RESEARCH PROGRAM ON Water, Land and Ecosystems

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RESOURCE RECOVERY & REUSE SERIES 3

3

Co-composting of Solid Waste and Fecal Sludge for Nutrient and Organic Matter Recovery

Olufunke Cofie, Josiane Nikiema, Robert Impraim, Noah Adamtey, Johannes Paul and Doulaye Koné

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Olufunke Cofie, Josiane Nikiema, Robert Impraim, Noah Adamtey, Johannes Paul and Doulaye Koné

The authors

Dr. Olufunke Cofie is a senior researcher with a background in soil science. She is based at the IWMI-Ghana office (o.cofie@cgiar.org); Dr. Josiane Nikiema is a researcher in environmental sciences. She is based at the IWMI-Ghana office (j.nikiema@cgiar.org); Dr. Noah Adamtey is a senior scientist at FiBL (Research Institute of Organic Agriculture), Switzerland (noah.adamtey@fibl.org); Mr. Robert Impraim is a research officer at the IWMI-Ghana office (r.impraim@cgiar.org); Dr. Johannes Paul is senior researcher at IWMI with a background in integrated waste management. He is based at IWMI's headquarters in Colombo, Sri Lanka (j.paul@cgiar.org); and Dr. Doulaye Koné is a Deputy Director, Transformative Technologies, Bill & Melinda Gates Foundation, Seattle, USA (doulaye.kone@gatesfoundation.org).

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Front cover photograph: Taking temperature readings of windrows containing different combinations of fecal sludge based compost. Bangladesh. *Photo:* Neil Palmer/IWMI

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ACRONYMS AND ABBREVIATIONS

AIT	Asian Institute for Technology, Thailand
BOD	Biological Oxygen Demand
DFS	Dried Fecal Sludge
EC	Electric Conductivity
ENC	European Compost Network
FS	Fecal Sludge
FSM	Fecal Sludge Management
GDP	Gross Domestic Product (the monetary value of all finished goods and services generated within a country's borders in a specific time period)
HIC	High Income Countries
IDRC	International Development Research Center
IFA	International Fertilizer Industry Association
IWMI	International Water Management Institute
LFS	Raw Fecal Sludge
LIC	Low Income Countries
MIC	Medium Income Countries
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
NPK	Nitrogen, Phosphorus, Potassium
SOM	Soil Organic Matter
SWM	Solid Waste Management
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TS	Total Solids
TVS	Total Volatile Solids
UNEP	United Nations Environment Programme
USEPA	Environmental Protection Agency of the United States of America
WRAP	Waste Resources Action Programme (www.environment-agency.gov.uk)

SUMMARY

Resource depletion, environmental degradation and climate change are among the greatest challenges we face today. In this context, the proper management of generated waste and efficient resource recovery become relevant aspects of environmental management systems that could support a circular economy and assist in addressing these global challenges. However, establishing sustainable waste management systems requires provision of technologies and capacities that fit into the specific socio-economic and geographical conditions of a country. Especially in low income countries, ongoing population growth and rapid urbanization exacerbate waste management issues, while poverty, lack of awareness and technology, expertise and funding constraints hinder the establishment of efficient waste management systems. Although emerging innovations such as mechanical-biological waste treatment, waste-to-energy technologies, engineered landfilling and so forth are available and have proven effective in industrialized countries, they are not ready for uptake in most low income countries yet. In this context, composting, as a low cost technology, remains a valid and relevant option to enhance waste management in developing countries where the bulk of collected solid waste is organic in nature but recycling rates are still low. Although composting reduces municipal efforts and costs, especially for waste disposal, compost operations are often unsustainable, because revenues from compost sales alone are insufficient to cover plant operation costs; hence, subsidy from the municipality served is needed. In this context the 'value-adding' aspect of recycling activities needs to be explored to identify innovations that could offer enhanced waste management services and more valuable products for potential users of compost.

Biological treatment, in particular composting, is a relatively simple, durable and inexpensive alternative for stabilizing and reducing biodegradable waste. Co-composting is considered as a suitable, low cost, waste treatment option for developing countries that allows recycling of organic waste from various waste streams in a combined manner, e.g. from municipal solid waste and excreta, likewise manure from livestock production. In particular, integration of 'biosolids' from the sanitation sector as potential input material for co-composting would provide a solution for the much needed treatment of fecal sludge from on-site sanitation systems. So far, fecal sludge removed from pit latrines or septic tanks is often disposed of close to the points of generation instead of being recycled in a proper manner in many developing countries. By combining various waste streams, new opportunities arise that could not only increase resource recovery rates but also enhance the quality of compost products, e.g. through mixing of selected input materials and additives that increase the content of crop nutrients and enhance application properties. Whereas co-composting offers many benefits, it can also have negative side effects if not properly managed. These include bad odor, leachate and methane emissions, or microbial as well as heavy metal contaminations that decrease the value and applicability of compost products. Therefore special care is needed to treat potential pathogen contaminations that could occur if human excreta or manures are used as input materials for co-composting. This research paper elaborates in detail the main parameters that govern the co-composting process as well as factors that control the production of a safe and valuable quality compost. It further explains technological options and proper design, conduct and monitoring of the co-composting process, including the specific conditions that arise during the main stages of biotransformation until its final maturation phase that delivers a stable, humus-rich and soil-like substrate.

Pit latrine emptiers in Bangladesh collect and transport human waste to a site where it is processed into fertilizer. Photo: Neil Palmer (IWMI)

1 INTRODUCTION

Composting provides many benefits. It not only diverts organic materials from disposal in landfills, it also helps to return nutrients and organic matter to the soil, providing a valuable material for agriculture, horticulture and landscaping. This research paper was prepared to provide practical guidance and the latest knowledge related to co-composting of organic waste from municipal waste streams, including human excreta, in order to support planners, researchers, development experts and practitioners in their work. It offers an in-depth review of framework conditions, methods and relevant process parameters that govern co-composting with special attention on the reuse of sensitive input materials such as fecal sludge, manure and municipal organic waste that influence compost quality and offer significant co-benefits for sanitation and agriculture.

1.1 Brief on Solid Waste Management

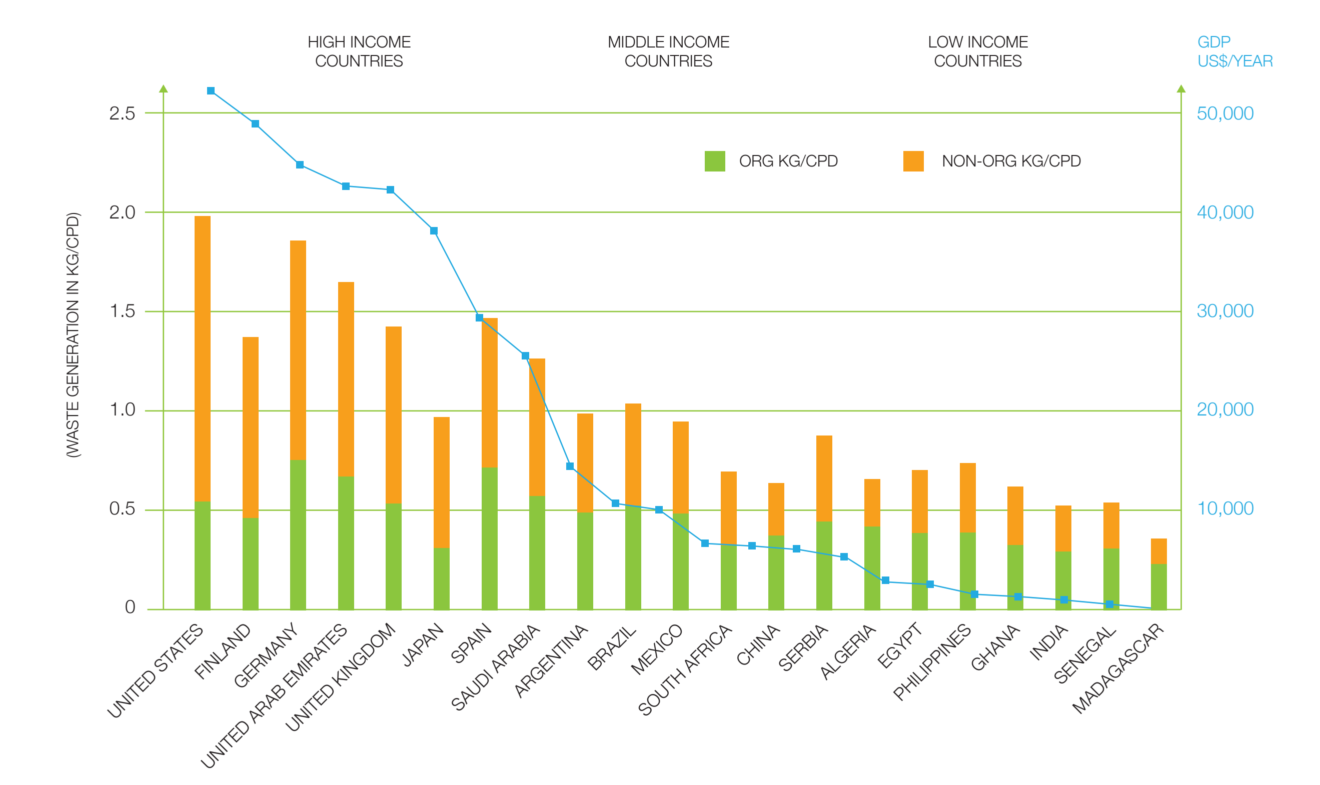
1.1.1 The Waste Situation in Developing Countries

Solid Waste Management (SWM) and Fecal Sludge Management (FSM) are relevant public tasks to enable sustainable and healthy human settlements, but they are severely constrained by various issues in many developing countries. Waste generation and the complexity of waste composition is steadily increasing due to population growth, urbanization and economic development, especially in larger cities. Although emerging innovations such as mechanical and biological waste treatment, waste-to-energy technologies, engineered landfilling and others are available and have proven effective in industrialized countries, they are not ready for uptake in most low income countries. In this context, composting, as a low cost technology, is a valid and relevant option to enhance waste management in developing countries where the bulk of collected solid waste is organic in nature but recycling rates are still low (UNEP 2011; D-Waste 2013). Whereas composting offers many benefits, it can also cause negative side effects if not properly managed. Such negative effects include, offensive odor, leachate and methane emissions, or microbial as well as heavy metal contaminations that decrease the value and applicability of compost products.

Current municipal solid waste generation on a global scale is estimated to be approximately 1.3 billion tons year^{-1}, and is expected to increase to approximately 2.2 billion tons year in 2025 (Hoornweg and Bhada-Tata 2012; D-Waste 2013). Based on this forecast, a significant increase in per capita waste generation rates will occur within the next 15 years. At present, average waste generation in industrialized countries varies between 1 and 2 kg person^{-1} day^{-1}, while waste generation in low income countries is usually much lower with generation rates of 0.4 to 0.8 kg person^{-1} day^{-1} (UNEP 2011; Simelane and Mohee 2012; Hoornweg and Bhada-Tata 2012; D-Waste 2013).

Figure 1 summarizes relevant trends in global solid waste generation.

FIGURE 1. GLOBAL TRENDS IN SOLID WASTE GENERATION.



Sources: UN-ESA 2011, 2013; D-Waste 2013.

Figure 1 shows that the overall waste generation rate correlates with the economic capacity of a country, whereby countries with lower Gross Domestic Product (GDP) are also lower in waste generation, if compared with higher developed countries. Similarly, if GDP decreases, the capacity to perform waste treatment and recycling activities likewise decreases, meaning the lower the GDP, the less recycling is formally conducted and reported by a certain country whereas the recovery rate from informal sector activities remains unknown. Figure 1 also indicates that municipal solid waste generation in low income countries (LIC) may increase over time due to changes of lifestyle, consumption patterns and extended use of disposable materials, e.g. from additional trade and excessive packaging, provided that economic development and population growth are increasing (Wilson et al. 2009; Hoornweg and Bhada-Tata 2012; Annepu and Themelis 2013). Related to this development trend, the composition of generated municipal solid waste may gradually change as displayed in Figure 2.

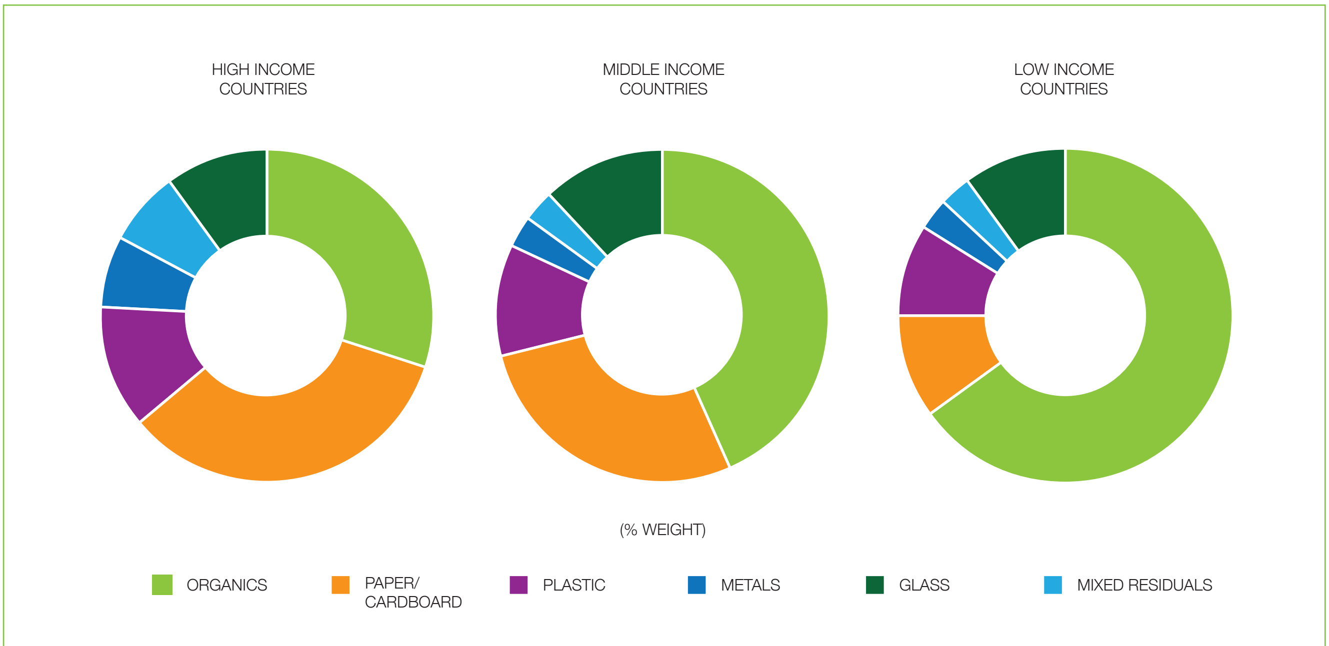
As shown in Figure 2, changes in waste composition due to economic development also affect the amounts and types of organic waste fraction whereby the latter relatively decreases with economic development. Projections to forecast waste composition changes are relevant for planning and are especially needed to identify and decide on best suited waste treatment options that allow accommodation of expected changes over time with the made investments.

According to the United Nations Population Division the global population is projected to increase from 6.9 billion in 2011 to 9.3 billion in 2050 with the highest growth trends in urban and peri-urban areas of LIC (UN-ESA 2011). The ongoing trend of urbanization is mainly driven by economic activities that increasingly place investments in larger cities where access to infrastructure and support mechanisms is highest. Consequently, most citizens perceive cities as more attractive habitations, probably due to increasing job opportunities with higher salary levels and other benefits. This perception becomes a relevant driver for population migration and urbanization and amplifies the role of cities as 'engines of economic growth' (Achankeng 2003; Otto et al. 2006; Hove et al. 2013). It is expected that the combined effects of rapid urbanization, population increase and economic development will result in additional waste generation in many developing countries and especially in urban areas, a trend that will most likely trigger environmental degradation and need for intervention (Wilson et al. 2007; UNEP 2011).

1.1.2 Challenges of Solid Waste Management

In developing countries, amounts of collected solid waste are usually less than half of what is generated so most of it is neither contained nor recycled (Simelane and Mohee 2012). Instead, it is often disposed of indiscriminately at illegal dump sites, at the periphery of urban centers, buried or burned in backyards, along roads or thrown into drainage systems, idle land or waterways. The magnitude of such malpractices in waste management correlates with the efficiency of available waste collection services, whereas lack of service increases illegal waste dumping, scattered waste burning and pollution of land, drainage systems and waterways. As a result, the aesthetic value of settlements decreases (Simelane and Mohee 2012). Moreover, uncollected waste is a nuisance and could serve as breeding ground for various disease-causing vectors such as mosquitoes, insects and rodents. It also endangers public health, contaminates water sources, causes emissions of odors and greenhouse gases and discourages tourism (USEPA 2002; UNEP 2005). Furthermore, due to clogging of drainage systems through solid waste disposal,

FIGURE 2. AVERAGE CHANGES IN WASTE COMPOSITION RELATED TO NATIONAL INCOME.



Source: UNEP 2011.

local flooding might increase. Impacts from waste disposal operations especially concern residents who live in the vicinity of dump sites but likewise threaten informal waste pickers who work on these dumps. Waste pickers are recognized as a marginalized and vulnerable group of around 15 million people worldwide (Durand 2013).

In total, developing nations presently spend about USD46 billion per year on managing municipal solid waste, whereas these investments could go beyond USD150 billion per year by 2025 (Durand 2013). Although many cities incur high costs for waste management, they achieve poor performances. Often, most of the available budget is spent alone on waste collection which restricts municipalities from establishing additional technologies that could reduce waste generation or increase reuse and recycling, for instance through enhanced material segregation and waste treatment technologies.

Current failures in solid waste management (SWM) have been attributed to weak institutional set-ups, financial constraints, inadequate organizational structures and policy responses, low public awareness, poorly designed collection systems, lack of collection vehicles as well as insufficient management and technical skills (Adamtey et al. 2010). In addition, mobilization of the private sector and other stakeholders that could support municipal waste management (MWM) is usually low, as is public support and cost recovery through user fees that would be needed to enable sustainable operation of SWM systems (Flipo 2012). Although the informal sector supports waste management through unorganized material recovery, most work is performed by waste pickers who usually operate on a low organizational level without proper management and adequate work safety measures (Wehenpohl and Kolb 2007; Wilson et al. 2007). Driven by poverty and demand for livelihood, the informal waste sector handles between 15 and 20% of generated MSW without any formal agreement and recognition or support from the served municipalities (Durand 2013). Main actors of the informal sector are waste pickers, also called ‘scavengers’, itinerant or stationary waste buyers, who often act as intermediaries, and consolidators who trade larger amounts of recovered materials (Wilson et al. 2007). Both the informal and formal private sectors are relevant actors in supporting MSWM, particularly related to material recovery and recycling initiatives. Although public authorities are usually aware of their contribution to material recovery, they often neglect to integrate them and especially fail to recognize and reward their efforts at waste management (Wehenpohl and Kolb 2007; Paul et al. 2012).

In general, organic wastes represent the main fraction of generated, collected and disposed municipal waste, in developing countries often to the magnitude of 50-70% (UNEP 2011; D-Waste 2013). In low income countries, where the agriculture sector provides the main source of income, composting has clear advantages for municipalities and farmers, but it may not automatically offer mutual win-win options for both parties unless it is properly planned and well-coordinated (Cofie et al. 2014). MSWM departments are mostly aware of the advantages they can gain from composting, especially by reducing cost and efforts for waste collection, transport and final disposal. On the other hand, the unavailability of land for waste disposal and high costs for construction and operation of engineered landfills call for alternative and cheaper management options and application of appropriate technologies (FAO/IWMI 2004). One hindrance for the set up and sustainable operation of composting projects is their dependency on subsidy. Although composting reduces municipal efforts and costs, especially for waste disposal, compost operations are often unsustainable, because revenues from compost sales alone usually cannot cover the plant operation costs. Composting could be performed ‘economically’ if the savings provided for reduced collection and disposal efforts through composting are made available for the project. However, most municipalities fail to provide an adequate processing fee for involved private operators who could secure ongoing recycling or composting operations.

1.2 Brief on Fecal Sludge Management

1.2.1 Fecal Sludge Generation in Developing Countries

Globally, about 2.6 billion people do not have access to improved sanitation (WHO/UNICEF 2010; Kvarnström et al. 2012; Rose et al. 2015). Whereas most residents in industrialized countries enjoy flush-toilets and connection to public sewerage systems, most households in developing countries depend on on-site sanitation systems, need to share facilities such as public toilets or have no access to toilets and hence proceed with open defecation. Graham and Polizzotto (2013) estimate that around 1.77 billion people in developing countries depend on pit latrines as their primary means of sanitation.

Excreta are the wastes produced from human bodily metabolism and consist of feces and urine (Daisy and Kamaraj 2010). Feces are usually fetid and mainly consist of water, bacteria, nutrients and food residues. They may also contain pathogenic viruses, protozoa cysts and helminth eggs; urine basically comprises of water and large quantities of nutrients that are mostly water-soluble (Vinnerås et al. 2006; Daisy and Kamaraj 2010).

Research has shown that excreta generation rates may differ considerably in various regions. Rose et al. (2015) reported average feces generation rates for high income countries as being 126 g cap^{-1} day^{-1} (wet weight) and 250 g cap^{-1} day^{-1} (wet weight) for low income countries, whereas the main factor affecting fecal mass production is the fiber intake of the population. Feces generation rates show higher variations on a global scale with 100-200 g cap^{-1} day^{-1} for Europe, e.g. 140 g cap^{-1} day^{-1} for Sweden (Vinnerås et al.

2006) but 400 g cap^{-1} day^{-1} for Africa (Mann 1999), even up to 540 g cap^{-1} day^{-1} for Kenya (Pieper 1987). As for urine, most reviewed research indicates daily generation rates in the magnitude of 1,000 to 1,500 g $capita^{-1}$ whereas the average dry solids content of urine is reported at 59 g cap^{-1} day^{-1} (Rose et al. 2015). The observed variability in the regions may reflect different dietary habits that result from various cultural, economic and climatic conditions.

Human excreta are a rich source of organic matter and plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K). About 30 grams (g) of carbon (51.7 g of organic matter), 10-12 g of N, 2 g of P and 3 g of K are produced every day through human excreta (IWMI/Sandec 2002). Most organic matter is contained in feces, while most of the N (70-80 %) and K (60-70%) is contained in urine. Phosphorus is equally distributed between urine and feces. The nutrient content of human urine (Table 1) varies with concentrations from 1.8-2.6 g L^{-1} for N, 0.2-0.4 g L^{-1} for P and 0.9-1.3 g L^{-1} for K (Kirchmann and Pettersson 1995; Jönsson et al. 2005).

Fecal sludge (FS) comprises all liquid and semi-liquid contents of pits and vaults accumulating in on-site sanitation installations, such as public and private latrines or toilets, aqua privies and septic tanks (Heinss et al. 1998; Niwagaba et al. 2014). About one-third of the world's population (approximately 2.4 billion urban dwellers) relies on such installations (Koné et al. 2010). This situation is likely to last for decades to come, since citywide establishment of sewerage systems is neither affordable nor feasible for most urban areas in developing countries.

FS represents a combination of human excreta more or less diluted with flush water and toilet paper, and sometimes other waste types such as tissue paper, food waste, sponges, bones, wood particles, textiles, plant seeds, stones, plastics and sand (Nikiema et al. 2014). Table 2 summarizes the main characteristics of human excreta and related values identified for the various FS containment systems.

Raw liquid fecal sludge (LFS) typically contains 8.2 g L^{-1} of N, 1.1 g L^{-1} of P, 2.2 g L^{-1} of K and 21.3 g L^{-1} of organic carbon

TABLE 1. AVERAGE AMOUNTS OF HUMAN EXCRETA GENERATION AND NUTRIENT CONCENTRATION.

PARAMETER	FECES	URINE	EXCRETA
g cap^{-1} day^{-1} (wet)	250	1,200	1,450
g cap^{-1} day^{-1} (dry)	50	60	110
Water content (%)			50-95
NUTRIENT CONTENT		% OF DRY SOLIDS	
Organic matter	92	75	83
Carbon (C)	48	13	29
Nitrogen (N)	4-7	14-18	9-12
Phosphorus (P_20_5)	4	3.7	3.8
Potash (K_2O)	1.6	3.7	2.7
FOR COMPARISON		% OF DRY MATTER	
	N	P_20_5	K_2O
Human excreta	9-12	3.8	2.7
Plant matter	1-11	0.5-2.8	1.1-11
Pig manure	4-6	3-4	2.5-3
Cow manure	2.5	1.8	1.4

Source: Strauss 1999.

TABLE 2. FECAL SLUDGE PER CAPITA CONTRIBUTIONS IN VARIOUS ON-SITE CONTAINMENTS.

PARAMETER	FRESH EXCRETA	SEPTAGE[1]	SLUDGE FROM PUBLIC TOILETS[2]	PIT LATRINE SLUDGE[2]
BOD (g cap^{-1} day^{-1})	45	1	16	8
TS (g cap^{-1} day^{-1})	110	14	100	90
TKN (g cap^{-1} day^{-1})	10	0.8	8	5
L cap^{-1} day^{-1}	1.5 (feces and urine)	1	2 (Includes water for toilet cleansing)	0.15-0.20

[1] Based on an FS collection survey conducted in Accra, Ghana.
[2] Unsewered systems; only assuming the received portion from pit emptying.
Source: Aalbers 1999.

(C) (Asare et al. 2003). LFS accumulation in septic tanks varies depending on water use habits, construction type, toilet use frequency and other features related to local geographical and socio-economic conditions. In Thailand for instance, LFS from septic tanks was found in variations from 135-180 L cap^{-1} $year^{-1}$ (AIT 2012), whereas filling rates of pit latrines were lower in general if compared with septic tanks (Koottatep 2014). The differences are mainly caused by the variability in amounts of water used for cleansing, evaporation and infiltration rates for liquids into the soil and level of degradation during storage. LFS contains higher levels of pathogens (e.g. *Ascaris, Trichuris*) which could cause harmful diseases if inadequately treated before being released into the environment.

Based on the discussed main parameters of human excreta generation, a city with 1 million residents would generate excreta in the magnitude of 45,000 tons feces $year^{1}$ and 510,000 m^3 of urine. These excreta would contain valuable soil nutrients if recovered as LFS with around 1,200 tons N $year^{1}$, 170 tons P $year^{1}$ and 330 tons K $year^{1}$.

1.2.2 Challenges of Fecal Sludge Management

Generally, when fecal sludge (FS) or excreta are collected from on-site sanitation installations, the extracted sludge would need to be treated prior to disposal. However, common practice in many developing countries is to transport FS from tank cleaning directly to dump sites or treatment plants or to dispose it in the vicinity into dug pits, drainage systems, natural depressions, rivers or other water bodies. FS is also being used without further treatment on farmlands, discharged into fish ponds and lakes or discarded on backyards in private compounds (Jiménez et al. 2010). These predominant methods of excreta disposal are applied by most urban dwellers in Africa and Asia as well as in many communities of Latin America.

On a global scale, most people tackle sanitation via two approaches which are the *'drop and store'* and *'flush and forget'* attitudes (Winblad 1997; Esrey et al. 2001; GTZ 2003). Water-borne sanitation as used in conventional sanitation systems in developed countries is based on the collection and transport of wastewater via a sewer system, using valuable freshwater (often drinking quality), as a transport medium (Lettinga et al. 2001). The system mixes comparatively small quantities of potentially harmful substances with large quantities of water thereby increasing the magnitude of the problem. Thus, the construction, operation and maintenance of such costly flush and discharge systems (sewer, wastewater and sludge treatment) are usually not applicable in developing countries due to high investment and operation costs. Even in developed countries, the chances that such conventional wastewater treatment systems become financially sustainable are considered low, because many sewerage systems are still subsidized substantially (Hauff and Lens 2001).

Onsite sanitation systems on the other hand include latrines, aqua privies and septic tanks and constitute the main options for capturing human excreta in low income countries. On a regular basis, they must be emptied either mechanically or manually and treated in a safe manner prior to disposal. However, most FS from tank cleaning is disposed into the environment without treatment in many developing countries. In larger cities, FS collection is more difficult and tank emptying and haulage can face severe challenges. Often, the vehicles used for emptying have no access to pits and traffic congestion prevents efficient emptying and haulage. Besides, the emptying services may be poorly managed and employed laborers are unskilled, and lack proper work safety instructions and equipment. In most cities, there are either no suitable sites for treatment and for final disposal or they are too far away and their use is avoided by haulers due to high transportation cost. To save time, cost and efforts, vacuum tankers discharge their load at the shortest possible distance from the points of collection. The malpractice of FS dumping especially affects squatter areas and low income settlements thereby worsening the health risks of those marginalized and vulnerable groups of urban residents. Children especially are at the greatest risk of coming into contact with indiscriminately disposed excreta (Ingallinella et al. 2002).

The conventional forms of sanitation systems are based on the perception of excreta being considered repulsive and 'not to be touched' (Stenstroem 1997). Therefore, design of excreta or FS treatment technologies is based on the premise that such waste is only suitable for containment and disposal (Esrey et al. 2001). Proper FS treatment, either in combination with wastewater or separately, is being practiced only in a few developing countries to some extent (e.g. Argentina, Ghana, Benin, Botswana, South Africa, Thailand, Indonesia and China). Although application of untreated FS or excreta on farmlands is attractive because of it is simple and cheap availability of organic matter and plant nutrients, in general, FS has to be treated prior to reuse or disposal. This is because of the high pathogen load and the high water content which makes it difficult to transport the sludge. However, low cost technologies that do not require skilled staff, high investment and energy costs are negligible in low income countries although they are available and applied in industrialized countries (Aalbers 1999). Conventional low cost FS treatment options include batch-operated settling-thickening units; Imhoff tanks; non-aerated stabilization ponds; combined composting with municipal organic refuse or extended aeration followed by pond polishing and anaerobic digestion (Ingallinella et al. 2002). Unfortunately, even these low cost technologies are often considered as 'too expensive' in many developing countries.

The use of FS and urine could result in various benefits within the urban context, especially for urban and peri-urban farming. Human urine for example significantly increases the yield of spinach, cabbage, tomato and cucumber compared to inorganic fertilizers (Heinonen-Tanski et al. 2007; Mnkeni et al. 2008). Municipal organic residues (both solid and liquid) represent valuable nutrient sources that can be used to improve soil fertility and sustain crop production (see Box 1). Human excreta are a rich source of organic matter and nutrients. When excreta are dewatered, its average N, P and K content is around 2.1, 2.4 and 0.5%, respectively (Adamtey et al. 2010). The fertilizer value of untreated human excreta and urine in cereal, potato, cabbage, cucumber and tomato production has been extensively studied and documented (Cofie et al. 2005; Guzha et al. 2005; Mnkeni et al. 2008). Human excreta also improved maize yields, water productivity (Adamtey et al. 2010; Guzha et al. 2005) and soil nutrient status, especially P and K (Mwakangele 2008).

Inappropriate disposal of wastewater and untreated human excreta or fecal sludge can contaminate water bodies and promote the spread of diseases, such as cholera and diarrhoea (MoH 2000; NESSAP 2008). IDRC (1998) estimated that 5.2 million people including 4 million children die every year, most of them living in cities, due to diseases caused by improper disposal of sewage and solid waste. Merchant et al. (2003) reported that child health and growth in developing countries is likely to improve if programs in water and sanitation are introduced to communities which lack these facilities. Providing safe water and adequate sanitation infrastructure as well as the practice of good hygiene are essential for protecting health and socio-economic development. Improvements in FS management can substantially reduce morbidity rates and enhance the quality of life of people living in developing countries, especially children (Mara et al. 2010).

BOX 1. FARM APPLICATION OF FS AND EXCRETA.

Many farmers in developing countries (Asia, Africa or Latin America) are keen to use FS as a readily available resource for agriculture. The usual practice in some parts of Ghana involves informal arrangements between farmers and people who clean latrines. Farmers invite these FS operators to empty their trucks on their farmlands during the dry season. The material is then allowed to dry for three to four months, before being used for the cultivation of cereals at the beginning of the farming season (Cofie et al. 2005). Although there may be monetary benefits for farmers, this practice raises concerns due to possible health risks if safe handling and processing procedures are disregarded. Moreover, the sludge itself can only be transported and placed in septic trucks, which limits its marketing potential. One better option to sanitize the sludge and to produce a safe and easy-to-handle fertilizer would be to apply a controlled treatment process such as co-composting or biodigestion.

The possibility of recycling nutrients from human excreta and MSW for use in agriculture creates a unique opportunity to likewise enhance FS management and urban sanitation.

Safe FS and wastewater recycling is not only a viable way of tackling increasing urban waste management issues in developing countries, but it also provides additional job opportunities. To date, the upscaling of promising initiatives is hindered by various barriers such as poor planning, low market development, lack of expertise, equipment and funding as well as unhygienic conditions for waste workers. Furthermore, poor stakeholder participation, lack of sectoral policies and enforcement mechanisms, bureaucracy and weak government collaboration may hinder or delay replication of innovative FSM approaches.

1.3 Use of Animal Manure for Agriculture

Historically, use of manure and other forms of organic fertilizers was the traditional practice and most widely applied method of nutrient replenishment for crop production worldwide. Although mineral fertilizer application is increasing in many countries, use of manure still contributes a very significant amount of crop nutrients on a global scale. In fact, the main crop nutrients provided by manure may reach a magnitude that is comparable to mineral fertilizer application. According to Potter et al. (2010), manure provided around 152.6 million tons (Mt) of N and P on a global scale in 2007, whereas mineral fertilizer use was reported to be 180.1 Mt (N,P,K) for 2011 (FAO 2012). Manure use is most commonly practiced in South America and Africa, whereas mineral fertilizer application prevails in North America, Europe and parts of China and India (Potter et al. 2010; FAO 2012).

The latest global livestock statistics estimate total numbers to be 1.43 billion cattle, 1.87 billion sheep and goats, 0.98 billion pigs and 19.6 billion chickens (Robinson et al. 2014). Although most livestock is scattered over many smaller farms, a significant number is raised in central production facilities where manure management becomes a relevant issue.

Use of manure may involve several activities such as collection, drying, treatment and blending with other organic wastes and transporting it to a treatment facility or a farm. Manure can also be used as an energy source, for example as a solid fuel or as biogas through anaerobic digestion that generates methane. A byproduct of anaerobic digestion is sludge which can be used as input material for composting. The choice of using manures for nutrient or energy recovery depends on specific economic conditions, geographical setting, energy and/or fertilizer demand, market development and various other factors which cannot be generalized. Because of the rising cost of commercial fertilizer and increasing emphasis on sound manure management due to environmental concerns, there is renewed interest in optimizing manure use for farming (Barker et al. 2002). Lately this trend is shared with increasing demand for manure as input material for biogas generation, especially in industrialized countries. Drivers for this development are new options arising from the carbon market that promote offsetting greenhouse gas generation from fossil fuels through use of renewable energies, which can be rewarded through 'carbon credits' based on international agreements under the Kyoto Protocol (www.unfccc.org).

In general, manure is valued by most farmers and considered as a low cost fertilizer. It could also be used as input material for co-composting depending on the local situation. In developed countries, livestock is kept in larger production sites with more than 70% of all livestock living in such facilities, while 45-80% of the livestock in low income countries is kept in smaller, resource-poor holdings (Herrero et al. 2013). Consequently, special composting projects or biodigesters are being designed to provide a suitable treatment facility for the handling of manure from large livestock production facilities in industrialized countries; however this is not so common in low income countries where compost operators could benefit from co-composting of manure that contains considerable amounts of crop nutrients as summarized in Table 3.

Manure management has to consider sanitation aspects and health risks in a similar manner as discussed later in detail for fecal sludge management (FSM). Manure characteristics are influenced by several factors, the most relevant being water content. Dilution by water, such as through rainfall, can cause leaching of nutrients and negatively affect substrate behavior in terms of storage and transportation. Manure drying on the other hand can cause N loss through volatilization. Therefore sound protection from the weather with regard to manure storage by maintaining sufficient substrate water content is a relevant factor for nutrient conservation.

TABLE 3. AVERAGE MANURE GENERATION FROM COMMON LIVESTOCK.

LIVESTOCK	AVERAGE ANIMAL WEIGHT (KG)	TOTAL MANURE ($T\ YR^{-1}$) (FECES+URINE)	TS (%)	NH_4-N[1])	P_2O_5[2])	K_2O[3])
Cattle (meat)	360	8.3	14.7	1.8	3.3	4.0
Cattle (dairy)	630	22.3	13.9	0.9	2.3	3.7
Pigs	60	1.9	10.3	3.4	4.2	4.0
Sheep	30	0.4	28.1	2.6	4.3	8.6
Horses	450	9.2	29.6	1.1	2.9	5.4
Chickens	0.9	0.024	25.6	3.0	7.4	5.3

[1] Nitrogen as ammonia in kg ton manure^{-1}
[2] P in kg ton manure^{-1}
[3] Potash in kg ton manure^{-1}
Source: Barker et al. 2002.

1.4 Global Trends of Fertilizer Application

In 2011, the Food and Agriculture Organization of the United Nations (FAO) reported annual global fertilizer consumption of nitrate-phosphorus-potassium (NPK as N+P_2O_5+K_2O) to be 180.1 Mt (FAO 2012). In 1990, the figure of 143.7 Mt was recorded (Bumb and Baanante 1996). With 1990 as a baseline, this indicates average global increase of fertilizer use of around 1.2% per annum during the last two decades. In parallel, agricultural production has increased 2.5-3 times during the last 50 years, supported by the use of mineral fertilizer, enhanced irrigation, improved seeds and better farm management technologies (FAO 2011). Out of the 179 Mt of NPK fertilizer applied on 1,563 billion hectares of arable land in 2012, N, P_2O_5 and K_2O constituted 109, 41 and 29 Mt respectively (Drechsel et al. 2015). Asia was the region with highest fertilizer demand (East Asia and South Asia accounting for 38 and 18% of global consumption respectively) while Africa only consumed 3% (IFA 2014).

Chemical fertilizer application emerged as a new global farming practice following the 'green revolution' that developed yield enhancing techniques (Mann 1999). This was supported by development of the Haber–Bosch ammonia synthesis process and a worldwide trend of mining rock phosphate and potash. These technologies allowed easier access to crop nutrients and modified agricultural practices to increase crop productivity (Tilman 1998; Vitousek et al. 1997). While manure application was the traditional practice to provide soil nutrients on farms, mineral fertilizers became widely available only in the mid-twentieth century. Since then, the intensification of existing agricultural activity through increased fertilizer application, rather than cropland expansion, has been a primary driver to increase food production (FAO 2002). While the benefits of intensified mineral fertilizer use provided higher crop yields, it has also resulted in widespread degradation of soil fertility and water quality (Richter 2007; Vitousek et al. 2009). Nutrients applied to croplands can leach into aquatic systems and alter ecosystem functions (Smil 2002). For example, excess nutrients can stimulate the growth of algae and other aquatic plants, and consequently the natural decomposition of this additional organic matter in water bodies consumes dissolved oxygen and degrades growth conditions. Some regions of the world have ample access to soil nutrients, while many others are adversely impacted by declines in soil fertility, especially where farmers do not have the means to replace the nutrients removed through crop harvesting or residues (Vitousek et al. 2009). Sub-Saharan Africa (SSA), for instance, suffers from low crop yields due to negligible replacement of crop nutrients and organic matter over the past decades (Smaling and Dixon 2006; Vitousek et al. 2009). In fact, average fertilizer use in SSA was only 11 kg NPK ha^{-1} $year^{-1}$ compared to average fertilizer use of > 100 kg NPK ha^{-1} $year^{-1}$ in other regions (Drechsel et al. 2015).

In many countries, fertilizer management is significantly influenced by two mechanisms: i) fertilizer subsidy and ii) nutrient management practices. In developing countries, fertilizer subsidy may be required to support smallholders' livelihoods and crop production for some decades to come, whereas in high income countries new quality standards are emerging to safeguard food production and environmental capital, which also influence fertilizer application. Furthermore, global market trends and price changes for fertilizer likewise affect fertilizer use (Heffer and Prud'homme 2014). As fertilizer demand often cannot be met in developing countries, the recycling of organic wastes could be a 'window of opportunity', if combined recovery and treatment of organic materials from various waste streams can be introduced and maintained on a larger scale.

2 CO-COMPOSTING OF FECAL SLUDGE AND OTHER ORGANIC WASTES

2.1 General Overview on Co-composting

Composting is the biotransformation of organic substrates in the presence of oxygen. The composting of organic material or waste allows the recovery of nutrients and organic matter for use in agriculture. Composting is a biological transformation that includes mineralization and humification of organic materials under controlled conditions into humus, whereas the latter represents a complex group of macromolecular organic compounds with high stability for safe use in agriculture. The composting process also reduces the mass and volume of organic materials through microbial degradation of organic matter and C in the form of CO_2 (Banegas et al. 2007; Gu et al. 2011; Shan et al. 2013). The composting process generates heat which creates an environment necessary for the deactivation of pathogens and seeds. The quality of the final compost depends on the control of various factors during composting which are: nutritional composition of the feedstock, C:N ratio, particle size, pH, temperature, moisture content, aeration and operational parameters such as turning frequency and monitoring. Understanding and appropriate application of these factors are major prerequisites for successful composting (UNEP 2005).

Haug (1993) provided an often cited definition of composting as follows: *"Composting is the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a results of biologically produced heat, to produce a final product that is stable, free of pathogens and seeds and that can be beneficially applied to land".*

Composting can include a wide variety of biosolids and organic wastes. In farming, composting of crop residues mixed with manures from livestock production was and is a common practice on a global scale. However, co-composting of FS with organic solid wastes is less widespread to date and replication of this recycling option will depend largely on country-specific context and socio-cultural conditions. Co-composting of FS is considered as a low-cost and appropriate technology to enhance sanitation and waste management in low income countries, especially in urban areas where on-site storage of FS is the main sanitation option for most households but proper treatment of removed sludge is often lacking.

As far back as 1987, Obeng and Wright of the World Bank and the United Nations Development Programme (UNDP) reviewed available literature and prevailing practices on the co-composting of human waste together with organic solid wastes. They highlighted the following key issues for consideration in planning for co-composting in developing countries: available waste materials, market for compost, type of technology, scale of composting, as well as benefits and justification for co-composting (Obeng and Wright 1987).

Cofie and Koné (2009) conducted in-depth research on the process dynamics of co-composting of fecal sludge and organic solid waste for agriculture and presented various options and performance data for combined treatment of FS and municipal solid waste (SW) through co-composting. The objectives were to investigate the appropriate SW type, SW/FS mixing ratio and the effect of turning frequency on compost maturity and quality. Solid waste from markets (MW) and households (HW) was combined with dewatered FS in mixing ratios of 2:1 and 3:1 by volume and aerobically composted for 90 days. Four composting cycles were monitored; the results were used to establish appropriate SW types and mixing ratios. Another set of five composting cycles was monitored to test two different turning frequencies: (i) turning once in three to four days during the thermophilic phase and every 10 days during the maturation phase and (ii) turning once every 10 days throughout the composting period. Samples were taken at every turning and analyzed for total solids (TS), total volatile solids (TVS), total organic carbon (TOC), electrical conductivity (EC), pH, ammonium and nitrate nitrogen (NH_4–N and NO_3–N) and total Kjeldahl nitrogen (TKN). Temperature, C:N ratio, NO_3–N/NH_4–N ratio and cress planting trials were chosen as maturity indicators. Results showed a preference for MW over HW and a mixing ratio of 2:1 over 3:1. There was no significant effect of different turning frequencies on the temperature changes and the quality of mature compost. The final compost product had a C:N ratio of 13:1 and a NO_3/NH_4-ratio of about 7.8, while TVS was about 21% TS and the NH_4–N content was reduced to 0.01%. A co-composting duration of 12 weeks was indicated by the cress test for achieving a mature and stable product within this research whereas a turning frequency of 10 days was chosen that allowed safe compost production with fairly high nutrient content.

In order to check options that could enhance co-composting with useful additives, Wong et al. (1997) conducted a series of co-composting tests that applied various ashes from coal power plants in China. In particular, this research was conducted to check the feasibility of using coal ash residues as additives to enhance co-composting with sewage sludge. Alkaline coal ash residues produced from a coal-fired power plant were co-composted with sewage sludge to evaluate their effects on heavy metal availability and the biological process of composting. Coal fly ash (FA) and lagoon ash (LA) were mixed with dewatered sludge adding 0, 10 and 25% (mass) to the dewatered sludge and the mixtures were composted for 100 days in laboratory batch reactors. The changes in pH, electrical conductivity (EC), CO_2 production, microbial population, soluble and extractable heavy metal contents were measured during the composting period. Following an initial increase, pH started to decrease from day 7 onward till the end of the composting period for all treatments. Sludge with FA amendment had a higher pH and EC than that of the control and LA-sludge composts. Increasing FA amendment levels resulted in a significant reduction in DTPA-extractable Cd, Cu, Zn, Mn and Pb contents of the FA-sludge composts while the reduction was less obvious in the LA-sludge composts. No significant difference in CO_2 production and number of thermophilic bacteria was observed for all treatments except for 25% FA-sludge compost which had reduced thermophilic bacterial growth and CO_2 production. The inhibition, which was possibly due to the high pH of FA, decreased with an increase in composting time. It was concluded that the co-composting of coal ash residues with sewage sludge was suitable for reducing metal concentrations in the compost product but did not exert a significant inhibition on the biological process of composting, except for 25% FA-sludge compost.

2.2 Input Materials for Co-composting

As a relevant initial step to assess the options and dimensions of a potential co-composting project—and later on to select the best suited co-composting technology—a thorough assessment of the waste generation situation and availability of suitable input materials and additives for co-composting is needed. Based on recommendations from prior research, an approach for identification of best possible technology options should consider and analyze the following key aspects of recycling (Drechsel and Kunze 2001; Cofie et al. 2008):

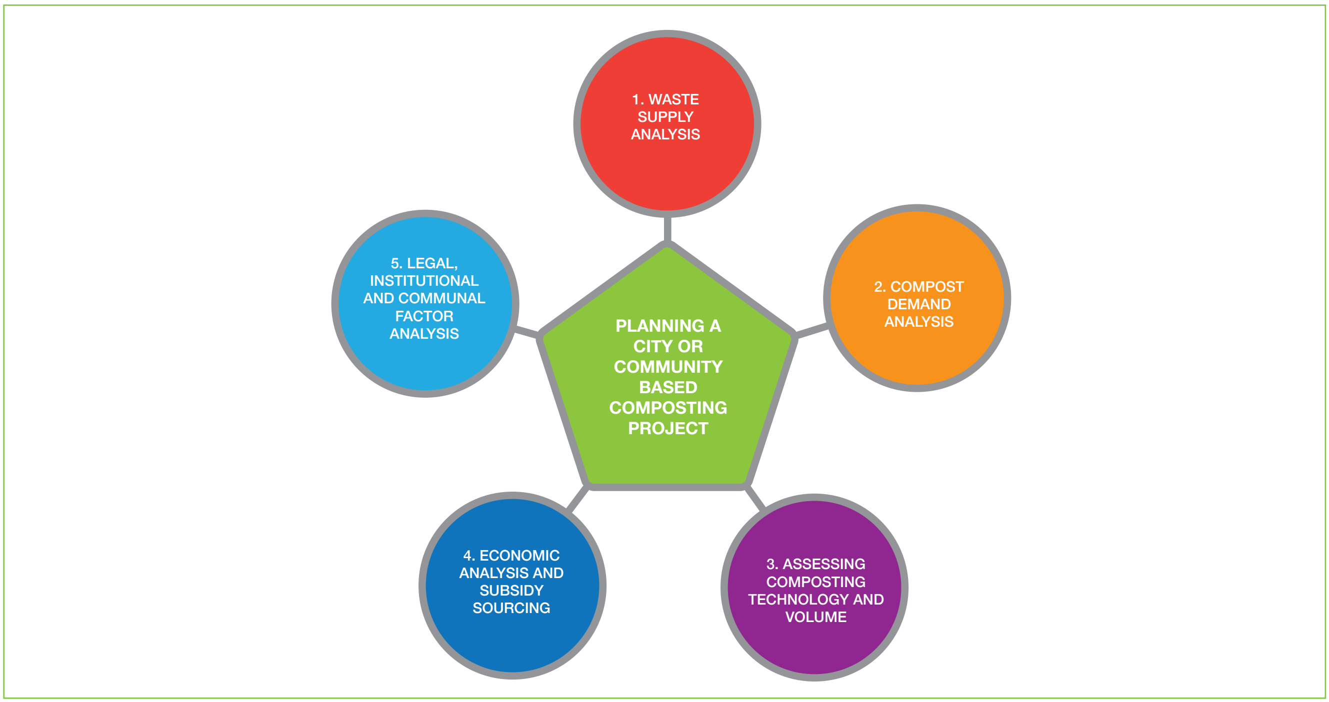
- Waste generation (quantitative and qualitative waste supply analysis);
- Compost demand by potential users (market analysis, willingness and ability to pay);
- Waste processing and scales (technical options considering supply vs. demand);
- Economic analysis (competing products, collection and processing costs, best locations, economies of scale, and subsidy sourcing); and
- Options and constraints related to legal, institutional and local communal settings.

The following discussion focuses on relevant features and parameters for selection of input materials that significantly influence co-composting as well as the pre-treatment for the composting process itself; other criteria mentioned in the waste recycling framework of Figure 3 are not discussed in detail in this publication.

Figure 4 displays the general material flow in a co-composting process. It starts with input materials on the upper left and progresses to pre-treatment activities such as sorting, drying and mixing, the co-composting process and final product distribution for either farm application or for other uses. Related details and relevant parameters for composting will be discussed in the following subsections.

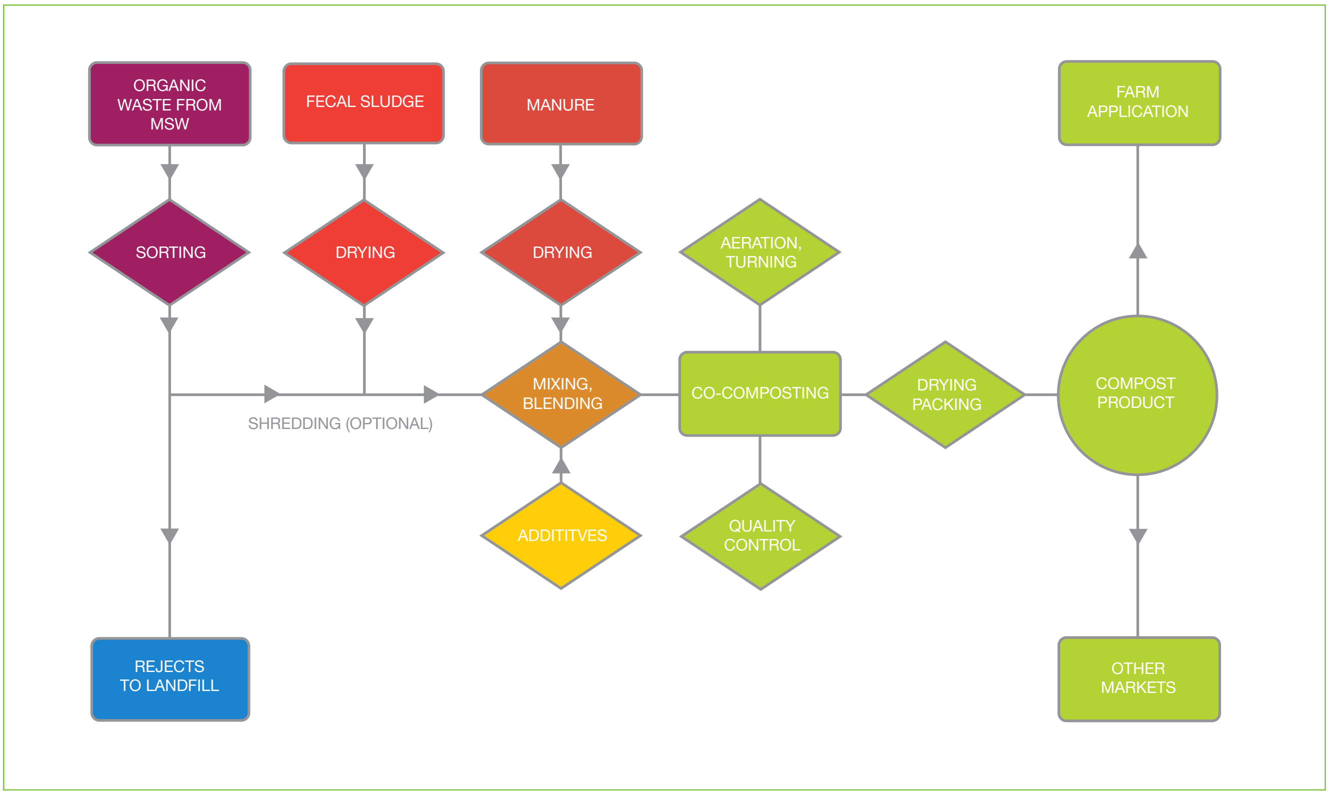
Feedstock materials for composting should be selected according to availability, cost and quality aspects and properties that favor the biotransformation process such as carbon and water content and appropriate C:N ratio. Carbon content should be at least 50% dry weight. Preferably, the material should be amenable to microbial decomposition and cost effective to use (e.g. locally available), but also suited to the proposed or applied composting technology. Although the composting of unconventional waste such as used disposable diapers together with yard waste has been reported (Espinosa-Valdemar et al. 2014), such waste would require specific adjustment and additional pretreatment technology. Manure and sludge can be processed through composting. However, due to their compactness and high moisture content, in most cases addition of a bulking agent is required to provide structural support, e.g. to create voids between particles that facilitate the composting process (Doublet et al. 2011). The types of bulking agent used have little effect on the level of organic matter stabilization and N availability in the final compost, but the time to reach organic matter stability is significantly influenced by the type of bulking agent used (Doublet et al. 2011). Additionally, the particle size of the bulking agent in the final mixture is an important factor to enhance the sludge composting process and mainly controls aeration (Wong et al. 1995; Larsen and McCartney 2000). The bulking agent may also have a diluting effect on toxic substances present in waste, e.g. sewage sludge. The type and proportion of bulking agent used will also influence the rate of decomposition, nutrient, carbon and water content and the final compost quality (Banegas et al. 2007). The most commonly used bulking agents are fibrous carbonaceous materials with low moisture content (Miner et al. 2001). Examples include cereal straw, cotton waste, husks, wood chippings or leaves, fruit pods or sawdust and materials that usually have a C:N ratio in the range of 50:1 to 80:1. In order to minimize additional operational cost incurred by purchasing, transportation and storage of the bulking agent, this input material may be adjusted to the lowest possible level but added to provide sufficient pore space in the compost matrix during the compost process (Ponsa et al. 2009). According to Gea et al. (2007), bulking agents with low particle size may offer

FIGURE 3. WASTE RECYCLING FRAMEWORK.



Source: Cofie et al. 2008

FIGURE 4. GENERAL MATERIAL FLOW AND MAIN PROCESS COMPONENTS OF CO-COMPOSTING.



better homogenous pore size distribution which acts as an efficient oxygen diffuser as well as an effective water absorber compared with bulking agents of larger particle size. Appropriate volumetric ratios for bulking agents with dewatered sludge were reported (1:1 to 3:1) by Gea et al. (2007) and Ponsa et al. (2009).

In the selection of feedstock, both green and brown organic waste should be considered in order to create optimum conditions for microbial activity during composting. Green or fresh waste or feedstock are in general higher in N content (a few percent in dry weight) or have a low C:N ratio (<30:1). Examples include fruits, vegetables, manure, fresh yard waste and kitchen scraps. Brown waste on the other hand usually have a high carbon content or higher C:N ratio (>30:1). Examples of brown feedstock are straw, rice husk, maize stalks, sawdust and other woody residues (Willson 1989; Bayard and Gourdon 2010).

Table 4 summarizes potential materials that could be used for composting. Organic waste input materials must be free from chemical contaminants. Consequently, input materials that contain potential hazardous wastes (e.g. hospital waste) should not be used for composting. In general, source separated materials are better and less prone to contamination. If mixed waste from MSW is used as input material, appropriate technologies for sorting and removal of hazardous materials should be provided.

The material quality of various feedstocks was tested in Ghana based on relevant parameters as shown in Table 5.

2.3 Health Risks Related to Co-composting

Pathogenic organisms in wastes can cause diseases. Various studies have reported microbial risks from excreta

TABLE 4. EXAMPLES OF BIODEGRADABLE/COMPOSTABLE MATERIALS.

SOURCE OF MATERIALS	TYPE OF WASTE
Residences and gardens	Garden trimmings, leaves, grass cuttings
Restaurants and canteens	Raw peelings and stems, rotten fruits and vegetables and leftover food
Market	Organic waste of vegetable and fruit markets
Agro-industries	Food waste, bagasse, organic residues
Parks and road verges	Grass clippings, branches, leaves
Municipal areas	Residential solid wastes, human and animal excreta
Dumping sites	Decomposed garbage
Animal excreta	Cattle, poultry, pig dung from urban and peri-urban farms
Slaughterhouses	Contents of digestive system

TABLE 5. TYPICAL CHARACTERISTICS OF A COMPOSTING FEEDSTOCK IN GHANA.

PARAMETERS	UNIT	HOUSEHOLD WASTE	MUNICIPAL ORGANIC WASTE	DEWATERED FECAL SLUDGE
pH		8.44 ± 0.68	9.04 ± 0.37	6.21 ± 0.99
Acidity	cmol kg^{-1}	1.03 ±1.27	2.15 ± 1.48	2.30 ± 1.61
Moisture	%	50.65 ± 0.92	68.05 ± 1.34	42.30 ± 0.42
Carbon	%	30.20 ±14.90	32.81 ± 19.08	11.39 ± 7.70
Nitrogen	%	1.43 ± 0.33	1.25 ± 0.93	1.05 ± 1.02
C:N		31.44 ± 6.93	28.49 ± 6.00	18.22 ± 11.12
K	%	1.30 ± 0.64	0.94 ± 0.03	0.39 ± 0.41
Ca	%	5.37 ± 3.77	6.17 ± 2.64	0.76 ± 0.54
Mg	%	2.32 ± 0.73	3.20 ± 2.93	3.29 ± 3.07
P	%	0.46 ± 0.30	0.54 ± 0.07	1.02 ± 0.36
E. coli	10^8 CFU g^{-1}	5.03 ± 0.91	5.70 ± 3.54	4.07 ± 2.04
Total bacteria	10^8 CFU g^{-1}	7.17 ± 2.75	2.71 ± 2.40	6.10 ± 1.05
Total fungi	10^6 CFU g^{-1}	5.10 ± 0.87	5.75 ± 5.02	4.67 ± 1.54
Clostridium	10^8 CFU g^{-1}	5.30 ± 1.30	4.50 ± 3.82	4.93 ± 1.48
Helminth	Eggs Gts^{-1}			25-83

Source: Cofie and Koné 2009.

use in agriculture (Feachem et al. 1983; Hussain et al. 2002). The survival of excreted pathogens in soils and crops is an important factor in determining the risk related to reuse or recycling of human waste. Factors that may affect the survival time of enteric bacteria in soil are numerous. In general, a greater survival time is observed at low temperatures (i.e., winter versus summer), in the presence of high water/moisture levels (i.e., in moist soils, during times of high rainfall) or in soils with greater water-holding capacity (versus sandy soils). Increased survival and possible regrowth are also observed when sufficient amounts of organic matter are present. However, survival time is lower in acidic soils (pH 3-5) than in alkaline soils (Westcot 1997).

Chemical contamination is a potential risk associated with waste recycling, especially if input materials are of industrial origin. As organic solid waste is often stored and collected together with other waste fractions, contamination of the organic fraction by chemical constituents or heavy metals in particular is possible. When applying contaminated compost, these constituents can accumulate in soils and the potential uptake by crops would result in chronic and long-term toxic effects in humans (Singh and Kalamdhad 2012).

Metals in municipal waste come from a variety of sources. Batteries, consumer electronics, ceramics, light bulbs, house dust, street sweepings, paint chips, used motor oils, plastics and some inks and glass can all introduce metal contaminants into the solid waste stream (Smith 2009). Composts may inevitably contain these elements, although mostly in low concentrations, even if foreign elements have been removed through sorting. In small amounts, many of these trace elements (e.g. boron, zinc, copper, and nickel) are essential for plant growth. However, in higher amounts they may decrease plant growth. Other trace elements (e.g. arsenic, cadmium, lead and mercury) are of greater concern primarily because of their potential to harm soil organisms or plants or by entering the food chain. The impact of these metals on plants grown in compost-amended soils depends not only on the concentration of metals and soil/compost properties as mentioned above, but also the kind of crop grown. Different types of plants can absorb and tolerate metals differently. Special care might be needed if, for example, mushrooms are cultivated on soil ameliorated with compost that contains mercury or cadmium. The application of composts might, however, increase the metal content of uncontaminated soils. This could also pose a risk to animals in the area who might ingest the composted soil directly.

Further nonpathogenic risks result from impurities of non-biodegradable origin such as glass splinters or other sharp objects contained in the compost product. Such impurities can result from insufficiently sorted municipal solid waste before or after the composting process. These risks also include indirect health risks due to the attraction and proliferation of rodents and other disease-carrying vectors (Furedy and Chowdhury 1996).

Health risks can be minimized if adequate control measures are consistently practiced, and co-composting workers adopt basic precautions and hygienic practices (Keraita et al. 2006). As most risks are related to the composition of the waste material, the quality of separation is a crucial indicator for risk reduction. The second factor is the composting process. If correct compost temperatures can be obtained in all parts of the pile (e.g. through turning), risks related to pathogens will be minimized as reported by various research (Cofie and Koné 2009; Koné et al. 2007). Another strategy for risk reduction is the continuous monitoring of compost quality and the provision of sanitation facilities for compost workers.

2.4 Waste Pretreatment for Co-composting

2.4.1 Fecal Sludge Pretreatment

Depending on the source of FS, some form of pretreatment will be needed prior to co-composting. Usually human excreta from public toilets and septic tanks are too high in moisture content (95-97%) and need to be dewatered prior to composting with organic solid waste to ensure aerobic composting. This requires the use of solid-liquid separation systems such as unplanted drying beds, constructed wetlands or thickening/settling tanks. The effluent from these systems must be treated (for example in facultative and maturation ponds, constructed wetlands) to meet discharge guidelines before being discharged into receiving water bodies. The effluent can also be used for watering the compost windrows at the early stages of composting or as irrigation water in peri-urban farming provided its quality meets the standards set for unrestricted irrigation. Nikiema et al. (2014) provide more information on selected solid-liquid separation technologies that can be used prior to co-composting.

2.4.2 Solid Waste Sorting

As solid wastes could have negative impacts on the final compost quality, it is important to ensure proper separation of organic from inorganic and especially hazardous materials. Usually an organic fraction of household waste, market waste or agro-industrial waste is recommended for use in co-composting. The solid waste should be mixed with the pretreated (e.g., dewatered FS) in the appropriate proportion to ensure an optimal composting process (Cofie et al. 2009).

2.5 Co-composting Technologies

Two main types of composting systems are generally distinguished: 1) open systems such as windrows and static piles and 2) closed 'in-vessel' systems. These in-vessel or 'reactor' systems can be static or movable closed structures where aeration and moisture are controlled by mechanical means. Such systems usually require an external energy supply, either by electricity or through decentralized electricity generators, whereas the latter is often provided by diesel engines. In general, in vessel or reactor systems require higher investment compared with static systems and are also more expensive to operate and maintain. Static composting systems on the other hand, require much lower investments and are hence the preferred option for composting in developing countries. Among them, windrow composting is the most commonly applied system.

The identification of the best-suited option for composting depends on numerous parameters. The main choices to be made are related to a) scale (household, community, commercial), b) input materials, c) business models (public, private or combined), d) demand and market situation, e) investment and operation cost, f) technology option and equipment, f) standards and legal framework and g) environmental and health concerns as shown in Figure 5. Decision-making has to be done on a case-by-case basis aiming at the highest possible cost- and co-benefits and sustainability level for the operator, community, stakeholder and the environment.

Different technological options are available to establish a specific composting project, as presented in Table 6.

FIGURE 5. MAIN FACTORS THAT INFLUENCE DECISION-MAKING TO SELECT A SITE SPECIFIC COMPOSTING TECHNOLOGY.

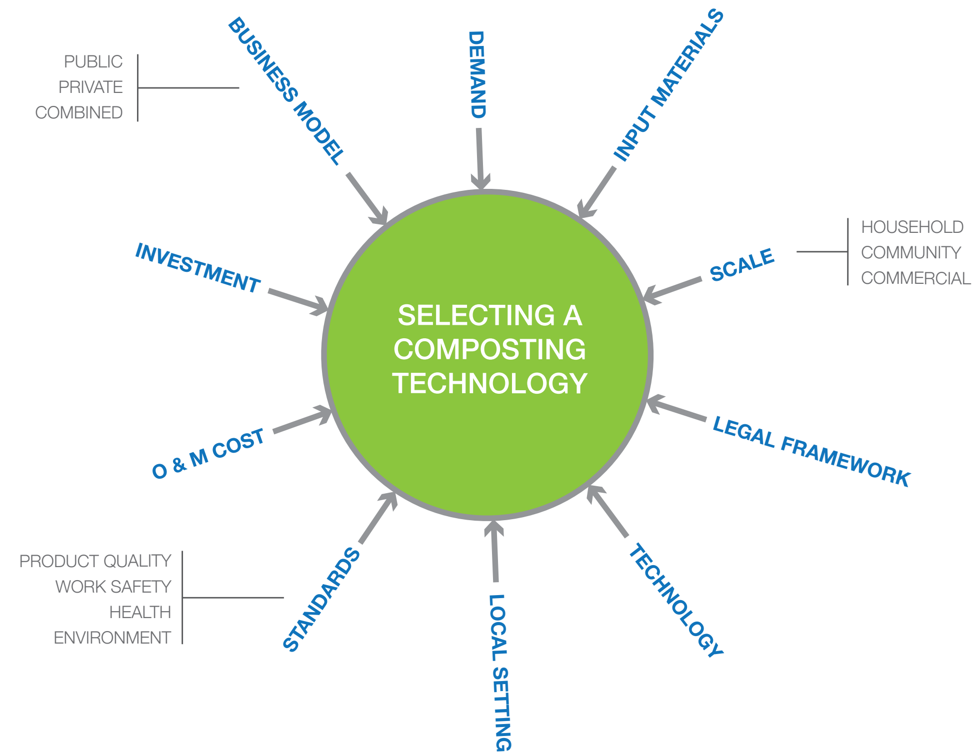


TABLE 6. ADVANTAGES AND LIMITS OF COMPOSTING TECHNOLOGIES.

	KEY FEATURES	ADVANTAGES	DISADVANTAGES
Static pile [a,1]	▪ Static piles are the simplest form of composting ▪ Typically larger than heap size whereas heaps are usually not turned ▪ Generally ideal for feedstock with larger particle size and higher porosity	▪ Requires minimal management and equipment ▪ Aerobic conditions can be achieved if the porosity in the initial pile is high (>60%) and if there is a high proportion of bulking materials to keep pores open for air exchange	▪ While simple, this method takes longer to produce matured compost; the final product is often quite heterogeneous due to the lack of mechanical treatment and physical breakdown of feedstock during the process. ▪ Anaerobic conditions can occur in the core of the heap which can also result in odor emissions
Trench and pit composting [a,2]	▪ Characterized by heaps which are partly or fully contained under the soil surface ▪ Structuring the heap with bulky material or turning is usually the choice for best aeration ▪ In some cases, composting materials are completely buried in the trench which then serves as a planting bed	▪ Requires low capital investment ▪ Requires less moisture, thus suitable for dry areas	▪ Control of leaching is difficult in trench or pit composting ▪ Monitoring the composting process is difficult ▪ The process is labor-intense, especially digging of the pit and emptying it

CONTINUED

TABLE 6. ADVANTAGES AND LIMITS OF COMPOSTING TECHNOLOGIES. *(CONTINUED)*

	KEY FEATURES	ADVANTAGES	DISADVANTAGES
Aerated static pile/heap [b,3]	▪ Aerated static pile (ASP) composting is comprised of forcing (positive) or pulling (negative) air through the pile. ▪ In a static aerated pile, a 15-30 cm thick layer of finished compost or wood chips is placed all around the MSW pile to provide insulation. This arrangement minimizes odor generation and also leads to uniform sustained heating of waste leading to destruction of plant pathogens and weed seeds ▪ The ASP can be used together with other composting technologies at the curing stage	▪ The land requirements for this method are lower than that of windrow composting ▪ The technology allows for capturing and treating air to reduce odor generation ▪ Large volumes of feedstock can be treated with the help of aeration systems	▪ The primary disadvantage of using this technology is the lack of mechanical agitation, which slows down physical breakdown of materials ▪ Usually suitable for feedstock of similar consistency and homogenity ▪ The compost pile/heap can dry out quickly and therefore requires regular monitoring ▪ The aeration system may require capita-intensive installations
Windrow composting [a,b,4]	▪ The material is piled up in heaps or elongated heaps (called windrows) ▪ Suitable for outdoor composting in piles that rely on passive, manual or mechanical aeration ▪ Some portions of waste piled up in the windrows may not be exposed sufficiently to a temperature of over 55 °C for a period of 7-10 days	▪ Can be low cost ▪ Windrow composting produces the highest volume reduction compared to static piling (passively aerated with minimum turning) and forced aeration (static aerated pile) ▪ Introducing air mechanically speeds up the composting process and greatly reduces emissions of methane ▪ Methane emissions from windrow composting are comparably lower, e.g. passively aerated piles produce higher methane emissions (x100) than windrow turned piles whereas forced aeration piles produced even 1,000 times greater methane emissions	▪ Anaerobic conditions could occur in the core of large piles or windrows, and together with a larger emitting surface, could result in odor generation ▪ Such plants often experience resistance from the community where they are set up ▪ Should be sited with consideration of the risk of odor ▪ Workers are in close contact with material during composting ▪ The minimum windrow/pile size must be 3 m^3
In-vessel (Enclosed) composting [a,b,5]	▪ Refers to a group of composting systems, which range from enclosed halls to tunnels and containers, rotary drum or bins ▪ Often have one exhaust air outlet	▪ Allows easy collection and discharge (through a chimney) or treatment of air (e.g. biofilter) to minimize emissions of odors and greenhouse gases ▪ Operating temperature is uniform, more efficient in sterilizing the compost compared to open composting techniques ▪ Production of leachate is low (can be recycled if any) ▪ Requires less processing time (2-3 weeks) and less labor ▪ Less land requirement ▪ Effect of weather on the composting process is limited ▪ Public acceptance of the facility is higher	▪ More costly than other units and, in addition, more equipment maintenance is required ▪ Skilled labor required for operation and maintenance ▪ Comparable higher investment cost and energy consumption ▪ Additional cost for operation and maintenance ▪ There is a need to treat exhaust air
Vermicomposting [a,b,6]	▪ A non thermophilic, biooxidative process that uses earthworms and associated microbes to transform organic waste into rich humus, similar to compost ▪ Local varieties of both surface and burrowing earthworms can be used ▪ In broad-scale vermiculture[7], the earthworms are introduced to organic waste piled in elongated rows that are covered with protection layers to prevent water logging[1] ▪ Appropriate process indicators are survival rate, biomass production and reproduction of earthworms	▪ Both pathogens and weed seeds can be destroyed in the intestines of worms during vermicomposting. Protozoa and fungi are important parts of their diet ▪ The earthworms mix, grind, aerate, fragment and digest waste ▪ Vermicomposting hastens the decomposition process by 2-5 times ▪ Produces much more homogeneous materials compared to thermophilic composting ▪ It is particularly suited to urban agriculture because it can be applied in a variety of settings and at different scales	▪ A pre-composting may be required before earthworms are added to the mixture ▪ Tolerates temperatures between 0 and 40 °C with pH of 7, while optimal growth is at temperatures from 25-40 °C ▪ Optimal moisture content: 40-45%. Higher moisture content may result in the death of earthworms ▪ Organic matter is rich in nitrogen ▪ Sorting is required after composting to allow removal of earthworms ▪ Earthworms may die when conditions are unfavorable; e.g. anaerobic ▪ They may be affected by pests/mites

[a] decentralized; [b] centralized

Sources:

1 Cooperband 2002; Hansen et al. 1995 (available at http://ohioline.osu.edu/).
2 Strauss et al. 2003.
3 Nema 2009; Composting Council of Canada 1999.
4 Cooperband 2002; Gruneklee 1998; Nema 2009; Lopez-Real and Baptista 1996; Brinton 1998.
5 Litterick et al. 2003; Singh et al. 2012; Cooperband 2002; USEPA 2000.
6 Adi and Noor 2009; Pathma and Sakthivel 2012; Bhatnagar and Palta 1996; Atiyeh et al. 2000.
7 Mid-to-large-scale vermiculture is an emerging composting approach that is being increasingly applied in developing countries (Guerro and Guerro-del Castillo 2005; Sherman-Hunloo 2000).

All composting technologies allow production of a safe recycling product but require variable processing time, process control, human and financial resources while having different impacts on the environment and health.

The degree of compost stability attained within a certain time is a key indicator which can be used to compare different composting techniques (Singh et al. 2012). Decomposition of organic matter through composting can be achieved in the presence or in the absence of oxygen. Therefore, different composting methods involve either aerobic (with oxygen), anaerobic (without oxygen) phases and sometimes even alternate between the two during the decomposition process. Under anaerobic conditions, composting is often achieved at mesophilic temperatures with the disadvantage that the process temperature may be too low to efficiently eliminate pathogens that are especially present if organic input materials from municipal waste management, manures and fecal sludge are utilized for composting. Anaerobic conditions may also generate strong odors which could pose a major nuisance in urban areas. Conversely, under aerobic conditions, composting is achieved at thermophilic temperatures due to the accelerated growth rate of bacteria that results in a higher biodegradation rate of the waste. As a result, pathogens are more quickly eliminated. A composting facility which is not well managed could generate odor that can expand over a radius of 2 to 3 kilometers (km) around the plant and bother residents. This could even be a reason for plant closure for example the compost plant at Thane (near Mumbai) in India that had to be dismantled in 2002-2003 after court intervention (Nema 2009). In a similar case, the Woodhue composting facility in New Jersey, USA in 2004, had to divert food residues used as input material for composting for 2 months following complaints from people living nearby the site (Goldstein and Goldstein 2005).

2.6 Feedstock and Operation Requirements

In the following section, key factors affecting the biological decomposition process and resulting compost quality are discussed. The formulation of a feedstock largely influences C:N ratio, porosity, moisture content, pH and nutrient content, while other factors actively influence but also change during the composting process such as moisture content, microorganisms involved, temperature, aeration and nutrient loss.

2.6.1 C:N Ratio and Other Nutrients

Carbon, water, nitrogen, phosphorus and potassium are the main substances needed to enable optimum microbial activity during composting besides sufficient aeration. Their availability during the process significantly influences the compost product and its value (Cooperband 2000; Turovskiy and Westbrook 2002; Tognetti et al. 2007). Carbon is the primary energy source for microorganisms while N, P and K are the primary nutrients. During composting, even though P is sometimes limited, C and N (which serve for building cell structure) are the main elements to be monitored closely. Although bacteria also need trace amounts of micronutrients such as sulphur (S), sodium (Na), calcium (Ca), magnesium (Mg) and iron (Fe), these elements are usually present in waste at sufficient quantities and therefore often have a limited impact on microbial growth but do not limit bacterial activity (Hoornweg et al. 2000).

The ideal ratio of C:N to enable composting should fall between 25:1 and 35:1 (Strauss et al. 2003; Bernal et al. 2009; Guo et al. 2012). This ratio corresponds with the fact that most bacteria need approximately 30 g of C for 1 g of N uptake. Insufficient N (i.e., C:N ratio > 35) will hinder microbial growth, which will slow down the composting process because microorganisms are forced to go through additional cycles of carbon consumption, cell synthesis, decay, etc., in order to burn off the carbon (GTZ 2000; Bernal et al. 2009). In contrast, too much N (i.e., C:N ratio < 20) allows rapid microbial growth through fast consumption of carbon and this accelerates decomposition and quick oxygen depletion. But quick oxygen depletion may cause anaerobic conditions. In addition, the composting process will experience higher losses of N as ammonia and nitrogen oxides because inorganic N is generated in excess (Bernal et al. 2009; Zigmontiene and Zoukaite 2010). Both phenomena are the main reason for odor generation due to wrongly set C:N ratios of input materials in compost plants. Therefore it is essential to ensure that the feedstock used for composting is chosen carefully and the C:N ratio adjusted before the composting process starts (Bernal et al. 2009; Nema 2009).

Mixing various feedstock allows control of the average C:N ratio as some raw materials are high in C while others are high in N. In practice, the ideal combination of different feedstock types can be determined by experimentation and experience (Guo et al. 2012; Ch'ng et al. 2013). As a rule-of-thumb, the mixture of equal volumes of 'green' materials (rich in N, e.g., fresh grass clippings, manure, garden plants or kitchen scraps) and 'brown' input materials (high C content, e.g., dried leaves and plants, branches and woody materials) provides an appropriate C:N ratio (Willson 1989; Bayard and Gourdon 2010). Furthermore, it should be considered that carbon-rich input materials may differ considerably related to the bioavailability of contained C. This is of particular concern because some C-rich materials (wood and other lignified plant materials such as sawdust) are known to be more resistant towards biodegeneration than many other organic materials (Cooperband 2000). In such cases, the C:N ratio must be above 30:1 as recommended earlier because a certain portion of the carbon is not easily available for microbial activity.

After completion of the composting process, around 50% of the C from the organic matter of input materials is lost as CO_2. The higher the organic matter loss, the higher the temperature is increased during the process (Singh et al. 2012). Whereas the input volume is mostly reduced to around 50% after compost maturation, the weight of the final product will be reduced by 30-40% if compared to the inputs (Bayard and Gourdon 2010).

2.6.2 Porosity and Particle Size

Porosity is a key composting factor determined by the particle size distribution, the shape, the texture and the moisture content of the feedstock. It determines air distribution during the composting process, i.e., the maximum amount of O_2 available during the composting period (Bernal et al. 2009). Feedstock with larger particle size may not be decomposed adequately in a reasonable time. In addition, when porosity is > 50% for an open composting system (e.g., a windrow), the temperature may not increase sufficiently to the expected values within the pile because of energy losses since the heat easily escapes through the larger pores. Microorganisms need to attach to the particle surface to grow; consequently a higher surface area is preferable because it favors bacterial growth. Larger particle size of input materials will result in lower total surface area compared with smaller particle size. Consequently, the smaller the particle size of organic waste components (e.g., achieved through shredding, chipping or mixing), the faster the biodegradation process. This is significant, especially to accelerate composting of slow degradable woody materials. However, feedstock with very small particle sizes can reduce the porosity within the compost heap too much, which especially hinders the early stages of composting. Besides, it also increases the tendency to compact, which could further negatively affect the aeration of the material (Cooperband 2000; Bernal et al. 2009).

Based on the discussed requirements, optimum particle size ranges from 1 to 2.5 cm for composting methods that apply forced aeration systems, and from 5 to 10 cm for methods that use passive aeration combined with mechanical or manual heap turning (Obeng and Wright 1987; GTZ 2000). With this approach a porosity level of 35-50% may result in the pile, which from experience was found to be satisfactory to enable aerobic conditions. To compost input materials with very small particle sizes and high tendency for compaction (e.g., manures or fecal sludge), C-rich materials such as sawdust, rice husks or similar materials were found to be very useful as a bulking agent, to adjust mixture quality, to increase porosity and to optimize the composting process (Chen et al. 2010; Singh et al. 2012).

2.6.3 Moisture

Regarding biological activities, the presence of water is also essential for microbial growth during composting and needs to be maintained at the proper level in order to achieve optimum degradation. It also serves as a means to convey crucial nutrients and assists in the dissipation of heat (Strauss et al. 2003; Bernal et al. 2009). Optimum moisture content varies with the type of feedstock used (e.g., the coarser the material the higher the moisture content could be) as well as with the composting method. Optimal moisture content lies between 40 and 65 percent by weight (Bernal et al. 2009; Kumar et al. 2010). Moisture levels > 65% hinder the decomposition process, promote nutrient leaching and may trigger anaerobic degradation because interparticles air spaces within the compost are filled with water and cannot be supplied with oxygen. This can result in foul smell, especially for materials with low C:N ratio (Cooperband 2000; Bernal et al. 2009). However, moisture levels < 40% reduce microbial activity and could even lead to their inactivation or decay. Due to changes in temperature, microbial growth/decay and volume losses related to the ongoing biodegeneration in the compost heap, moisture varies as well and needs to be adjusted to maintain an efficient composting process.

Adjusting the moisture level is often achieved simultaneously with aeration, i.e., during turning of the compost. In a closed vessel, water addition may not be required considering that the water losses could be minimal (Chen et al. 2010; Singh et al. 2012). When needed, moisture level in compost can be easily increased by sprinkling liquid on the material, e.g., water, or a mixture of urine and water (recommended mixing ratio of 1:4, as the growth of the microorganisms are boosted by urine which is rich in urea) while the mixing allows humidifying to be uniform. When the composting is achieved in an open mode, the facility must be covered or roofed to allow better control of moisture (see Box 2). This would protect the composting material from rain and reduce infiltration into the composting heap which would otherwise cause excessive moisture. It also protects against excessive heat which would increase evaporation and eventually lead to dryness. To establish optimal moisture levels during composting, there are simple field tests for rapid assessment that can assist process control and adjustment:

1. Fill the hand with compost (the composting material must feel damp to the touch); press or squeeze the compost strongly with the hand; if a few drops of liquid are released this would indicate water content fairly high.

2. Put a bundle of straw in the heap for five minutes. Upon removal, it should feel clammy. If still dry, the moisture level is too low while presence of water droplets on the straw indicates that the moisture level is too high.

BOX 2. CONTROLLING HEAP MOISTURE.

Heap moisture must be monitored and adjusted by watering when necessary to about 50-60% during the active phase of composting (2 months). During the maturation phase (1 month), the heap moisture must be maintained at 40-50%.

2.6.4 Temperature

Temperature is both an operating parameter, which must be controlled during the composting process, as well as an indicator of biological activity during composting (see Box 3).

BOX 3. CONTROLLING HEAP TEMPERATURE.

A thermometer with a long probe could be used to monitor temperature during composting. Ideally, temperatures should be recorded daily.

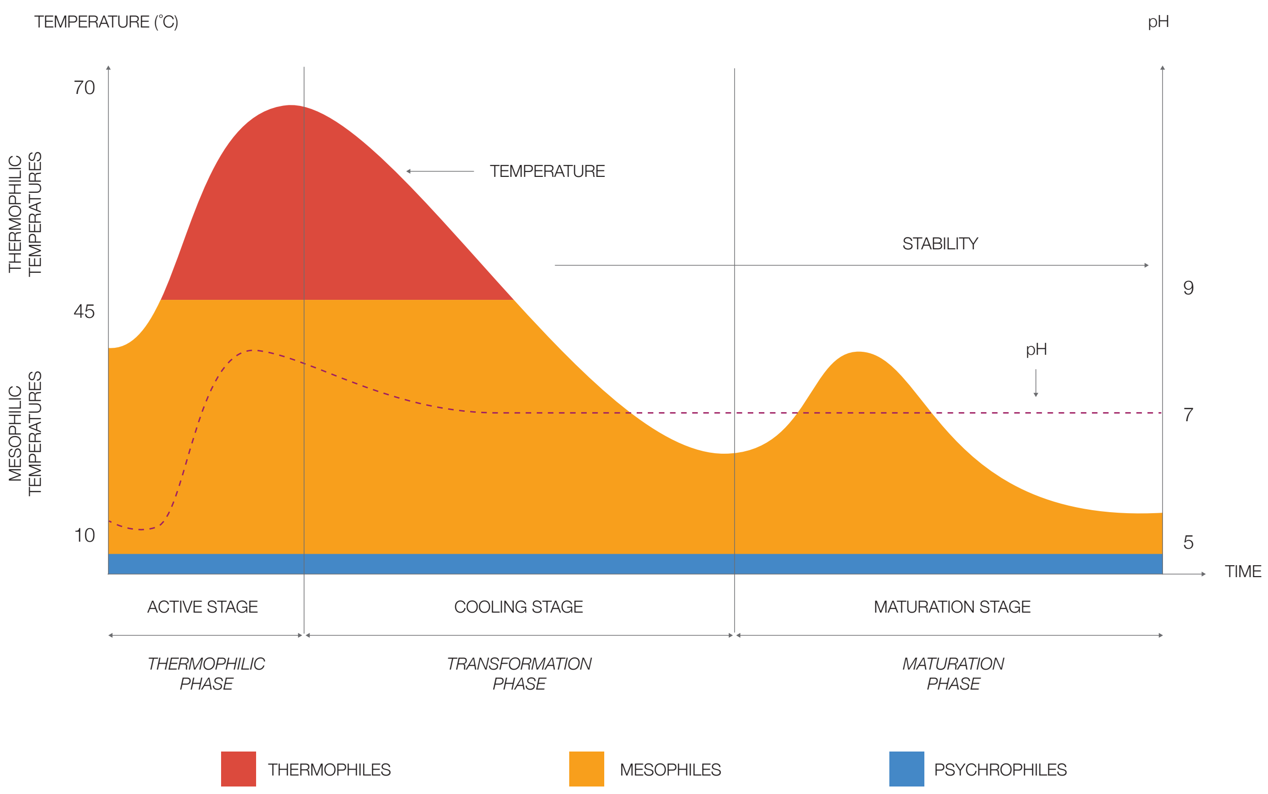
Temperatures must be measured in the inside (up to a depth of 1 meter) and outside of the windrow at different and sufficient points to provide a temperature profile of the composting material. The average temperature value for inside and outside can then be calculated and recorded.

Temperature control is an essential part of the composting process. Temperature must be recorded to confirm that its profile is satisfactory for pathogen reduction and destruction of weed seeds, and that the rate of decomposition of waste is satisfactory. Temperature measurements must be documented for traceability.

During composting, two main stages are often differentiated: the oxidative phase and the maturation (or curing) phase. In fact, during the aerobic oxidative phase, thermophilic temperatures develop independently of ambient temperatures because of the heat generated in aerobic/exothermic decomposition of waste (Wang et al. 2013). Temperature of a compost pile or inside the compost reactor at this point in time is mainly affected by the material characteristics (moisture content and readily biodegradable organic matter content), or operating conditions (turning frequency, aeration method, size of the compost pile, type of composting device) (Wang et al. 2013). During the first days of composting, the temperature increases steadily in proportion to the amount of biological activity until equilibrium, until heat loss is reached or the feedstock is used up. With adequate levels of oxygen, moisture, C and N, compost piles can heat up to temperatures in excess of 65 °C (Chen et al. 2010; Wang et al. 2013). Such high temperatures have a negative impact on microbial activity and can become lethal at 70 °C (Bernal et al. 2009; Luangwilai et al. 2011; Singh et al. 2012). This explains why temperatures must be reduced at this point in time, e.g., through turning or forcing air through the compost heap and humidification.

A typical temperature profile is as follows: Increase of the material to temperature levels from ambient temperature to 60-70 °C within 1-3 days; stable temperature in the range of 55-65 °C for 2-3 weeks; gradual decrease in temperature for up to 4-6 weeks on levels from 40-55 °C. Conversely, an aerobic system that is unable to achieve expected high temperatures is an indication of process failure. Unfavorable conditions will extend the process duration, increasing the time needed for these steps to be achieved (Wang et al. 2013). Figure 6 shows a typical temperature sequence as observed during the first three months of composting:

FIGURE 6. TEMPERATURE/PH CURVES AND STAGES OF BIOTRANSFORMATION OBSERVED DURING COMPOSTING.



Source: Modified from Waste Balkan Network n.d.

After the thermophilic-mesophilic phase, which allows the rapid decomposition of readily available organic matter, the maturing or curing phase begins, which is characterized by low microbiological activity and initial temperatures of around 40 °C (Razali et al. 2012; Bien et al. 2013; Wang et al. 2013). As the compost becomes mature (i.e., all biodegradable material has been decomposed), the temperature in the compost heap approaches ambient temperature conditions. This indicates that the compost has become stabilized and as the overall rate of decomposition decreases, heat generation also reduces (see Box 4). This step is essential for the quality of the final compost product and to meet regulatory compost quality standards. It also helps to prevent on-site and off-site nuisance (e.g., odor, dust, litter, birds and vermin).

BOX 4. PATHOGEN CONTROL.

- Higher temperatures are not always better; generally, microbial activity is maximized around 45 °C, the temperature where the mesophilic and thermophilic microorganisms thrive.
- Microbial activity may become severely affected if longer exposure above 70 °C occurs, which results in slower decomposition and N loss especially at low C:N ratio. When the temperature reaches such high values, an intervention must be made to reduce the temperature.

The duration of the curation period is often between one and two months, even though longer periods (≥ six months) have been applied in some instances depending on the feedstock (Cooperband 2002) (see Box 5). During the curing period, the NH_4-N to NO_3-N ratio decreases through nitrification of NH_4-N to NO_3-N, and the pathogenic load decreases while the organic/volatile matter content of the feedstock decreases.

BOX 5. CURING AND MATURATION PHASE.

Specific activities during the curing phase and finishing operation can include:

- Discharge from enclosed systems.
- Occasional turning of the material, for moisture content adjustment or air supply (at least once per month, ideally once a week). Optimal moisture levels should be maintained in the range of 40-55%.

The presence of offensive odor indicates that compost is not yet mature. Mature compost produces an earthy smell.

2.6.5 pH

Organic material can be composted within a pH range of 3 to 11 providing a wide range of environmental conditions that favor microbial growth. In most cases, pH of feedstock does not represent a major issue for decomposition of organic waste. Whereas most bacteria prefer a neutral pH, fungi develop better in a less acidic environment. Optimal pH values for the composting process are between 5.5 and 8 whereas the end product usually shows pH values in the range of 4 to 7 (Ch'ng et al. 2013). However, it has been reported that low pH values (below 6) can inhibit the transition from mesophilic to thermophilic phases in composting (Sundberg et al. 2004).

During the initial phase of the composting process, the pH may drop down to as low as 4, depending on the used input materials, as organic acids are formed (Himanen and Hanninen 2009; Singh et al. 2012). Subsequently, microbial ammonification will cause the pH to rise to pH levels of 8-9 (typically from day 5 onwards). An increase in pH could be attributed to increase of thermophilic bacteria (Ahmad et al. 2011). At pH > 7.5, ammonia loss becomes particularly high (Bernal et al. 2009). Furthermore, during the starting phase of composting, pH values are also affected by CO_2 levels from the various feedstock materials. Therefore, sufficient aeration, that decreases CO_2 levels, supports increase of pH levels and reduces ammonia loss.

Only during maturation, when the ammonium compounds are nitrified to nitrate, will the pH decrease once more below or around 8. If the pH in the final compost is rather high this is an indication of immature compost, meaning the maturation phase is unfinished.

Monitoring of pH during composting may be useful to adjust new mixtures but is not absolutely essential.

2.6.6 Microorganisms and Invertebrates

The breakdown of the feedstock during composting is carried out by a succession of microorganisms (predominantly bacteria, actinomycetes, fungi and some protozoan) and during the maturation phase supported by macrofauna such as worms, ants, flies, mites and nematodes especially in pit or trench composting methods (Cornell Composting 1997; Bayard and Gourdon 2010; Singh et al. 2012). Thus the rate of biological decomposition depends mainly on the efficiency of microbial activities. Consequently, all factors that affect microbial growth and metabolism are relevant for process control and optimization. In general, the growth rate of aerobic microorganisms is higher than that of anaerobic ones. Aerobic processes are an efficient treatment method if compost production is the main target whereas anaerobic processes are the preferable option if energy production is targeted (Bayard and Gourdon 2010).

Microorganisms that support the composting process show a wide variation related to their optimum living conditions, especially pH and temperatures. Three main groups are distinguished by their optimum process temperature. They are called 'psychrophilic' when their optimal growth temperature falls in the range 5 to 20 °C, 'mesophilic' for temperatures between 20 and 50 °C and 'thermophilic' for temperatures in the range of 50 to 70 °C. Considering that the composting process involves a wide temperature range, diverse microorganisms are necessary for the stepwise decomposition of the organic matter to produce stable compost (humic substances and nutrients). A properly arranged compost feedstock needs materials and conditions that enable an interactive biological and ecological system, i.e., a diversity of microbial species and conditions that allow their gradual development for emerging in response to changes in the nutritional and environmental conditions of the compost pile, including alterations of temperature and pH (Bernal et al. 2009; Bayard and Gourdon 2010; Sundberg et al. 2011). In most cases, the feedstock contains sufficiently diversified microbial populations, which excludes the need for enrichment at the beginning of the process. However, to safeguard a proper and efficient start-up phase of composting, adding of mature compost into the fresh compost input materials has proven useful (Bayard and Gourdon 2010). To avoid or minimize start-up problems, an inoculation of around 5-10% mature compost of total input material is recommended (Bayard and Gourdon 2010).

In the initial stage of composting, when temperature rises up to 50°C during mesophilic conditions, microbes dominate the composting process. As temperature rises, thermophilic bacteria take over. The thermophilic phase can occur within a few hours to five days and is especially accelerated if the feedstock is made up of components that can easily be degraded by microbes (Cofie et al. 2009; Yu and Huang 2009; Himanen and Hanninen 2011; Zu et al. 2011; Razali et al. 2012). The presence of toxic substances (e.g., heavy metals) can reduce the level of thermophilic temperatures (Banegas et al. 2007). Most fungi and actinomycetes are mesophiles and can barely withstand high temperatures, compared to the thermophilic bacteria. If excess heat is removed by ventilation or turning, these populations will be maintained while overall rates of bacterial activity will remain high (see Box 6). After thermophilic bacteria have used up the most easily available substrates, a deceleration in their thermophilic microbial activity occurs, because they can no longer produce heat to maintain high temperatures. As temperatures reduce, actinomycetes and fungi populations increase, allowing more complex substrates (e.g., organic polymers) to decompose (Bernal et al. 2009). As temperatures drop further the remaining substrates, which are more resistant to decomposition, are degraded by fungal populations. Various invertebrates such as mites, millipedes, beetles, earwigs, earthworms, slugs and snails also contribute to the maturation process by altering the physical and chemical conditions of the substrate, e.g., through mixing and digestion of compost particles. Besides, their burrowing activities support aeration of the compost pile whereas their excreta change particle size, and surface area and provide nutrients for microbes for continued biodegradation (Dominguez and Aira 2011; Ismail 1997).

BOX 6. NECESSITY OF COMPOST TURNING.

- To inactivate pathogens, the composting material must be maintained at a temperature of at least 50 °C for longer than four weeks during the thermophilic phase of composting.
- Turning of compost is essential for uniformity and to ensure that all materials are sufficiently exposed to the 50 °C minimum temperature. A minimum turning frequency of one turning per heap every 10 days should be applied.

During the process, the total microbial population varies following the gradual changes and biochemical conditions, especially in response to changes of process temperature. However, microbial composition remains nearly stable during the maturation period (Abouelwafa et al. 2008).

2.6.7 Aeration

Aeration provides the necessary aerobic conditions for rapid and odorless decomposition of the organic matter and generation of thermophilic conditions with high temperatures that allow destruction of pathogens. Oxygen concentration within the composting matrix should not fall below 5 to 7%. This is achievable by providing porosity and free air space of about 30% within the composting heap (Haug 1980; Bayard and Gourdon 2010). Maintaining oxygen levels above 10% was also reported (Banegas et al. 2007; Razali et al. 2012). Sufficient oxygen supply during composting is not only needed for aerobic metabolism and respiration by the microorganisms but also for oxidizing various organic molecules present in the mass (Cornell Composting 1997). During composting, the aerobic microorganisms must have constant supply of fresh air to maintain their metabolic activities (Bernal et al. 2009; Guo et al. 2012). The rate of O_2 uptake increases in proportion to the proximity to optimum conditions of composting (UNEP 2005). Aeration can also be used to control the temperature and moisture content.

Three mechanisms can be used for O_2 replenishment in the compost. First and most commonly, through turning of the compost heap, which is also useful in ensuring homogeneity of the material and of operating conditions, especially in terms of temperature, moisture and oxygen levels (Makan et al. 2013). Compost turning is a low cost technology for aeration and can be done either manually or mechanically (Winblad and Kilama 1980). Mechanical turning is reported to accelerate the decomposition of lignin, which is more resistant to microbial breakdown (Razali et al. 2012). However, frequent turning may also increase ammonia losses. Secondly, passive aeration can be provided, which takes advantage of the natural diffusion of air through the pile and can be enhanced by ventilation structures such as perforated pipes, openings in the walls of composting bins or by providing appropriate particle size distribution and structure of the raw materials in the heap. To stimulate passive aeration, addition of a bulking material to the feedstock can be beneficial (Bernal et al. 2009). In general, passive aeration alone is not sufficient during composting. Finally, forced aeration can be applied (methods which actively blow air through a compost pile).

Following each aeration event, the gas contained in the interstitial spaces of the composting mass varies in composition, with the carbon dioxide content gradually increasing and the oxygen level decreasing (Singh et al. 2012). Levels of other by-products of the decomposition process such as water vapor, ammonia, nitrate and methane may also increase gradually (Singh et al. 2012). To sustain aerobic microorganisms, the oxygen content of interstitial gas within the pile should ideally remain > 15% because microorganisms achieving fermentation and anaerobic decomposition begin to exceed aerobic ones when the oxygen level in the air falls below 10%.

The oxygen consumption rate during composting is directly proportional to microbial activity and consequently oxygen consumption, temperature and aeration rates show a direct relationship (Singh et al. 2012). At the early composting stages, which are characterized by rapid decomposition and higher moisture content, sufficient aeration is crucial to maintain aerobic conditions while consumption of oxygen is greatest (see Box 7). Anaerobic conditions cause generation of methane gas and malodorous gas compounds such as hydrogen sulfide and ammonia. This may attract mites and juvenile flies, but could also deteriorate living conditions for aerobic microbes and macrofauna, e.g., earthworms that would enhance aeration within the compost heap if provided with optimal living conditions (Adi and Noor 2009). During the composting process, the overall oxygen demand gradually decreases as the composting process slows down towards substrate maturity.

BOX 7. AERATION FREQUENCIES.

- Turning should be performed at least once every 10 days. This could be done manually for smaller operations but for commercial composting would require a loader, excavator or specialized windrow turner, depending on the composting method applied.
- Outdoor turning should consider weather and wind conditions, to minimize potential off-site odor. Enclosed systems typically apply specialized mixing technology, either through rotating reactors or by using mechanical devices that mix compost at regular intervals, e.g. as applied in tunnel systems.
- Excessive aeration increases loss of ammonia, which escapes more easily when the composting material is exposed to the atmosphere. Hence, an optimum frequency of turning must be found, which balances the need for all parts of a mass to be subjected to high temperatures for pathogen inactivation with the need to limit N loss.
- Water lost during the composting process should be replenished during the turning events.

2.6.8 Nutrient Conservation

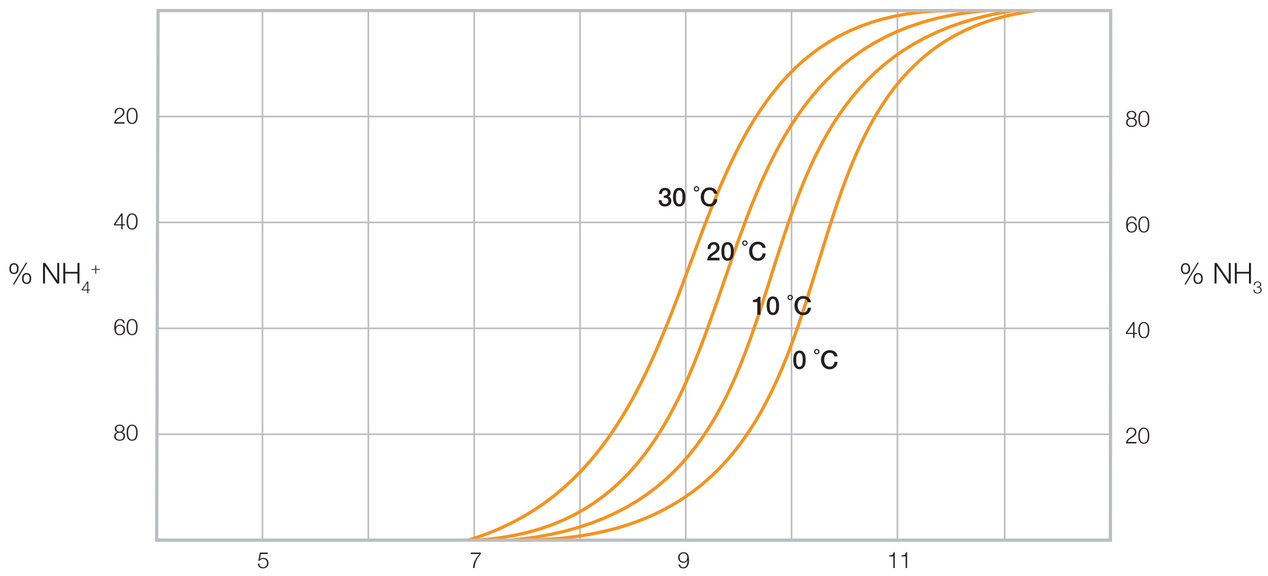
Nutrients (N,P,K and micronutrients) may be lost through leaching during the composting process. Production of acids during the decomposition of the organic matter is responsible for the solubilization of P and K insoluble fractions (Adi and Noor 2009). Yet, in contrast to these nutrients, the greatest portion of lost N occurs through volatilization in the form of ammonia (NH_3) and other nitrogenous gases. All nutrient losses have impact on the fertilizing value of the compost product and hence must be minimized as much as possible. Loss of N is also a major cause of odor generation during composting. The conventional trend of NH_4-N in the feedstock being composted is as follows (Chen et al. 2010; Singh et al. 2012):

- Decrease in N concentration during the first few (typically two) days of composting;
- Gradual increase of N concentration, within the first week (initial thermophilic phase), probably added through breakdown of organic matter from input materials;
- A major/sudden drop of N concentration at the end of the thermophilic phase; and
- Stabilization of N concentration as maturation is completed.

Ammonia levels are affected by the C:N ratio, pH, moisture, aeration, temperature, the prevailing chemical form of N in the feedstock, adsorptive capacity of the composting mixture and windrow turning frequency. Gaseous ammonia (NH_3) and dissolved ammonium (NH_4^+) are in pH and temperature dependent equilibrium as shown in Figure 7.

Figure 7 also indicates that higher pH and higher temperature move the equilibrium in favor of ammonia formation. Thus higher levels of pH developing during the composting process or high pH in the initial feedstock might enhance ammonia volatilization. This could occur, for instance, if the input materials contain relevant portions of ash (ash exhibits a pH of 10-11). While excessive dryness will enhance NH_3 volatilization, this will be reduced by far under optimum composting conditions with water content ranging from 50-70 % that allows maintenance of highly soluble ammonia in a dissolved state (Schreiner 1997; Trösch and Mohr 2005). A similar balance has to be striven for in temperature development. High temperature exposure of around 60-65 °C is desirable to attain good pathogen inactivation, yet longer exposure to temperatures of around 70 °C must be avoided as ammonia formation is enhanced and N losses would increase considerably (Pagans et al. 2006).

FIGURE 7. AMMONIA-AMMONIUM EQUILIBRIUM AS A FUNCTION OF DIFFERENT TEMPERATURES AND PH.



Source: Schreiner 1997. Graphic online at http://www.ruschmidt.de/NH4-NH3-Gleichgewicht.jpg

2.7 Amendments and Additives

During the decomposition of organic materials various gases and substances can be generated that negatively influence the composting process or even result in environmental impacts, e.g. through methane generation as a result of anaerobic conditions that may set in. To avoid generation of odorous gases and substances such as sulfuric and nitric compounds, acids, aldehydes, ketone or methane, additives can be used to stabilize or enhance aerobic conditions within the compost heap. (Zigmontiene and Zuokaite 2010). In order to minimize ammonia losses, which mainly occur if pH values are too high, various amendment materials such as alum, peat, charcoal, elemental sulphur, zeolites or bamboo chippings can be added. The addition of 6% charcoal for instance can reduce around 60% of related losses, alone or in combination with bamboo and vinegar (Bernal et al. 2009; Chen et al. 2010; Himanen and Hanninen 2011). Sodium acetate has also been used as an amendment for controlling low levels of microbial activity due to the production of organic acids, especially during the initial phase of composting (Yu and Huang 2009). Other alkaline materials used as pH control amendment include NaOH, ash and lime (Hong et al. 2006; Alipour and Torkashvand 2009). Heavy metals can be immobilized by adding amendments such as lime or coal ash (Chen et al. 2010). However, some additives may result in negative effects on soils, for example in case they increase salinity or metal concentration. The use of alkaline amendments may result in increased ammonia emissions (Nakasaki et al. 1993; Sundberg et al. 2004). Further additives and methods can be applied to accelerate decomposition of the organic waste. The use of microbial inoculum is one of these techniques. Gotaas (1956) discussed the option of inoculation to enhance microbial degradation. The use of *Thiobacillus thioparus* (bacterium capable of oxidizing both organic and inorganic sulphur) for instance could increase the concentration of available sulphur, reduce the emissions of hydrogen sulphide, sulphur dioxide and ammonia (Gu et al. 2011). However, the debate about the need, usefulness and effects of inoccula application for composting and the identification of specific, laboratory-cultured strains of bacteria, enzymes, catalysts, hormones and so forth is still ongoing. Although related enhancers are available on the market, the concrete effects and long-term impacts of these inoccula are uncertain. Some inoculants are being used by households and applied to pits and vaults of on-site sanitation installations to lessen odor generation. Likewise, many trials have been conducted in solid waste composting and on dump sites to enhance biochemical degradation and to prevent odor generation.

Use of biosurfactants for compost treatment has also been recommended on some occasions. Such chemicals are supposed to create favorable conditions for microbial growth and could theoretically enhance composting as well. However, biosurfactants are known to be rather costly whereas their impact on compost quality is limited. It was reported that their application resulted in an overall increase of temperature by 2 °C, while the temperature profile within the heap remained similar to control heaps that did not apply this additive. The EC was slightly higher within the treated composts (Zhang et al. 2011). In other cases, levels of N were reported as higher with up to 80% increase, even though the change in total N was limited (0.05% increase with surfactant being added).

To increase nutrient levels, such as for NPK, enrichment with additives is a common practice. Recent studies report on application of various organic sources such as urine, poultry waste, vermicompost, bone meal and microbial inoculants (e.g. *Azotobacter, Phosphobacteria* and *Pseudomonas*) to enhance nutrient content and the fertilizer value of composts (Biswas and Narayanasamy 2006; Kavitha and Subramanian 2007; Rao et al. 2007; Tognetti et al. 2007; Adamtey et al. 2009).

2.8 Compost Quality

At the end of the decomposition process, a stable organic matter called humus, a complex group of macromolecular organic compounds with high stability, has been formed. This organic compound is known to have a chemical structure close to that of soil, but is higher in organic matter and nutrient content and hence very useful to enhance certain soil properties (Singh et al. 2012). Humus can be subdivided into three fractions, humic acid, fulvic acid and humin based on the solubility of compounds in acid/base solutions (Shan et al. 2013). Maturity and stability are relevant and desirable properties of a compost product (Benito et al. 2003). The agronomic quality of compost is limited mainly by its chemical properties and by the stability and maturity of the organic matter. Both stability and maturity depend on the state of organic matter during composting and on the levels of certain chemicals in the compost, especially those that may occur as 'intermediate substances' during the decomposition process (Cornell Composting 1997; Benito et al. 2003). In general, a final compost product should be mature and meet quality criteria as formulated in product or compost guidelines valid for the specific location. Operators of composting sites should be cautious to accept only such feed materials for the composting process that will ensure that the final compost product will meet the local quality criteria guideline. The following Table 7 summarizes main requirements of compost quality from various country standards that underline the relevance of quality control of input materials, e.g. related to foreign components and non-organic matter.

Compost quality criteria usually include nutrient levels and properties of the compost such as essential plant nutrients (N, P, K, Ca, Mg, organic matter and trace elements) but also provide thresholds for pathogens, soil contaminants such as heavy metals or pesticides, content of seeds and perceivable foreign components among others (USEPA 1993; WRAP 2002).

2.8.1 Stability and Maturity

The stability of compost determines the potential benefits for soil application, as well as organic matter and nutrient content available for plant growth. Compost stability also indicates the extent at which the biodegradable matter has been decomposed (Singh et al. 2012). It can therefore be related to the level of microbiological activity still occurring in the material and can be assessed directly through the measuring of O_2 uptake rate, CO_2 production or by an indirect measure, i.e., through measuring of the heat released, which reflects ongoing biological activity (Bernal et al. 1998; Benito et al. 2003). Any of these parameters may be useful for evaluation, however, compost quality cannot be assessed based on a single parameter alone (Cornell Composting 1997; Bernal et al. 2009; Raj and Antil 2011). If no determination of compost stability/maturity is made, the compost must be cured for at least one month. Compost must be stabilized before being used on agricultural land. If compost is applied 'immature' nutrients may not be available for crop growth but would result in further microbial activity that may even result in negative soil effects (Singh et al. 2012). Unstable compost or remaining wastes are detrimental to the environment while stable composts can be safely applied (Chen et al. 2010).

Compost maturity, or relative stability of the compost output material, is the degree or level of completeness of composting (Benito et al. 2003; Singh et al. 2012). The degree of decomposition of phytotoxic organic substances produced during the active composting stage is measured with the maturity parameter (Benito et al. 2009). When immature compost is applied to a soil, it may hinder plant growth, rather than promote it. Reasons for immature compost toxicity include high concentrations of volatile organic acids, NH_4-N and/or heavy metals (Shiralipour et al. 1997; Tiquia and Tam 1998). Immature compost, with organic matter still not degraded, will exhibit microbial activities when applied on soil and may result in microorganisms competing with the

TABLE 7. MAXIMUM FOREIGN MATTER PARTICLES ALLOWED IN COMPOSTS IN VARIOUS NATIONAL STANDARDS.

COUNTRY WITH STANDARD	STONES % OF DRY WEIGHT	MAN-MADE FOREIGN MATTER GLASS, PLASTIC, METAL, AS% OF DRY WEIGHT
Australia	must be < 5% of > 5mm size	< 0.5% for > 2mm fraction
Belgium	< 2%	no visible contaminant, max 0.5% > 2mm
France	—	Max. Contamination 20%; < 6%of > 5mm fraction
Germany	must be < 5% of > 5mm size	< 0.5% for > 2mm fraction
Italy	—	< 3% total
Netherlands	must be < 3% of < 5mm size	< 0.5% for > 2mm fraction
Spain	—	"free of contamination"
Switzerland	must be < 5% of > 5mm size	< 0.5% for > 2mm fraction; max 0.1% plastic

Source: Brinton 2000.

plants for the availability of soil N (N block) and oxygen in the rhizosphere. Immature compost may also contain high levels of organic acids and other intermediate products of biodegradation such as ammonia and phenols that can damage plant growth when used for agricultural applications. Immature compost may also lead to the development of anaerobic 'pockets' resulting in odour and toxic substances.

Indicators for compost maturity or the degree of decomposition are: C:N ratio, color and smell, drop in pile temperature, degree of self-heating capacity, nitrate-N/ ammonium-N ratio, amount of decomposable and resistant organic matter in the decomposed material, pathogen destruction, volume or bulk reduction, redox potential and oxygen uptake. The maturation is accompanied by a decline in NH_4-N concentration, water soluble carbon and an increase in NO_3-N content (Benito et al. 2009).

Due to the wide range of heterogeneous organic material used in compost production, the use of one indicator as a means of assessing compost maturity is insufficient (see Box 8). However, there is no consistency in the types of tests required for assessing compost maturity or stability. This is explained by the fact that most of the applied parameters relate to chemical properties (e.g. nutrients, pH, oxygen) which may vary with feedstock and the composting method used (Benito et al. 2009).

The determination of compost stability and maturity can be based on several indicators such as C:N ratio, nitrate/ ammonium ratio or seed germination index (GI) (Chen et al. 2010; Zhang et al. 2011). Most compost quality standards require a C:N ratio test whereas a C:N ratio of < 20 is considered as 'acceptable' but a C:N ratio of < 12-15 is the preferred range that indicates proper compost maturity (California Compost Quality Council 2001; Adi and Noor 2009; Benito et al. 2009). However the C:N ratio alone is considered insufficient to assess compost maturity, mainly because of the wide range of C:N ratios encountered. Therefore additional tests are applied that fall into two dissimilar groups (A and B). Tests under Group A are more or less related to compost stability whereas tests of Group B are related to compost maturity. The outcome of these tests will allow placement of the compost into one of the following maturity levels: a) very mature, b) mature or c) immature (Brinton 2000). In other cases, the seed germination index has been used as an indicator, and a minimum value of 50% set as the condition to meet the requirement (Zucconi et al. 1981). Higher values of germination index, in the range of 70 to 120%, have also been reported (Ko et al. 2007; Raj and Antil 2011). Values of the germination index should be interpreted with respect to the type of seed used and compost extract concentration used (Bernal et al. 1998; Tang et al. 2006). Soluble carbon in the mature compost should be no more than 0.5 to 1.7%, depending on the feedstock (Benito et al. 2009). The NH_4-N to NO_3-N ratio at which level a compost can be considered as 'matured' has to be taken into consideration as well. A compost with NH_4-N to NO_3-N ratio less than 1 is reported to be suitable for land application as a soil amendment (Himanen and Hanninen 2011). Values in the range of 0.16 and 2 have been proven to be acceptable, depending on the feedstock (Bernal et al. 1998). Furthermore, a humic-to-fulvic acid ratio of 1.7 to 1.9 or greater has been used as an indicator for compost stability (Raj and Antil 2011; Shan et al. 2013). Within a co-compost study that tested pruning waste and spent horse litter, Benito et al. (2009) found that both organic matter loss as well as CO_2 respiration could be used to confirm maturity and stability phases during composting. The following Table 8 summarizes main parameters used to assess compost maturity.

2.8.2 Enrichment of Compost

Compared to inorganic fertilizers, compost is typically low in nutrients which results in high application rates, often more than 10 t ha^{-1}. Most of the total N in compost is in organic form (>90%) and hence not readily available for plant use (Doublet et al. 2011). Nitrogen mineralization rates of 6-7% in 12-24 weeks were reported by Hartz et al. (2000) while Adamtey et al. (2009) observed organic N mineralization of 7%. Due to the low mineralization rate, large quantities of compost in the range of 12-48 t ha^{-1} are required to achieve agronomic N efficiency of 6-22% (Murrilo et al. 1995). Other research has applied municipal waste compost before planting but added inorganic N fertilizer during crop growth to meet N requirements (Ofosu-Budu and Adamtey 2002; Sikora and Enkiri 2003; Han et al. 2004; Shi et al. 2004; Tejada et al. 2005). However, this practice—apart from being more labor-intensive—was associated with higher losses of N, P and K compared with use of organo-mineral formulation (Tejada et al. 2005). Enriching compost with inorganic fertilizer (for both macro and micro nutrients) is recommended instead, especially in areas with abundant water supply (Veeranagappa et al. 2010; Adamtey et al. 2010). Enrichment with bacterial inoculants, such as *Azotobacter* and *Pseudomonas,* as well as other organic nutrient sources such as poultry waste, urine and vermicompost have also been reported (Biswas and Narayanasamy 2006; Kavitha and Subramanian 2007).

Enrichment of co-compost with inorganic fertilizers was also tried, i.e., urea and ammonium sulfate applied in three different forms, dry, paste and liquid to attain 3% total N as reported by Adamtey et al. (2009).

Mixing of compost and inorganic fertilizer (e.g., urea) was tested to sanitize the product because inorganic fertilizer can kill pathogens that are present in the co-compost (Vinnerås et al. 2003; Vinnerås 2007). Combining co-compost and inorganic fertilizer can also enhance application efficiency since such substrate can supply simultaneously high organic matter to the soil as well as the needed nutrients to increase crop yields (Han et al. 2004; Ahmad et al. 2008), and minimize work load for application (Ahmad et al. 2007b). The synergistic effect provided by the organic matter from compost and the inorganic fertilizer contributes to:

BOX 8. STANDARD MEASUREMENTS IN COMPOSTING.

TS, TVS, NH_4-N, TKN and NO_3-N are measured following standard methods for the examination of water and wastewater. Total organic carbon (TOC) and N are measured using the dry combustion method (CNS-Analyser). The sample is dried at 105 °C until constant weight. Afterwards it is milled and measured according to the standard procedure of the CNS-Analyser.

TABLE 8. INDICATORS TO ASSESS COMPOST MATURITY LEVEL.

	METHOD	UNIT RATINGS		
		VERY MATURE	MATURE	IMMATURE
Group A	Oxygen uptake O_2/VS/hr VS^{-1} hr^{1}	<0.5	0.5-1.5	>1.5
	CO_2 C $unit^{-1}$ VS^{-1} day^{-1}	<2	2-8	>8
	SCL CO_2 C $unit^{-1}$ VS^{-1} day^{-1}	<2	2-8	>8
	WERL CO_2 C $unit^{-1}$ VS^{-1} day^{-1}	<5	5-14	>14
	Dewar temperature rise (°C)[1]	<10	10-20	>20
	Solvita index value[2]	7-8	5-6	<5
Group B	NH_4- : NO_3-N ratio	<0.5	0.3-3.0	>3
	Total NH_3-N ppm, dry basis	<75	75-500	>500
	VOA ppm, dry basis	<200	200-1000	>1000
	Seed germination % of control	>90	80-90	<80
	Plant trials % of control	>90	80-90	<80
	Nitrogen draw-down	0	<10%	>25%

[1] Dewar self-heating text; [2] Solvita test
Source: Brinton 2000.

- Storing nitrogen in the soil—N is gradually made available to plants over time (Ahmad et al. 2007b);
- Gradually releasing plant nutrients thereby increasing nutrient uptake (Ahmad et al. 2007b; Ahmad et al. 2008);
- Reducing N losses by up to 90 percent and P losses by up to 75 percent; and
- Mitigating soil erosion and subsoil leaching by improving the physic-chemical properties of soil through increased organic matter and biomass generation (Soumare et al. 2003; Adediran et al. 2004).

The use of N-enriched co-compost also reduces the application rates for inorganic N and P fertilizers (Vinnerås 2007; Adamtey et al. 2009) and thus directly contributes to reducing greenhouse gas emissions that result from fertilizer production and transport. Furthermore, compost application can enhance carbon sequestration significantly, typically from 0.1 to 4.5% in terms of total soil organic carbon (SOC) and soil organic matter (SOM) content (Lal 2001). Consequently, it contributes to attenuating soil erosion and increasing soil health and the availability of natural crop nutrients over longer time spans. To reach optimal effects Dalzell et al. (1987) recommended application of a mixture of inorganic fertilizers and compost in such ratios that at least 30% of the N is supplied by each source.

The amount of inorganic fertilizer to be added to the compost depends on the intended use and crop production targets and is therefore quite variable. Han et al. (2004) used urea solution to add 60% of the total N provided by urea and 40% by compost. A further study recommended a mixture of compost from biosolid/municipal refuse plus approximately 65% ammonium nitrate fertilizer; this mixture resulted in equal crop yield if compared to a 100% inorganic fertilizer application alone (Sikora and Enkiri 1999).

Sridhar and Adeoye (2003), Rao et al. (2007) and Ahmad et al. (2008) reported on the use of urea or ammonium sulfate to enrich compost to obtain a compost-fertilizer product. For instance, Sridhar and Adeoye (2003), Han et al. (2004) and Ahmad et al. (2008) used urea, whereas Rao et al. (2007) used ammonium sulfate. Furthermore, Shridhar and Adeoye (2003), Rao et al. (2007) and Ahmad et al. (2008) applied inorganic fertilizer in dry form, whereas Han et al. (2004) dissolved it in water. Since fertilizer type and form of application could affect enrichment potential and N dynamics, further research may be needed to better understand how N losses through denitrification and/or how potential hazards like NO_3-N leaching can be minimized. Understanding the magnitude of the chemical changes (e.g., N dynamics) in the N-enriched co-compost during storage and for soil application is paramount for appropriate fertilizer management and environmental protection.

2.8.3 Content of Contaminants

Compost quality assessment includes analyzing the level of heavy metals, organic pollutants and impurities (Binner et al. 2008). Some organic materials may contain substances that are toxic to aerobic thermophilic bacteria or are capable of accumulating in soils and crop products (Hargreaves et al. 2008). Heavy metals such as manganese, copper, zinc, nickel, chromium and lead may fall into this category. Heavy metals may be immobilized chemically prior to composting. In some manures, heavy metals are present in appreciable concentrations (see Box 9).

Composts may be acceptable for land application when their metal concentrations are consistent with certain threshold values. The criteria displayed in Table 9 are derived from European countries' standards and the Canadian Council of Minister of the Environment (CCME 2005) guidelines for Category A compost.

Co-compost that contains human excreta or other biosolids has to meet specific standards before it can be applied as organic fertilizer. Because of its potential use in crop production the issue of compost quality is increasingly being discussed lately. In Europe, quality and marketing of compost are the most crucial issues. To compete with other soil enhancers such as peat-based, soil-based or from bark industries, compost plants need to safeguard their compost quality (WRAP 2012; ECN 2014). Nunan (2000) suggested that the quality of compost required should be investigated as part of project-related market research. Furthermore, he suggested that the selection of composting materials and mixtures, composting processes, product quality and storage should be based on scientific data and research in order to establish standards and to safeguard application.

Salinity is a relevant parameter in composting and can significantly deteriorate the composting process and product quality if concentrations are too high. Electric conductivity (EC) corresponds with the salinity of a material, and hence informs about potential phytotoxic effects (see Box 10). During the composting process, the EC first increases as a result of ammonium being generated during initial breakdown of organic components from the feedstock. Subsequently, as ammonia is released and salts are precipitated, a decrease in EC occurs. Once maturity is reached, the EC ranges from 1.0 to 10 dS m^{-1}. Final compost blends with soil or growing media should not exceed 4 dS m^{-1}. Excess soluble salts can be phytotoxic to plants whereas this can be reduced through watering at time of planting (US Composting Council 2010).

2.8.4 Pathogens

The applicable WHO Guideline provides in-depth information about health risks related to the reuse of excreta and wastewater from sanitation (WHO 2006). Besides

BOX 10. ELECTRICAL CONDUCTIVITY MEASUREMENTS.

Electrical conductivity (EC) is measured in 1:10 water soluble extract (w/v) using digital measuring instruments. Most composts have a soluble salt conductivity of 1.0 to 10.0 dS m^{-1}, whereas typical conductivity values observed in soil range from 0 to 1.5 dS m^{-1} in most countries.

BOX 9. MEASURING HEAVY METALS IN COMPOST.

To quantify heavy metal concentrations, X-ray spectroscopy with an adjusted methodology for soil samples is being applied. 50 g of a sample are dried at 100 °C for 48 hours. After drying, 10 g of the sample are taken and milled in a tungsten carbid mill (Retsch RS1) for 20 seconds. Then 4 g of this sample are mixed with 0.9 g of wax and mixed for 8 minutes in a shaker. The mixture is pressed into a tablet while heavy metal concentrations are measured with an X-ray spectroscope.

TABLE 9. HEAVY METAL LIMITS IN COMPOST BASED ON STANDARDS FROM EUROPEAN COUNTRIES AND CANADA.

HEAVY METAL	CONCENTRATION [MG KG DRY MATTER^{-1}]						
	UK[1] STANDARD	ECN[2] STANDARD	SWEDEN[3] STANDARD	AUSTRIAN[4] LIMITS A+	AUSTRIAN[4] LIMITS A	EU ECO[5] LABEL	CANADIAN[6] LIMITS A
Cr^{tot}	100	60	100	70	70	100	210
Ni	50	40	50	25	60	50	62
Cd	1.5	1.3	1	0.7	1	1	3
Hg	1	0.45	1	0.4	0.7	1	0.8
Pb	200	130	100	45	120	100	150
Cu	200	300	100	70	150	100	400
Zn	400	600	300	200	500	300	700

Sources:
[1] Compost standard BSI PAS 100:2005, UK (Russel and Best 2006).
[2] European Compost Network (ECN 2014).
[3] Guideline values of QAS, (Working Group Composting 2004).
[4] Compost Ordinance Austria (Class A+ [organic farming] and Class A [hobby gardening]), (Working Group Composting 2004).
[5] EU Eco Label for soil improvers and growing media, Working Group Composting (2004).
[6] Canadian Council of Ministers for the Environment (CCME 2005).

other microbial indicators (compare Table 11), eggs of nematodes, called helminth eggs, are considered as a very strong indicator to assess health risks because they show a comparably long survival time and are difficult to eliminate. Based on this WHO guideline, the viable helminth eggs content of the finished co-compost must not exceed occurrences of 1 Ascaris egg gTS^{-1}. In this context it is emphasized that maintaining high temperatures during the thermophilic phase is necessary for pasteurization of the waste as it allows removal of relevant human pathogens as well as destruction of weed seeds, insect larvae and potential plant pathogens that may be present in the waste material (Victoria and Galván 2003; Chen et al. 2010). Exposure to temperatures of 55° C or higher should be maintained for a minimum of 14 days to destroy the viability of pathogens and weed seeds (Alberta Government 2005). This was achieved for example in the case of co-compost production in Ghana (Koné et al. 2007).

The following Table 10 provides typical temperature ranges that can be achieved by various compost methods to eliminate critical pathogens of input materials during the thermophilic stage of composting process.

The need to reduce pathogens during composting process correlates largely with the used input materials. However, most input materials from municipal waste management, sanitation or waste water management contain high concentrations of potential harmful pathogens as summarized in Table 11 (see also Box 11).

2.9 Compost Post-treatment and Storage

The required steps for post-treatment of compost mainly depend on the quality of the final product aimed at, customer requests and considerations for storage, transport and marketing.

The extent of related activities will depend on the end market requirements. They may include screening, blending or enrichment, packaging and loading material for shipment. Post-treatment and packaging is recommended in weather-proofed sites (sheds) or as in-house activity to prevent product deterioration but also to minimize emissions that could occur during unfavorable wind conditions.

Only dried compost with a water content of <40% should be bagged in order to prevent the development of anaerobic spots within the bag. Bagged compost should be kept in areas with low humidity and protected against rain.

To avoid off-site dust development, moistening of dry final compost products on heaps may be required. If the feedstock was collected in plastic bags, care must be taken to ensure that the screening operations do not generate litter. To ensure proper customer information and product application, relevant data and instructions for use should be provided on every packaging unit; marketing strategy should follow the standards of the specific country. In

TABLE 10. SELECTED COMPOST HYGIENE STANDARDS FROM VARIOUS COUNTRIES.

COUNTRY	COMPOST METHOD	TEMPERATURE/PATHOGENS
Australia	All methods	> 55 °C for at least 3 days; allowance for variation and lower temperatures
Germany	Open windrow Closed/in vessel Plus all new facilities: No presence in 25g of No survival of added	> 55 °C 2 weeks or > 65 °C for 1 week > 60 °C for 1 week Human/Veterinary Hygiene: *S. senftenberg* W775 Phyto-hygiene: Tobacco-mosaic Virus (TMV) & *Plasmodiophora Brassicae*
Austria	All composts	> 60 °C 6 days or > 65 °C 3 days, or > 65 °C 2 x 3 days
Switzerland		> 55 °C for 3 weeks, or > 60 °C for 1 week, or proven time temperature relationship
Denmark	All compost	> 55 °C for 2 weeks

Source: Brinton 2000

TABLE 11. COMMON CONCENTRATIONS OF PATHOGENIC ORGANISMS IN EXCRETA AND WASTEWATER.

TYPE OF PATHOGEN	FECES G^{-1a}	FECAL SLUDGE L^{-1}	RAW WASTEWATER L^{-1}
Viruses			
Enteric viruses	10^6-10^7	10^3	10^5-10^6
Rotavirus	10^{11}	No data	10^2-10^5
Bacteria			
Fecal coliform	10^7-10^9	10^7	10^8-10^{10}
Salmonella sp	10^8-10^{10}	10^3	1-10^5
Shigella	10^8-10^{10}	10^2	10-10^4
Vibrio	10^8-10^{10}	No data	10^2-10^5
Campylobacter	10^8-10^{10}	No data	10-10^4
Protozoa			
Entamoeba	10^7	10^2-10^3	10^2-10^5
Giardia	10^7	10^2-10^3	10^2-10^5
Cryptosporidium	10^7	10^2-10^3	10^2-10^5
Helminths			
Ascaris	10^4	10^2	1-10^3
Ancylostoma/Necator	10^4	10^2	1-10^3
Trichus	10^4	10^2	10-10^2

[a] Excreted during acute phase of illness, carriers may excrete less and noninfected individuals may excrete zero or few pathogens.
Source: http://www.sanicon.net/tp2table2

BOX 11. HELMINTH EGG ANALYSIS.

Helminth eggs (Ascaris and Trichuris) are determined in compliance with USEPA (2003) modified by Schwartzbrod (2003).

The helminth eggs analysis is conducted with 4 g of compost. 250 mL of tap water is added to the 4 g sample and the mixture blended with a kitchen blender for 1 minute at high speed. The blended sample is poured into a 1-liter beaker and topped up with a phosphate-buffered H_2O solution. The mixture is left to settle for at least three hours or overnight. The sample is subsequently poured through an 80-mesh sieve to remove coarse particles and the sieve is thoroughly rinsed with tap water. The percolate and rinsing water is collected in a 2-liter bucket and left to settle for at least three hours to allow the eggs to deposit. After settling of the eggs, the supernatant is removed with a water jet pump and the sediment centrifuged in 150 mL tubes for 5 minutes at 400 g. The supernatant is poured off and 60 mL of an $MgSO_4$ solution (specific gravity = 1.29 g cm^{-3}) is added to the pellet in each tube. The pellet is resuspended by stirring carefully. On account of the lower density, Ascaris and Trichuris eggs (1.10 g cm^{-3} and 1.15 g cm^{-3} respectively) will float in the $MgSO_4$ solution. Ten minutes after $MgSO_4$ addition, the tubes are centrifuged again for 5-10 minutes at 800 g (without the use of a brake), the supernatant is poured into 2 liters of tap water and left to settle for at least three hours. After settling, the supernatant is extracted by a water jet pump and the sediment is collected in several 15 mL tubes and centrifuged for 5 minutes at 800 g. The supernatant is subsequently poured off and 7 mL of H_2SO_4-ethylalcohol and 3 mL of ethyl acetate are added to each tube. The tubes are shaken several times and centrifuged again for 5 minutes at 660 g. The two supernatant layers are carefully removed by a pipette. The sediment is then diluted with 0.1N H_2SO_4 and the total eggs are counted in a Sedgwick–Rafter cell under an at least 100x magnified microscope.

However, to determine viable eggs, the Safranine dyeing method developed by de Victorica and Galvan (2003) is used. Following the last centrifugation (660 g) and supernatant removal, the sample is stained by adding two to three drops of Safranine O (2.5% in H_2O) to the sediment. After 10 minutes, the tubes are filled with water and centrifuged for 5 minutes at 800 g. The supernatant is poured off, the pellet resuspended with water and the tubes centrifuged again. This process is repeated three times. The sediment is then diluted with 0.1N H_2SO_4 and the total eggs are counted in a Sedgwick–Rafter cell under an at least 100x magnified microscope. If the dye has penetrated the eggs, they are counted as nonviable.

general, the following parameters should be provided on every packaging unit: Nutrient content, organic matter and moisture content, compost maturity, contained volume as well as heavy metal content, pathogen levels, production and packing dates and producer contact details.

2.10 Monitoring

Monitoring may serve several functions but should at least provide data and feedback related to product quality, safe application and environmental criteria related to product application (WRAP 2012; ECN 2014). Monitoring should integrate the various stages of the composting process and report about volume and quality of used input materials, the compost process itself and the final compost quality, including maturity and nutrient levels. For certain parameters, procedures for sample taking and laboratory analysis as well as threshold values for contaminants and pathogens should be outlined in country-specific guidelines.

2.10.1 Raw Materials

Operators of composting sites should only accept input materials for composting that are suited to producing quality compost and meet the targeted quality criteria. Operators must provide a screening system that checks incoming raw materials and ensures that only those categories of organic waste are accepted that are suitable and permitted for processing at their composting facilities. Specifically, operators must reject the following types of organic waste:

- Organics that are contaminated by non- or barely biodegradable chemicals (e.g., waste contaminated with nonacceptable levels of heavy metals);
- Organics that are contaminated by pathogens that may not be safely handled and/or removed during the composting process (e.g., clinical waste); and
- Organics containing contaminants classified as hazardous waste or industrial waste.

Upon arrival at the composting facility, waste should be sorted, weight and registered.

2.10.2 Process Documentation

To ensure that the composting operation follows the outlined procedures and quality concerns, regular monitoring, control measures and product analyses are required. This includes checking of operation and production records as well as a specific sampling and analysis program for self-monitoring and, if indicated, process adjustment; in this way external control procedures, e.g., those requested by involved governmental agencies, will be satisfied (see Box 12).

2.10.3 Compost Quality Control

The plant manager is responsible for implementing the monitoring program and must retain proof that the compost product meets all set quality criteria to allow some traceability.

BOX 12. MONITORING REQUIREMENTS IN COMPOSTING.

Plant owners or operators must record and keep the following information regarding their activities. This information has to be made available to any appropriate governmental agency upon request:

- The sources, types and quantities of waste received;
- Process operating information (e.g., temperature control) and any significant operating problems;
- The quantity by weight and volume of co-compost and residues produced;
- The quantity of co-compost and residues delivered to third parties by the composting plant;
- A listing of involved co-compost distributers/ markets; and
- Information on all analyses carried out with copies of laboratory reports and other supporting documents.

The parameters to be analyzed and reported on should include the following at least:(i) Micro- and macronutrients, (ii) heavy metals and (iii) pathogens (e.g. helminth eggs).

3 ENVIRONMENTAL CONSIDERATIONS IN SITING OF A COMPOSTING FACILITY

Various countries have laws and regulations that address composting and provide guidance for relevant aspects such as (i) siting procedure for compost facilities, (ii) regulations for compost production and distribution and (iii) compost quality and application. As for all waste management facilities, the identification of an appropriate composting plant site is a relevant aspect of environmental management. The siting process includes a variety of specific technical, social, environmental and economic factors that have been proposed to support decision-making (Table 12). Important considerations include:

- Provisions on adequate distance between the facility and adjacent land uses, especially sensitive land uses, and other sensitive environmental features;
- Conformity with municipal land-use plans and local zoning by-laws,
- Selection of a site with sufficient space, ensuring convenient access to transportation routes; and
- Integrated watershed planning and protection of surface and ground water.

TABLE 12. REQUIREMENTS FOR COMPOST PLANTS.

	GENERAL REQUIREMENTS
Receiving and tipping area	▪ Should be underlain by an impermeable pad (in general concrete or asphalt surface) ▪ All drainage from the receiving area shall be collected for treatment or for recycling ▪ Should be located in an enclosed or weather-protected structure
Composting area	▪ Should be designed to fully contain the compostable organic material and to collect all leachate which may be generated ▪ The composting area shall utilize permanent roof structures and/or otherwise proven techniques suited to control moisture and to minimize odor and leachate generation[a] ▪ The composting area should be impermeable; it may be useful to provide working surfaces constructed of concrete or asphalt, or other suitable materials[b]
Curing area	▪ Should be underlain by an impermeable pad (in general concrete or asphalt surface) ▪ Should facilitate collection of composting drainage ▪ Should utilize permanent roof structures and/or proven management techniques to control moisture and to minimize odor and leachate generation ▪ Where space limitations prevent the production of mature finished compost at in-vessel composting facilities, immature compost may be transferred to an otherwise appropriate composting area in order to complete the maturation process ▪ For immature compost to be transported to a secondary curing area, it must have one of the following requirements: (i) cured for at least 21 days and must not reheat above 20°C, (ii) cured for at least 21 days and organic matter is reduced by at least 60% by weight or (iii) able to germinate 90% of cress seed vs control and has a plant growth rate of compost/soil at least 50% of control
Leachate management system	▪ A leachate management system should be developed which has infrastructure and monitoring systems designed to collect, monitor, control and treat leachate prior to being discharged into the surrounding environment. The system shall: (i) have a leachate collection and removal network in the active area, (ii) function year round; (iii) monitor all treated leachate discharges and (iv) record both instantaneous and total flow volumes ▪ The discharge standards for all liquid effluent should be based on the background water quality in the receiving water, and the specifically provided national standards for leachate discharge
Surface water management	▪ Surface water management systems should be designed as follows to: ▪ Divert surface and storm water from the active areas; ▪ Control runoff discharge from the facility; ▪ Control erosion, sedimentation, siltation and flooding; and ▪ Minimize the generation of leachate.
Contingency plans	▪ Contingency plans should identify all reasonably foreseeable emergencies including fire, explosion, leachate leakage or spills and should describe appropriate responses to prevent adverse impacts on the surrounding environment ▪ Should address problems associated with vectors, ground water contamination, equipment failure, odor generation and complaints
Ground water management	▪ To ensure that ground water is adequately protected, each facility should include a ground water monitoring program. Should any of the active area not be protected from precipitation with permanently constructed roof structures, then the ground water monitoring program should stipulate the following minimum requirements: ▪ At least one ground water monitoring well to be installed hydraulically above the gradient of the active area and at least three monitoring wells to be installed downstream of ground water flow direction ▪ The monitoring well(s) to be sufficiently close to the active area to allow early detection of contamination and implementation of remedial measures ▪ Monitoring well(s) to be retained throughout the lifespan of the facility
Odor control systems	▪ Potential odor generation of composting process should be controlled as follows: ▪ All open windrow facilities that exceed 10,000 tons annually of total feedstock, should provide prevention measures, and assess potential for odor at the property boundary and for potential receptors near the facility[a] ▪ Sufficient aeration should be provided for the composting area, areas for the storage of compostable organic feedstock and any other area containing readily putrescible materials such as the storage room for residuals[b]
Separation distances	▪ It is recommended to maintain a safe distance between the active area and the nearest residential, institutional, commercial or industrial sites, with a minimum of 500 meters ▪ The distance between the active area and the nearest commercial or industrial building should be a minimum of 100 meters ▪ The distance between the active area and the nearest property boundary should be a minimum of 100 meters ▪ The distance between the active area and the nearest watercourse or waterbody, including salt water, should be a minimum of 30 meters

[a] This applies to all open windrow composting facilities except small-scale composting facilities
[b] This applies to all in-vessel composting facilities

Sources: Forgie et al. 2004; Department of Environment and Conservation (NSW) 2004; Washington State 2011.

Co-compost facilities should be sited with a maximum possible buffer zone to property line – a minimum of 30 meters. This will ensure that, regardless of any future development on adjacent lands, minimum separation distances can be maintained.

4 BENEFITS OF CO-COMPOSTS

Co-compost application to soils is very beneficial in several ways. It positively affects the physical, chemical and biological characteristics of soils and replenishes organic matter and crop nutrients.

4.1 Effects on Soil Organic Matter and Physical Properties

Soil organic matter is the fraction of the soil composed of degraded organic matter from 'anything that once lived'. It includes plant and animal remains in various states of decomposition, cells and tissues of soil organisms, and substances from plant roots and soil microbes.

Application of organic matter to the soil increases soil aggregates and porosity, thereby improving aeration, soil tilth and workability, soil properties that also reduce erosion and runoff (Faucette et al. 2004; Zougmoré et al. 2008). Besides, it increases the water-holding capacity of the soil and water infiltration (Bationo et al. 1998; Agassi et al. 2004). Many authors have demonstrated that the continuous application of compost gradually increases the organic matter content of soil (Gallardo-Lara and Nogales 1987). A long-term field experiment on acid and alkaline soils also showed that, by raising municipal compost doses, soil organic matter content was increased in an acidic soil by 2 to 6.9% (Hoffmann 1983). Dalmat et al. (1982) showed that co-compost from municipal refuse and pit latrines provided a stabilized form of organic matter and a source of plant nutrients that could significantly increase tilth, fertility and productivity of soil. Ouédraogo et al. (2001) on the other hand did not observe any significant increase in soil organic carbon after three months of compost application.

Through its effect on soil organic matter and thus soil physical properties, compost can prevent the degradation of land resources. Land degradation is characterized by loss of soil production capacity (FAO 2002) and appears in several forms including: (i) depletion of soil organic matter (SOM), (ii) nutrient loss and imbalance, (iii) accelerated soil erosion and (iv) decline in the soil's water and nutrient retention capacities with reduction in water- and nutrient-use efficiency (Lal 2009; Ahmad et al. 2007a).

Land degradation poses a significant threat to food production, food security and the conservation of natural resources. More than 50% of the arable land in Africa has been reported as 'degraded' and crop yield loss, due to this phenomenon, has been estimated within a range of 2 to 50% decline over the last few decades (Scherr 1999) (see Box 13). Poor farming methods such as inadequate nutrient management strategies and bush burning are among the principal causes of declining soil fertility and productivity (Tulema et al. 2007). High soil temperature and high rainfall also promote rapid SOM decomposition which triggers nutrient depletion (Bationo et al. 1998). Considering soil quality and prevailing climatic conditions, it is estimated that about 55% of the agricultural lands in Sub-Saharan Africa are fragile and easily degradable (AFS 2006) and thus would require high external inputs (organic and inorganic nutrient sources) to maintain the resource base for sustainable crop production (Lal 1997). Moreover, agricultural systems remove more nutrients through crop harvests than are replaced from external fertilizer inputs (Sanchez and Jama 2002; Kirchmann et al. 2005). The export of nutrients in the form of harvested goods exacerbates the problem of soil nutrient mining and soil fertility decline and degradation in food-producing areas (Vlek et al. 1997; Drechsel and Kunze 2001; Cofie and Drechsel 2007).

Increasing SOM content can increase soil productivity (Lal 1997). Application of compost provides direct C and N input and also provides an indirect source of mineral N through net N-mineralization during subsequent decomposition due to increased SOM content. Compost enhances soil nutrient content, making it more suitable for producing high yields (Singh et al. 2012).

4.2 Effects on Soil Chemical and Biological Properties

Compost affects soil chemical properties including soil pH, acidity, conductivity and overall nutrient retention capacity. Availability of nutrients for plants is greatly influenced by soil pH. With the exception of P, which is most available within a pH range of 6 to 7, macronutrients (N, K, Ca, S and Mg) are more available within a pH range of 6.5 to 8, while most micronutrients (B, Cu, Fe, Mn, Na, Ni and Zn) are more available within a pH range of 5 to 7 (Singh et al. 2012). For modifying the soil pH of acidic soils, municipal solid waste compost has a neutral or slightly alkaline pH and enhances buffering capacity. The application of compost from municipal waste appears to be extremely useful on acidic soils. It acts as a pH corrector, thus avoiding the risk of aluminum or manganese toxicity which is likely to take place at pH values below 5 (Gallardo-Lara and Nogales 1987). Several researchers have reported increases in soil pH through addition of compost. For example, Gallardo-Lara and Nogales (1987) found increases in soil pH values from 2.8 to 5.8 through addition of compost while others reported increases in soil pH after compost use in the range of 4.9 to 7.6 (Mkhabela and Warman 2005; Shanmugam 2005; Zhang et al. 2006). The observed increases in soil pH were usually proportional to the compost application rate rather than compost quality. The increase in soil pH may

BOX 13. TURNING AN ENVIRONMENTAL CHALLENGE INTO A BUSINESS OPPORTUNITY.

THE '*FORTIFER CASE'* TO PROVIDE ORGANIC FERTILIZER IN GHANA

Photo: WLE

Many farmers in developing countries (Asia, Africa or Latin America) need to enhance their crop production and are keen to use organic fertilizer. Whereas millions of tons of organic solid waste and human excreta from settlements as well as manures from livestock are generated every day, most is disposed of and results in environmental hazards instead of returning its valuable nutrients and organic compounds to soils and for agricultural production. To strategically address these issues, IWMI initiated a development project that explores how to successfully recycle various organic wastes including fecal sludge in Ghana through co-composting. This project was initiated to produce fortified excreta pellets called *Fortifer.* The project will develop a marketable organic fertilizer for local farmers and clarify marketability, acceptability, ease of handling and on-farm distribution, and propose options to enhance fertilizer efficiency and affordability. Initial research findings indicate a number of beneficial outcomes from the use of fortified excreta pellets as fertilizer. Producing dried pellets ensures volume reduction of fertilizer required in the field (50-70% of the initial volume), and hence reduces transport costs. The pellets have been designed to release nutrients at a steady pace, thus reducing potential nutrient losses after application. Whereas chemical fertilizers only supply nutrients to the soil, *Fortifer* returns organic matter and crop nutrients in a combined manner and hence offers many co-benefits for the enhancement of soils and ecosystems. Besides, the reutilization of organic waste significantly contributes to avoiding unorthodox waste disposal and its related environmental impacts (see also Nikiema et al. 2014).

be due to the mineralization of carbon and the subsequent production of OH^- ions by ligand exchange as well as the introduction of basic cations, such as K^+, Ca^{2+} and Mg^{2+} (Mkhabela and Warman 2005).

Compost application can also affect EC and salinity level. The EC of a soil solution corresponds to the dissolved components of soil and is often used to assess soil salinity (Brady and Weil 1996). Plants are negatively affected by excess salts in soils and Na for example can be detrimental to soil structure. High EC decreases osmotic pressure between plant roots and growth substrate which affects water availability to the plant (Himanen and Hanninen 2011). The EC of soil ranges from 3.69 to 7.49 dS m^{-1} as reported by Brady and Weil (1996). The EC content of compost is related to the feedstock used in the compost and compost facility procedures (Hicklenton et al. 2001). Incorporation of compost into soil increases salt content as well as soil EC, especially if high doses of compost are applied (Gallardo-Lara and Nogales 1987; Iglesias-Jimenez et al. 1993; Walter et al. 2006). However, increased EC values decline over time, most likely because of nutrient removal by crops and leaching (Zhang et al. 2006).

Due to compost application, not only pH and EC but also soil cation exchange capacity (CEC) may be affected. CEC refers to the quantity of negative charges existing on the surfaces of clay and organic matter components of the soil. The negative charges attract positively charged ions, or cations, hence the term 'cation exchange capacity'. Many essential plant nutrients exist in the soil as cations and are accumulated by grass plants in this form. Examples are potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and ammonium (NH_4^+). The primary factor determining CEC is the clay and organic matter content of the soil. Higher quantities of clay and organic matter in soil implies higher CEC. As only a small percentage of the essential plant nutrient cations (K^+, Ca^{2+}, Mg^{2+}, and NH_4^+) is readily available for plant uptake, CEC provides a reservoir of nutrients to replenish those removed from the soil water through plant uptake. Similarly, cations in the soil water that are leached below the root zone by excess rainfall or irrigation water are replaced by cations formerly bound to the CEC.

The addition of compost to soils encourages the growth of many soil organisms. Populations of bacteria (Bulluck et al. 2002; Bonilla et al. 2012), fungi (Naseby et al. 2000;

Bonanomi et al. 2007; Smolinska and Kowalczyk. 2014), nematodes (Bulluck et al. 1999; Garcia-Ruiz et al. 2009) and Collembola and Acari (Miyazawa et al. 2002) are increased due to additions of organic matter to soils. Furthermore, microbial activity measured either as basal respiration or enzymatic activity (Bhattacharyya et al*.* 2005; Madejon et al. 2006) is increased through organic amendments. The increase in microorganism population and activity is dependent upon the availability of consumable substrate in the compost. Moreover, compost suppresses the incidence of soil-borne plant diseases (Bonanomi et al. 2007; Bonilla et al. 2012).

According to Composting Council of Canada (1999), the benefits of compost for soil amelioration and soil ecology can be summarized as follows:

- Improves soil structure, porosity and density thus creating a better plant root environment;
- Increases infiltration and permeability of heavy soils, thus reducing erosion and runoff;
- Improves water-holding capacity thus reducing water loss and leaching in sandy soils;
- Supplies a variety of macro- and micronutrients;
- Controls or suppresses certain soil-borne plant pathogens;
- Improves soils CEC and growing media thus improving their ability to hold nutrients for plant use;
- Increases organic matter and provides beneficial microorganisms for soil and growing media;
- Improves and stabilizes soil pH; and
- Binding, degrading or neutralization of specific pollutants.

5 CONCLUSIONS

Worldwide, ongoing trends in population growth, urbanization and economic development have not only led to steadily increasing consumption of raw materials and energy but also to increase of waste generation and other environmental pressures, mainly in larger cities. While urbanization could be an opportunity to create new markets and to foster well-being and economic growth, it also poses various risks and challenges. In particular, not only does improper waste disposal cause air, soil and ground water pollution, but it also results in loss of valuable resources. In this context, the management of organic waste from solid waste streams and sanitation emerges as a priority task for every municipality because most generated waste in human settlements is organic in nature. However, instead of being reused, a large portion of municipal organic waste is disposed in many countries, often in an uncontrolled manner that results in various negative impacts for public health, living conditions and the environment, such as through generation of odour, disease vectors, leachate and methane emissions. Approximately 40-70% of municipal solid waste is comprised of organic waste in most urban settings, for example as food waste, biowaste and garden waste. If this major waste fraction could be segregated, a significant amount of biomass would be made available either for energy recovery or to produce compost that could be used as organic fertilizer and for soil enhancement. This would likewise reduce the cost and impacts of waste disposal. Furthermore, excreta from human settlements are not considered for reuse in most countries and hence are not treated and utilized in an optimal manner yet. Often fecal sludge obtained from tank cleaning is dumped close to the places of generation and on land, into dug pits, drainage systems or discharged into waterways instead of applying treatment and material recovery options. By combining various waste streams new opportunities arise, such as through co-composting, that could not only increase resource recovery rates but also enhance the quality of compost products, for instance through mixing of such input materials and additives that increase the content of crop nutrients and enhance application properties. Biological treatment, in particular composting, is a relatively simple, durable and inexpensive alternative for stabilizing and reducing biodegradable waste. Besides, the use of compost for soil amendment contributes towards carbon sequestration and assists in avoiding GHG emissions, for example by substituting synthetic fertilizer or peat application.

The reuse of organic waste and its return to farmlands faces several challenges, such as the need for segregated collection, the establishment of new and appropriate production sites/storage facilities and additional efforts to collect and transport suitable input materials and to distribute products to farmlands. Co-composting is considered as a relevant waste management option that adds value to compost products and allows to jointly serve waste management, sanitation and agricultural demands in an integrated manner. Although its validity has been proven by various researchers and specifically designed pilot projects, co-composting is not applied on a large scale yet. Support and further innovations are needed, such as through pelletizing or value adding by blending of special input materials and additives that enhance fertilizer value and application properties among other benefits (see also Nikiema et al. 2014).

Whereas composting offers many benefits, it can also cause negative side-effects if not properly managed. Such negative effects include, bad odour, leachate and methane emissions, or microbial as well as heavy metal contaminations that decrease the value and applicability of compost products. Special care is needed to treat potential pathogen contaminations that could occur if human excreta or manure are used as input materials for co-composting. In this context the need for proper design and conduct of composting processes, especially during the thermophilic phase, are emphasized to eliminate related risks.

An alternative is to transform the compost, or compost raw materials (including fecal sludge) into biochar which allows to maintain a large part of the nutrients and carbon, while immobilizing heavy metals and fully eliminating any pathogens (Woldetsadik et al. 2016).

However, if composting is managed in a proper manner, municipal organic waste and excreta can be transformed into a quality compost which would allow reuse of valuable crop nutrients and the organic matter they contain. Additionally, compost application contributes to improving soil structure, increasing water-holding capacity, enhancing soil ecology and neutralizing soil toxins and heavy metals. The benefits related to return of organic matter into soils are manifold and could counteract ongoing organic matter depletion and nutrient mining in arable soils, a trend that especially affects tropical soils in developing countries.

It is foreseen that the conduct and scaling up of co-composting activities will require private sector involvement especially for compost marketing, and increased investments. Initial promising results have been achieved within several pilot projects in various developing countries, such as those initiated by IWMI for *'Fortifer'* organic fertilizer production in Ghana. Related new business opportunities could benefit significantly if suitable raw materials and resources from municipal waste management, sanitation and agricultural production are utilized in an integrated manner. However, the realization of such endeavors will largely depend on public support, for instance through amendments to waste management and sanitation policies and enhancement of framework conditions that attract and sustain potential private sector engagement.

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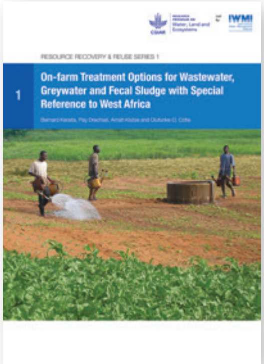

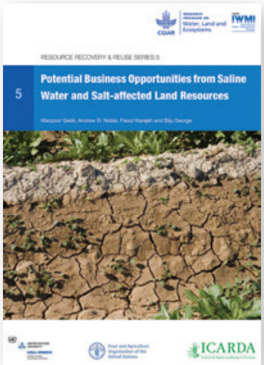

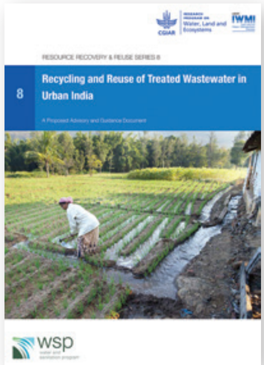

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International Water Management Institute (IWMI)
127 Sunil Mawatha, Pelawatta
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