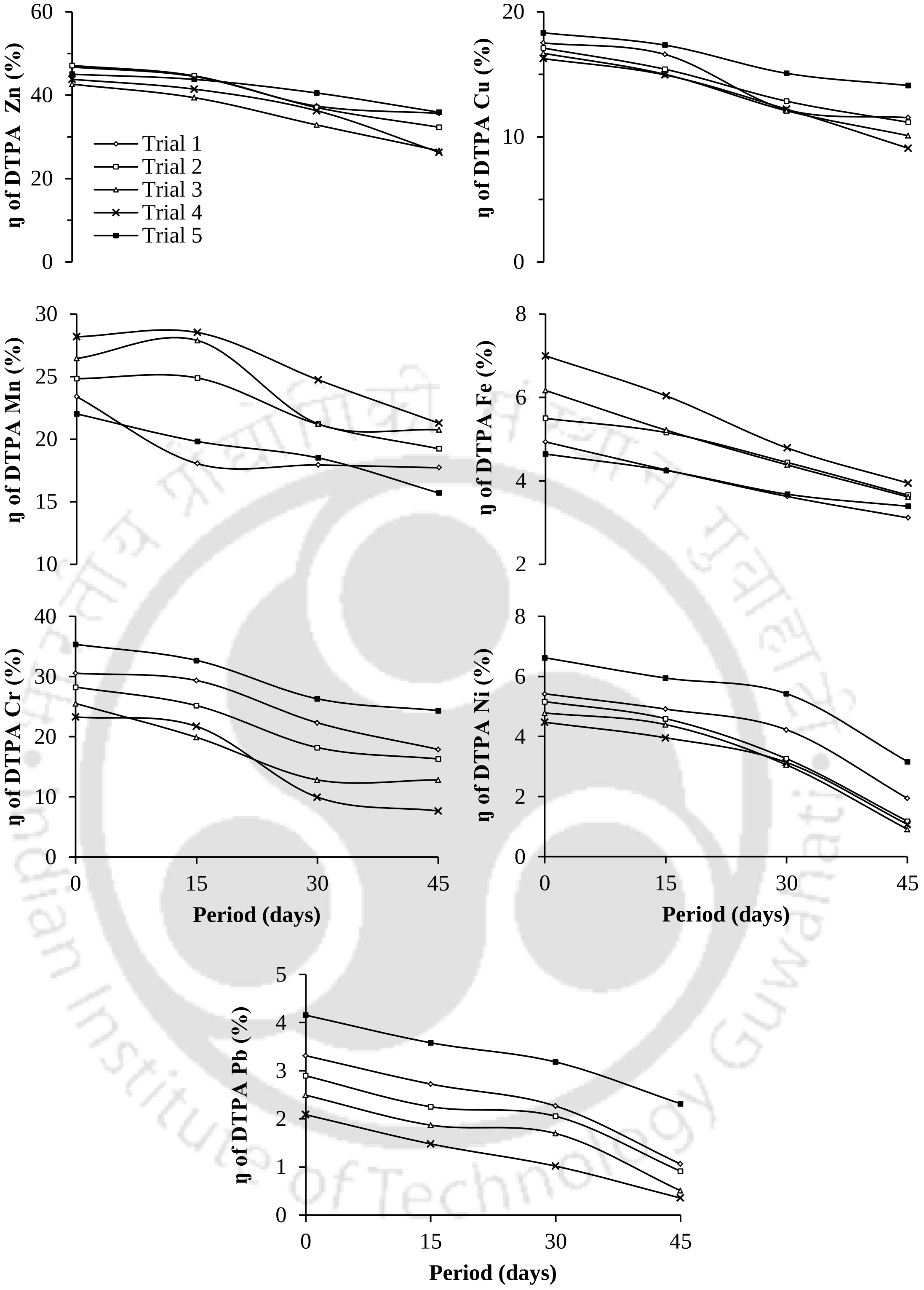

Fig. 5.4.5. Variation of "ŋ" of DTPA extractable heavy metals during vermicomposting of *Salvinia natans*.

9.1–14.1% for Cu, 15.7–21.3% for Mn, 3.4–3.7% for Fe, 7.6–24.3% for Cr, 0.9–3.2% for Ni and 0.4–2.3% for Pb. Therefore, vermicomposting of *Salvinia natans* was the most effective for removal of the DTPA extractable heavy metals.

Table 5.4.6. Variation of TCLP extractable Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr during vermicomposting of *S. natans*

Days	DTPA extractable heavy metal (mg/kg dry mass)									
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Zn					**Ni**				
0	108 ± 1.1	99 ± 0.7	89 ± 0.2	81 ± 1.0	129 ± 1.0	164 ± 2.0	144 ± 1.5	124 ± 1.5	103 ± 2.0	205 ± 2.5
15	103 ± 0.1	90 ± 0.4	74 ± 0.3	74 ± 0.2	125 ± 0.5	156 ± 1.9	126 ± 1.2	113 ± 1.5	89 ± 1.3	200 ± 1.1
30	94 ± 1.5	84 ± 0.2	72 ± 0.4	72 ± 0.3	121 ± 0.5	150 ± 1.2	120 ± 1.1	94 ± 1.7	79 ± 1.3	186 ± 2.1
45	88 ± 1.8	73 ± 0.4	65 ± 1.5	54 ± 3.6	116 ± 1.2	135 ± 1.9	96 ± 1.9	60 ± 1.6	49 ± 1.4	173 ± 1.8
	Cu					**Pb**				
0	19.6 ± 0.05	18.1 ± 0.01	16.7 ± 0.05	15.3 ± 0.02	23.1 ± 0.05	52.1 ± 0.75	45.9 ± 0.80	39.8 ± 0.81	33.6 ± 0.87	62.7 ± 0.78
15	17.1 ± 0.04	16.4 ± 0.05	14.7 ± 0.05	13.5 ± 0.05	22.4 ± 0.05	44.5 ± 0.78	45.6 ± 0.90	37.6 ± 0.84	43.8 ± 0.89	65 ± 0.75
30	17.0 ± 0.04	15.2 ± 0.02	12.2 ± 0.05	12.2 ± 0.02	21.5 ± 0.13	38.3 ± 0.80	33.9 ± 0.98	23.4 ± 0.89	27.6 ± 0.87	56.9 ± 0.76
45	16.5 ± 0.04	14.2 ± 0.05	11.2 ± 0.02	9.9 ± 0.15	19.6 ± 0.14	32.6 ± 0.69	28.0 ± 0.90	15.6 ± 0.90	10.4 ± 0.65	48.3 ± 0.85
	Mn					**Cd**				
0	282 ± 1.1	298 ± 1.0	314 ± 1.5	330 ± 1.4	291 ± 1.1	2.9 ± 0.01	2.8 ± 0.02	2.7 ± 0.01	2.6 ± 0.02	2.4 ± 0.01
15	273 ± 1.8	293 ± 1.6	307 ± 1.7	324 ± 1.6	287 ± 1.6	2.2 ± 0.04	2.1 ± 0.01	1.3 ± 0.02	1.1 ± 0.03	2.3 ± 0.01
30	246 ± 1.1	275 ± 1.2	256 ± 1.8	277 ± 1.2	269 ± 1.1	1.4 ± 0.04	1.1 ± 0.01	0.8 ± 0.07	0.3 ± 0.03	1.7 ± 0.02
45	231 ± 1.4	246 ± 1.3	238 ± 1.6	250 ± 1.9	259 ± 1.3	1.3 ± 0.01	1.0 ± 0.01	0.4 ± 0.02	0.1 ± 0.05	1.5 ± 0.02
	Fe					**Cr**				
0	413 ± 2.5	396 ± 0.6	382 ± 2.5	366 ± 2.0	474 ± 1.4	55.0 ± 0.1	49.6 ± 0.4	44.5 ± 0.3	39.4 ± 0.2	66.4 ± 0.3
15	394 ± 3.6	367 ± 1.3	271 ± 1.9	318 ± 1.7	452 ± 1.5	50.3 ± 0.7	44.1 ± 1.8	39.4 ± 1.4	29.7 ± 0.3	65.4 ± 1.2
30	383 ± 2.9	374 ± 1.9	283 ± 1.3	357 ± 1.9	444 ± 1.0	46.5 ± 1.6	33.8 ± 1.4	28.0 ± 0.4	16.5 ± 0.4	58.0 ± 1.3
45	321 ± 2.8	305 ± 2.8	265 ± 2.5	247 ± 1.3	416 ± 1.4	39.1 ± 1.4	29.1 ± 0.9	25.5 ± 0.2	14.5 ± 0.4	50.8 ± 1.7

(Mean ± SD, n = 3) SD –standard deviation, n –no. of observations, $P < 0.05$

5.4.5.3 TCLP extractable heavy metals

The mobility of heavy metals assessed by the TCLP test decreased after the vermicomposting of *Salvinia natans* (Table 5.4.6). The leachable fractions of the heavy metals during the vermicomposting process reduced in the following order:

Zn: T4 (33.5%) > T3 (27.5%) > T2 (26.2%) > T1 (18.7%) > T5 (9.8%)
Cu: T4 (35.3%) > T3 (33.1%) > T2 (22.0%) > T1 (15.9%) > T5 (15.1%)
Mn: T3 (24.3%) > T4 (24.1%) > T1 (18.1%) > T2 (17.4%) > T5 (10.8%)
Fe: T4 (32.6%) > T3 (30.7%) > T2 (22.9%) > T1 (22.2%) > T5 (12.9%)
Ni: T4 (52.7%) > T3 (51.3%) > T2 (33.6%) > T1 (17.9%) > T5 (15.7%)
Cd: T4 (98.0%) > T3 (84.2%) > T2 (64.9%) > T1 (54.0%) > T5 (39.1%)
Pb: T4 (69.2%) > T3 (60.8%) > T2 (39.1%) > T1 (37.4%) > T5 (23.0%)
Cr: T4 (63.2%) > T3 (42.7%) > T2 (41.4%) > T1 (28.9%) > T5 (23.5%)

(Note: T–trial)

The TCLP extractable heavy metals were reduced significantly in all trials ($P < 0.05$). The order of the concentrations of the leachable fraction of heavy metals of the *Salvinia natans* vermicomposts was Fe > Mn > Ni > Zn > Cr = Pb > Cu > Cd. The leachable concentrations of the heavy metals of the final *Salvinia natans* vermicomposts were within the prescribed standards for agricultural applications (USEPA, 1992). The results of the bioavailability study carried out during composting and vermicomposting of phumdi biomass and *Salvinia natans* indicated that vermicomposting process was the most effective for removal of the toxic forms of heavy metals.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter draws conclusion from the study carried out in two phases on the biotransformation of phumdi and *Salvinia natans* biomass employing agitated pile composting, drum composting and vermicomposting techniques. The chapter also recommends future works for the readers.

6.1 CONCLUSIONS

The phumdi and *Salvinia natans* biomass indicated high moisture content (MC) and therefore, addition of bulking agent was required to adjust the moisture content of the composting materials. The phumdi and *Salvinia natans* biomass also indicated presence of heavy metals requiring study of the fate of the metals during the bio-transformation process.

Appropriate proportion of cattle manure and rice husk facilitated the agitated pile composting process as indicated by the higher temperature rise in trial 4 of phumdi biomass and trial 3 of *Salvinia natans* pile composting. The highest reduction of volatile solids (VS), lower oxygen uptake rates (OURs) and CO_2 evolution rates, highest reduction of soluble BOD and enhanced pH of the trials were also indicative of more effective composting process. Rotary drum composting enhanced the composting processes of phumdi and *Salvinia natans* biomass as indicated by the higher temperature profiles and early occurrence of thermophilic and post mesophilic stable temperature phase compared with agitated pile composting. The lower temperature in phumdi piles and drums and the delayed arrival of thermophilic stage during the process indicated that phumdi biomass was slow in degradation or less degradable compared with *Salvinia natans*.

Vermicomposting of phumdi and *Salvinia natans* biomass were also effective with appropriate proportion of cattle manure and sawdust indicated by the highest increase of total earthworm biomass in trial 4 for both the biomass. The growth of earthworm biomass and efficacy of the vermicomposting process was dependent on the proportion of cattle manure especially during the vermicomposting process of *Salvinia natans* as indicated by highest reduction of VS, soluble BOD, OUR and CO_2 evolution rate. The earthworm *Eisenia fetida* could adapt to the phumdi and *Salvinia natans* biomass in due course of time and prior acclimatization of the earthworms to the substrates of phumdi and *Salvinia natans* biomass may be required for effective vermicomposting.

The concentrations of the nutrients i.e. total Kjeldahl nitrogen; total phosphorous; total potassium; total sodium; total calcium; and total magnesium were enhanced significantly during composting and vermicomposting due to net loss of dry mass. The increase of the bioavailable forms of the nutrients was most significant during vermicomposting due to the combined action of the enzymes in the earthworm gut and the associated microbes. Vermicomposting was also the most effective in terms of reduction of organic matter during the decomposition process.

The total concentration of all heavy metals increased during the controlled decomposition processes also due to the net loss of dry mass. The increase in the concentration of heavy metals was low during vermicomposting possibly due to the bio-accumulation of some amount of the metals. Composting and vermicomposting with appropriate proportion of cattle manure reduced the bioavailable and leachable forms of the heavy metals which is indicated by the reduced water soluble, diethylene triamine penta-acetic acid extractable and leachable forms of heavy metals during the composting process. Vermicomposting also reduced the bioavailable forms of heavy metals of the substrates. The variation of the bioavailable forms of heavy metals was dependent on the nature of the composting materials as different trials showed different pattern of variation of the concentration of bioavailable heavy metals with increasing pH.

Therefore, drum composting (phumdi: trial 4; *Salvinia natans*: trial 3) and vermicomposting (trial 4 for both biomass) were found effective.

6.2 RECOMMENDATIONS

Determination or identification of microbial community or consortia using rRNA and rDNA sequencing will be useful for understanding and controlling the different stages of the composting process. Concise compost maturity and quality criteria are also still lacking and microbiological tests of the compost may provide information on a multitude of features of the compost material.

Food waste is another aspect that requires proper management in the region. The co-composting of food waste with phumdi biomass is also required to be investigated for the scope of simultaneous management of household and aquatic waste.

Research may be carried out on the use of non-organic recyclable materials as bulking agents to do away with consumable organic bulking agents.

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