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Product-Oriented Composting

From open to closed bioconversion systems

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Appendix

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Abstract

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p. 25 Fig 4: should be .... b instead of a and a instead of b....
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Abstract

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The thesis recapitulates and defines what composting is and presents a summary of four primary research papers, two experimental and two theoretical. The themes represent steps from scientific reductionism to studies on system-level complexities, i.e. from cultivation and composting experiments to a holistic approach to sustainable management of solid and liquid organic waste, focusing on efficient recycling of plant nutrients. This work motivate a paradigm shift where 'composting' became 'aerobic bioconversion' and 'compost' became 'biofertiliser'.

In the cultivation experiments, crop response to compost was studied and a novel method for calculating compost amendment rate was developed. The results showed that compost from source separated municipal solid waste, when mixed with peat, can give similar or higher yields than a number of peat-based cultivation media. Composts from centrally sorted waste are not acceptable for cultivation purposes. The cultivation experiments were stimulating for research on composting methods.

For composting experiments on standard substrate, with and without additives, static and rotated bioreactors were constructed. The effects of internal and external factors on the process of microbial transformation were investigated. A high degree of efficiency, a short retention time, and increased control of the bioconversion are some of the advantages of using bioreactors.

A thought-provoking comparison of economical assessments between present and future methods of organic waste management was made. Completely closed local bioconversion systems for plant nutrient recovery were suggested. The impact of the whole system - including collection, transport, and treatment by microbial transformation on the environment and economy was estimated.

At the end follows an assessment of the potential hidden in organic waste, which can be used as renewable raw material for efficient plant nutrient recycling and for conservation of bioenergy in organic matter. By microbial transformation in decentralised facilities, the solid and liquid organic wastes and residues can be upgraded to valuable biofertilisers and biogas.

Proper management of organic material by closed bioconversion will bridge the gap between industrial prosperity and biological requirements. Present polluting systems can be counteracted by environmentally friendly technology.

Keywords: aerobic and anaerobic bioconversion systems, bioreactor, composting, cultivation experiments, microbial transformation, organic waste management.

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To Jan and Tom

Contents

Appendix

Papers I-IV

This thesis is based on the following primary research papers, two experimental and two theoretical, referred to by Roman numerals.

I. Gajdos, R. 1997. Effects of Two Composts and Seven Commercial Cultivation Media on Germination and Yield. *Compost Science & Utilisation* 5(1):16-35.

II. Gajdos, R. Methods for Laboratory Studies on Composting of Standard Substrate in Static or Rotated Bioreactors. *Bioresource Technology.* (Accepted for publication - shortened.)

III. Gajdos, R. Bioconversion of Organic Waste in Ecologically and Economically Efficient Systems. *Journal of Environmental Management.* (Submitted.)

IV. Gajdos, R. Bioconversion of Wastes by the Year 2010 in Cycling of Elements and Saving Energy. (Manuscript.)

Introduction

Composting

The theory of composting is, like other theories in science, a body of knowledge based on repeated and refined experimentation and observation.

By composting we try to speed up processes of aerobic microbial transformation of substrate which originate from organic compounds for two main reasons:

- In 'process-oriented composting', we want to get rid of organic wastes, residues, and by-products. Volume and weight is reduced but emissions are not taken into consideration.
- In 'product-oriented composting', we want to utilise organic wastes, residues or by-products, and even fuel crops, as raw material to manufacture useful products. Plant nutrients will be recycled, energy saved and used again, pathogens and seeds inactivated, and pollution avoided.

Local, national and international variations in meaning and significance of the word compost occur, making the nomenclature in literature confusing.

Art and science

In the late fifties we were taught that compost is a symbol of the gardeners' professional skilfulness to manage cultivation of horticultural plants. At that time, growers made composts of varying quality, according to demands of the cultivated crops. Different kinds of plant residues were mixed with or without additives of organic or inorganic origin. Then, for each pot plant, a special mixture was created of soil and the particular compost, which sometimes was amended with sand, peat, or other materials. Many growers used their own composting recipes, taylored to physical, chemical, and biological factors in their top soil layer. Composting was an art, and the methods were improved throughout generations. Unfortunately, it is not possible to collect all these recipes and make generalisations. Therefore, there is a need of scientific empirical methods to increase the knowledge in this field.

New cultivation systems with the aim of conservation of natural resources and increased environmental concern call for new proficiency. The knowledge from engineering, microbiology, soil science, crop science, plant pathology, and many other disciplines meet. Composting becomes a science. Recycling of organic wastes on land provides the best possible means for maintaining and improving soil productivity, and for protecting soils from erosion (Parr and Willson, 1980).

Nature of composting

The potential of organic wastes from households, gardens, public.areas, commerce, various industries and cultivation systems, has not yet been determined in value of plant nutrients, renewable energy, microbial activity and humic substances. Organic waste is organic material (OM), which consists of living organisms (biomass), their excreta, and non-living residues (bark, straw, old leaves, branches, roots, and include food, feed, paper, furniture, and other used man-made products).

Bioconversion of OM during composting is similar to processes in the soil as they are described by Lynch (1982). In soil, the organic matter is diluted by inorganic matter. Handling concentrated organic matter by composting means considerable increase of feed for microorganisms. It results in higher speed of conversion of plant, animal, and microbial residues by microbial activity. Seen from the human point of view - OM in compost, biofertiliser, manure, green manure, and crop residues serves as a substrate for both antagonistic and beneficial organisms in the soil.

Composting is an aerobic bioconversion where dissimilation of complex organic molecules, as well as assimilation of new ones, is carried out by various microbial populations with different demands on their life conditions. During composting microbial transformation processes occur. Organic structures in raw material are broken down and microbial biomass is build up. The multitude of biochemical processes which arise within microbial cells can be found within composting process. Anabolism arises when energy-requiring syntheses of cell constituents from simple molecules take place. The opposite process of catabolism occurs when complex organic molecules break down, releasing energy (Peltczar, 1993). Composting is called an aerobic process, but anaerobic microorganisms act in the processed substrate as well. Their metabolites are used by aerobes.

Composting is an engineered process which can be steered and regulated, but it is not set up to fully decompose all degradable OM (Stentiford, 1993). Composts with various degrees of decomposition or maturation are available. They are of use for different purposes, such as a soil improvement, fertiliser, as components of horticultural substrates, and soil amendments for remediation. Composts can also be used as a medium that suppresses soil-borne plant pathogens (Hoitink *et al.*, 1976). Glass (1992) described the possibility of using microorganisms for bioconversion of OM, developing microbial fungicides and insecticides, and for research on the use of plant pathogenic fungi as biological weed-control agents.

The aim of making and using composts must be to switch the balance towards organisms that are beneficial to plant growth. Stentiford (1993) wrote that after

some 60 years of research on composting we are still unable to specify the plant performance in terms of the final product. He also pointed out the waste management is in infancy when compared to the chemical engineering industry. The product specification lacks specificity and authority. Methods of process and product evaluation are still areas of strong debate.

The history of composting research, differences in technology development of composting process and its principles are described by several authors as Gotaas (1956), Gray and Sherman (1970), Golueke (1972), Poincelot (1975), Jeris and Regan (1973*a,b,c*), Minnich and Hunt (1979), Morgan (1980), Par and Willson (1980), de Bertoldi *et al.* (1983), Avnimelech (1986), Haug (1986), Viel *et al.*(1987), Inbar *et al.* (1989), Hogan *et al.* (1989), Hoitink *et al.* (1991), de Bertoldi (1995) and many others.

Some definitions on expressing 'compost' and 'composting' are given below as example on the great variation:

Gotaas, 1956:

"The decomposition or stabilization of organic matter by biological action has been taking place in nature since life first appeared on our planet. In recent times, man has attempted to control and directly utilise the process for sanitary disposal and reclamation of organic waste material, and this process has been termed "composting" and the final product of composting has been called "compost".

Generally speaking there are two processes: (a) aerobic decomposition and stabilisation, and (b) anaerobic fermentation. In these processes, bacteria, fungi, moulds, and other saprophytic organisms feed upon organic materials such as vegetable matter, animal manure, night soils, and other organic refuse, and convert the waste to more stable form."

Gray and Sherman, 1970:

"Composting is the decomposition of heterogeneous organic material by a mixed microbial population in a moist, warm, aerobic environment .... Composting is a complicated ecological process governed by many interrelated factors. As the indigenous mesophilic organisms multiply, the temperature rises rapidly; the mass becomes more acidic because the decomposition products of the more easily attacked constituents are the simple organic acids. At higher temperatures the thermophilic organisms take a major part in the reaction, the pH becomes alkaline and ammonia is sometimes liberated. After the peak temperature is reached, the mass cools slowly back to ambient, while the pH drops slightly, though remaining alkaline .... As much as 60% of the initial dry weight may be lost by conversion to carbon dioxide and water."

Golueke, 1972:

"Composting is the biological decomposition of organic wastes under controlled conditions. The term "biological" distinguishes composting from other types of decomposition, such as chemical or physical (e.g. incineration, pyrolysis, etc.). "Organic" is applicable because, with few exceptions, only the organic portion of wastes is subject to biological break down. The term "controlled" distinguishes composting from other decomposition which take place in an open dump, a sanitary landfill, in a manure heap, in an open field, etc."

Minnich and Hunt, 1979:

"Composting is, in broadest terms, the biological reduction of organic wastes to humus. Whenever a plant or animal dies, its remains are attacked by soil microorganisms and larger soil fauna, and are eventually reduced to an earthlike substance that forms a beneficial growing environment for plant roots.

This process, repeated universally and continuously in endless profusion and in every part of the world where plants grow, is part of the wheel of life, the ever-recurring natural process, awesome in its contribution to all plant and animal life, is probably impossible to contemplate in its full dimensions. Let's just say that compost and composting are, like water and air, essentials of life .... All of the environmental problems we face are rooted in a failure to appreciate the need to understand the life cycle and to keep it intact .... Composting is one way to use our understanding of life's cycle in the furthering of our welfare.

Compost is more than a fertilizer, more than a soil conditioner. It is a symbol of continuing life."

Parr and Willson, 1980:

"Composting is an ancient practice whereby farmers have converted organic wastes into useful organic soil amendments that provide nutrients to crops and enhance tilth, fertility, and productivity of soils. Through composting, organic wastes are decomposed, nutrients are made available to plants, pathogens are destroyed, and malodors are abated.

Composting is a microbial process that depends on the growth and activities of mixed populations of bacteria and fungi that are indigenous to the various organic wastes to be composted. The microbes utilize the organic materials for carbon and energy, nitrogen and other nutrients. As the process continues, the temperature begins to increase from the heat generated through microbial oxidations and respiratory activity..."

Viel, Sayag and Andre, 1987:

"Composting is an exothermal biological oxidation of organic matter carried out by different groups of aerobic organisms (bacteria, fungi, actinomycetes). The heterogenous organic matter present in the starting material is transformed into a stabilised end product through partial mineralisation and humification."

Inbar, Chen and Hadar, 1989:

"The main products of aerobic composting are stabilized organic matter (often called humus), CO_2, water and minerals (ash). Well composted organic matter is traditionally applied to field, vegetable or horticultural crops as a source of nutritional elements and/or as a soil conditioner.

During the composting process, organic materials are formed that are chemically complex and difficult to fractionate."

Hoitink, Inbar and Boehm, 1991:

"The composting process can be divided into three phases. The first is during the first 24-48 hours as temperature gradually rise to 40-50°C and when sugars and other easily biodegradable substances are destroyed. During the second phase, when temperatures of 40-65°C prevail, cellulose and other substances that are less biodegradable are destroyed. Lignins, the darker components in plant tissues, break down even more slowly, but the rate varies among plant species. Plant pathogens, weed seeds, and biocontrol agents - with the exception of *Bacillus* ssp. - are also killed by the heat generated during this high-temperature phase of the process."

de Bertoldi, 1995:

"Composting is basically an aerobic process during which different kinds of organic molecules are microbiologically oxidized to carbon dioxide, water and transformed into humified organic matter. From this derives that oxygen is the most important parameter controlling the process. Oxygen consumption through microbial aerobic respiration produces heat; as a consequence, temperature increases in the mass because heat is generated at a rate exceding its loss to the surroundings. The main consequence of temperature increase is the hygienization of the mass......Oxygen also contributes to prevent odour formation during the process; most odours are caused by reduced molecules of N, S, and P. Their oxidation will transform bad-smelling gas into liquids without odour......"

Current technology in composting

Stentiford (1993) described diversity of present composting systems such as tower, multi-floor in vessel, horizontally flow bay system, covered pile system, and other more or less open systems. He stated that for open systems codes of practice for composting are meaningless when the distribution in the mass is considered. Uniformity of the raw substrate can be improved by proper pre-processing. Then the substrate should be processed in controlled and regulated closed systems.

During aerobic processing, the substrate can contain anaerobic zones. Some investigators call them anaerobic pockets (Lynch, 1983). These are surrounded by aerobic zones. Most of the metabolites, which are intermediates produced by anaerobic microorganisms, can be consumed and transformed by aerobes. This principle could be used in biofilters to prevent odour. In biofilters the outlet air from closed systems has to pass through carbon rich bulking material. Different molecules can be used by aerobic microorganisms or bound on particles in the filter. After use the material from biofilters can be treated in the next batch of the closed system together with new substrate. Biofilters are important for preventing infections and allergic reactions (Finstein and Hogan, 1993).

Production and utilisation of composts seldom raises the issues of all positive and negative impacts on waste management, cultivation systems, and the environment. Merillot (1992) called attention to the fact that waste management policy requires more than the simple application of a treatment process. Most important is the fate of the final product. He stated that end-product requirements are as important as treatment requirements.

Great diversity and great similarity of raw materials

Diversity of OM used for composting causes, according to Zucconi and de Bertoldi (1987), heterogeneity of the products offered and their relatively poor quality. de Bertoldi *et al.* (1987*a*) postulated that the greatest problem with municipal solid

waste (MSW) is the separation of the organic fraction. Separation at the source will support rapid processes and quality products. It will also explore the impact of separate collection of waste on simplifying the recycling of the various fractions and reducing processing costs.

Raw material is very often difficult to sample representatively because of the variation throughout the collected mass (Stentiford and Zane, 1995). Rivard (1993*a*) announced the fast degradable constituents "the ultimate biodegradable fraction of the waste". This fraction should be treated as soon as possible, otherwise emissions (which are polluting losses) occur.

As long as raw material for composting consists of unsorted or centrally sorted municipal solid wastes or contains sewage sludge, one can expect almost anything in the end product. In particular heavy metals, which originate from unsorted solid wastes or from containers, vehicles, shredders, and other equipment, are limiting factors. They delaye compost quality for use in cultivation systems. They can also negativelly affect microorganisms during processing.

The total content of elements in plant biomass (dry matter and water) (Fig. 1) is made according to the characteristics of dry matter of plants presented by Salisbury and Ross (1969). The following conclusions can be made: (1) The content of the main elements in plant residues or in the main stream of municipal organic waste is similar to the content in plants. (2) Using substrates containing

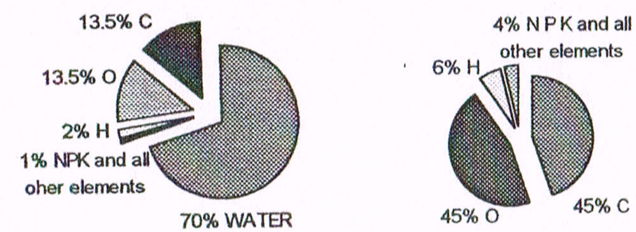

Figure 1. Plant biomass. a - fresh matter content, b - dry matter content.

animal residues with a high protein content affect mostly levels of of nitrogen. (3) By mixing various raw materials the necessary balance in the substrate will be achieved before the bioconversion starts.

In spite of the fact that the waste stream can be very changeable, there are still many possibilities to improve the various procedures in waste management and achieve both satisfactory processes and products. Organic waste, i.e. the raw materials, always contains the main elements of which organic matter is synthesised. The challenge is to improve technology and use suitable additives or activators which speed up processing.

Pre-processing, processing and additives

The role of pre-processing is to provide adequate dispersion of substrate, of the microorganisms, their intermediates and their end products. Efficient pre-processing requires energy input, but will minimise power requirements during both processing and post-processing. This statement is supported by many investigators. Grinding and shredding hasten decomposition (Goluecke, 1977). The advantages of using shredders and bioreactors can be great compared with the disadvantages (Handreck and Black, 1984). Small particle size will permit easy manipulation and encourage microbial transformation. Using well-disintegrated material directly affects costs of the equipment, process performance, and product quality. The reactor volume can be significantly reduced and power use maintained or decreased (Rivard *et al.*, 1989).

To achieve a satisfactory result it is necessary to see composting as a process based on the control of ecologically selective factors (Miller, 1992). The decomposition rate for different organic and inorganic compounds is strongly temperature dependent (Edelman and Engeli, 1993). By modifying the temperature, one is able to control not only the rapidity of bioconversion but also the conservation of the nutrient elements, especially the nitrogen, as well as the nature and the effectiveness of the resulting compost (Waksman *et al.*, 1938). Bågstam and Svensson (1976) showed effects on temperature and pH development during experiments where spruce bark was composted with different nitrogen sources. For similar studies Bågstam (1977) used spruce bark with various amounts of sewage sludge. To elevate the temperature to the required levels in the whole mass we need good insulation of the equipment (Stentiford and Zane, 1995).

Waksman *et al.* (1938) described that under conditions of active decomposition, the soluble forms of nitrogen were rapidly transformed into microbial cell substance, accompanying the decomposition of the carbohydrates. Thus, the losses

of nitrogen can be reduced to a minimum by transformation of the ammonia nitrogen into microbial protein nitrogen. They emphasised the fact that, when the available carbohydrates were reduced to a certain minimum, the proteins, both originally being in the substrate and they freshly synthesised by microorganisms, began to decompose, liberating the nitrogen in mineralised form. Further they pointed out that the optimum temperature, at which the decomposition is greatest and microbial growth reaches the maximum, lies between 40 and 55°C. They also stated that nitrogen can be conserved in the composted substrate only when immediate decomposition sets in. When the temperatures are too low or too high losses of the volatile forms of nitrogen occur.

Heat analysis or O_2 uptake during composting provides a clear view of decomposition (Miller, 1992). Mixing during processing results in an enhanced rate of bioconversion by bringing the microorganisms and the composted substrate in closer contact. Some kind of agitation or use of mixers is necessary to ensure homogeneity of the end-product.

Most microorganisms show a time of adaptation when transported to a new environment e.g. when reinoculated in biochemical processes and this affects the reaction rate for substrate consumption and product formation (Edelman and Engeli, 1993). Additives and activators or starters can change the duration of the lag phase of the process, the total microbial activity, temperature development, as well as the quality of the final product. In batch-type processing, all nutrients required during one run of microbial transformation are added to the substrate before decomposing is started (Edelman and Engeli, 1993). Actually, there are still possibilities to add various compounds during the process, especially when advanced monitoring and control systems are used.

Lynch (1993) introduced new techniques that are available to determinate the beneficial and harmful microorganisms. He also pointed out the importance of the role of lignin in composts and suggested inoculation with N_2-fixing bacteria. The current systems of composting may be modified for more efficient use of the results from mentioned investigations.

Post-processing and emissions - pollution - losses

This part of compost management is less developed. It is often mentioned that after the short period of intensive composting, curing is necessary for achieving mature compost. Unfortunately, processes of maturation are mostly carried out in open systems. Influence of wind, rain, and unwanted microbial attack cannot result in reproducible and safe products. Old compost had less of nitrogen readily available for plants. These composts can be used as conditioners when mixed with cultivation media i.e. soils and horticultural substrates. In oposite the biofertilisers from completely closed systems should be used immediately or preserved in ways that can guarantee or possibly even improve their quality.

Investigations on nitrogen availability (Waksman *et al.*, 1938; Gajdos, 1992*a*) and mobility show that after the composted substrate became cooler, ammonia disappeared from it and polluted the environment. The use of well-processed "fresh" or proper preserved biofertilisers can probably hasten the whole organic waste management and increase the recycling of nitrogen, the microbial biodiversity, and the amount of preserved bioenergy.

Existing "old-fashioned" methods of organic waste management, as composting and rotting, are seldom optimised with consideration to material and energy flows. Therefore, overcapacity often appear in process-oriented composting plants. Most of them cause emissions into the atmosphere and leakage into the soil and water (Denecke *et al.*, 1995). It is the putrescible part of the waste which create odours when breaking down under uncontrolled anaerobic conditions (Stentiford, 1993). Therefore new strategies for bioconversion in completely closed equipment, which include post-processing as well, have to be developed and implemented.

Walker (1993) identified odour compounds at sewage sludge plants. They are ammonia, inorganic sulphurs such as hydrogen sulphide, dimethyl disulphide, aliphatic (fatty acids) amines, and aromatics. Some of these odours, as for example ammonia, can be very intense on-site and mask other odours. Similar gaseous emissions are produced at composting plants both during active composting and curing or maturation. In compost piles some parts can be under anaerobic conditions with the associated odour problems. Unfortunately, not only gaseous but also liquid compounds originate from composting piles or bins. At the same time many microorganisms in their various forms can fill the air. Thus the current open systems can be the potential pathogen hazard for humans, animals, and plants. They also produce emissions that are difficult to identify (Zucconi and de Bertoldi, 1987). Problems at open composting plants can also be caused by rats and mice.

In a report from Brazil, composting was seen as the solution for all sanitary and environmental problems related to it. Unfortunately, it was also seen as a technique worthy of exploitation by greedy speculators and suppliers. This fact brought forth several technologies, mostly emphasising only the equipment side (enormous industrial electromechanical plants) and neglecting the biological side of the process (Neto, 1996). Similar development was observed during the seventies in Sweden and recently the same trend is coming back again.

Emissions from open biological and other waste management can be briefly summarised as follows: Environmental degradation increases with emissions as a result of work of from incineration plants, wastewater treatment plants, landfills and all open or partly closed systems for composting and rotting. The main source emissions of particles are incineration and transport by lorry (Hoffman *et al.*, 1995). Emissions pollute air, water, soil, and sooner or later affect all living organisms. Emissions also cause economical losses when nutrient elements and energy are not reused. Information on exhaust gas from incinerators has not always been systematically gathered, nor properly interpreted (Edelman and Engeli, 1993). The solid remainder from incineration of municipal solid waste is ash (about 25 weight %), which in some countries is classified as hazardous waste. From Switzerland for example ash was exported to other countries and dumped (1989) for about 800 US$ per metric ton (B. Hjortdal, director of composting plant in Falkenberg, private communication). By incineration organic matter is destroyed - no humus returns to cultivation systems and microbial diversity decreases.

Value of composting; quality of composts - biofertilisers

Jeris and Regan (1968) declared that the value of composting lies in its ability to reduce the bulk volume of the waste materials, produce an aesthetically non-objectionable and safe residue which meets public health standards, and produce a useful humus material by which carbon and nutrient elements are returned in usable form to the ecological cycle.

Recently an examination has been presented of the framework for successful composting of source-separated MSW by Peltczar *et al.* (1993). The authors describe composting as a cost-avoidance activity when organic waste is diverted from landfills or incineration to avoid the cost (both monetary and environmental) of these disposal methods.

de Bertoldi *et al.* (1987*a*) proposed production of diversified composting products to suit different utilisation requirements. When considering the impact on product quality and on improving technology of composting, the new approach has to promote strictly controlled conditions not only during processing (Zucconi and de Bertoldi, 1987), but also during collection of raw material, pre-processing as well as post-processing, transportation, marketing, and application of end-products.

Zucconi (1986) described heterogeneity of the composts which is caused by a great diversity of materials. Therefore, specific recipes capable of balancing the composition of materials must be devised for each substrate. de Bertoldi *et al.* (1987) declared that the chemical composition of the substrates is still a relatively unexplored field. There is still lack of sufficient knowledge on the impact of various elements and compounds.

Diener *et al.* (1993) wrote that the commercial composting facilities produce compost in two main classes: unrefined (with minimal processing) and refined (with grinding, screening, and finishing to improve texture and eliminate visible impurities). These strategies are still concentrated on old and low composting technology. Therefore, product-oriented management of organic waste should advance from heaps and bins to bioreactors. By efficient bioconversion various biofertilisers of high quality can be produced.

Effects of composts: soil improvement - productivity - fertility

Soil that supports plant life is composed of a dynamic mixture of variously sized organic and mineral matter, living organisms and their non-living remains (Metting Jr., 1992). Handreck and Black (1984) described what happens in the soil when compost is added. They alleged that using partly maturated composts would cause an explosion in the microbial activity in the soil and crumb formation would be extended. Microorganisms secrete slimes that glue particles together loosely. Thus, aggregation of soil particles is a result of microbial activity. They also stated that anything that encourages microbes to multiply rapidly in a soil will encourage crumb formation. Worm casts are also held together mainly by slimes produced by bacteria in the worm's gut. Soil fungi hyphen weave through the soil and behave like sticky string bags in holding particles together.

Addition of all kinds of organic matter affects the biological, chemical, and physical properties of the soil. The advantage of using compost, in comparison with for example peat, is in the higher content of nutrient elements, microorganisms, dry matter, and higher pH. Effects of compost on cultivated soils have been described by many investigators, and some of their results are mentioned here.

Goluecke (1977) stated that in general, regardless of species of plant, growth was always enhanced by the addition of compost to a higher degree than by mineral fertilisers alone - provided of course, that proper C/N ratio was maintained in the soil receiving compost. He declared that humus increases the ability of the soil to absorb rapid changes in acidity and alkalinity, and the neutralisation of certain toxic substances. He also mentioned that phosphorus from humus is more readily available to higher plants, but nitrogen in bacterial protoplasm is insoluble and becomes available later when bacteria die and decompose.

Humus importance as base for soil fertility is described by Stevenson (1982).

Humus formation and metabolism of the lignin during composting of straw was studied by Giovannozi - Sermanni (1987) in solid state fermentor. Bulking agents with high cellulose-lignin content such as straw and sawdust may promote the formation of humic matter during composting (Viel, 1987).

Sommerfeldt and Chang (1985) recommended application of MSW to soil to improve soil properties such as increase of organic matter content, bulk density, soil aeration, porosity, water infiltration and water holding capacity, and in turn control soil erosion and enhance soil productivity.

Elliott and Papendick (1986) stated that surface managed residues beneficially affect the upper portion of the soil profile. Sikora and Azad (1993) wrote that use of composts imply that less of the highly mobile mineral fertilisers, which may pollute groundwater, are added to fields. Dick and McCoy (1993) wrote that nitrogen deficiency can be caused by an excessive nitrogen demand of soil microorganisms which utilise the added compost containing high C/N ratio. If the compost has been sufficiently cured prior to soil incorporation, this problem can be avoided.

Finck (1982) implied that in the future, precise and comprehensive fertilisation will be necessary in order to meet the increased demand with respect to the quality and quantity of the crops. He also mentioned that knowledge of new and old fertilisers, as well as many basic questions of agricultural chemistry relevant to fertilisation, is indispensable. He pointed out that a deficiency or imbalance of nutrient supply can considerably reduce the yield and primarily the net profit when production costs are high. Furthemore he stated that to ensure an optimum nutrient supply, fertilisation must be carried out according to extended and improved concepts and therefore a newly oriented theory will be necessary in order to achieve increased control of biological production in agriculture.

In the review on composting, Dick and McCoy (1993) declare that maximum benefit of compost for soil fertility improvement requires an understanding of the interactions of all physical, chemical and biological properties altered by compost. They pointed out that this task not only involves knowledge of the soil but also the crop being grown.

Pollution prevention and other benefits

Hadar (1986) wrote that various groups of soil microorganisms may be able to tolerate mineral fertilisers and chemical pesticides with the help of composts. Thus, costs will be lowered and environmental hazards and pollution reduced. Composts and/or biofertilisers can be produced for special purposes to remediate soils by microbial transformation of man made chemicals to harmless substances and thus alleviate the effects of pollution.

It was stated by several investigators that compost lowers the uptake of heavy metals by plants. Andersson (1983) studied the influence of composted municipal solid waste on heavy metal concentration in soil and crops which he compared with influence of sewage sludge, manure and NPK fertilisers. He concluded that increase of heavy metals in soil by addition of composts or sewage sludge does not always result in a higher content in plants, because the relationship between the concentration in soil and plant is complicated. Organic fertilisers also affect solubility and availability of heavy metals to plants by increased pH and humus content. The levels of organic matter in soil have to be maintained, otherwise the beneficial effects will eventually disappear, due to acidification and mineralisation of organic substances. He also stated, that high levels of toxic heavy metals in soil will always be potentially hazardous. Stilwell (1993) demonstrated that the decrease in cadmium content in tomato fruit and leaves when compost was added to soil was probably due to increase in soil pH. This happened in spite of the 7-8 fold higher cadmium content in the MSW compost.

Composts can be used as peat substitute in container media. Hoitink *et al.* (1991) wrote that composted pine bark is the most widely used for this purpose. Glass (1992) described possibilities for use of microorganisms for bioconversion of organics, for developing microbial fungicides and insecticides. He also suggested novel research on the use of plant pathogenic fungi as weed control agents.

Combined bioconversion processes, biogas and biofertilisers

The most well-known example on using anaerobic or aerobic process of microbial transformation is producing wine or acetic acid from the same fruit juice. The similarity in the requirements on the substrate between aerobic and anaerobic microorganisms in this case is obvious. The difference lies mainly in the adaptability of microorganisms to oxygen from the air. In a similar way we can steer and regulate production of biogas and biofertilisers.

Rivard *et al.* (1989) described anaerobic digestion in landfills as a natural process of bioconversion, which occurs very slowly due to changes in temperature and moisture content. The high-solids anaerobic bioconversion on landfills is very slow because of lack of process control. They suggested that this process can be economically viable in reactors designed to maximise the rate of microbial transformation.

Several studies indicate that combined aerobic and anaerobic processes can be

most beneficial both from the environmental and economical point of view. The bioenergy from organic materials can be converted by microorganisms to biogas and the remaining solids can be used as biofertilisers.

The treatment of solid organic wastes in combined facilities, using both aerobic and anaerobic bioconversion, is recommended by Edelman and Engeli (1993). They also suggested that there is a great need to realise decentralised professional plants. Combined plants may be cheaper than existing facilities. At the same time, the treatment and use of OM will be improved. Transports can be minimised which decreases energy use and pollution of the environment. Archer (1989) pointed out that the most effective control over bioconversion of waste has already been lost once waste has been landfilled, therefore to optimise methane production purpose-built reactors should be used. Organic wastes on landfills are actually representing a loss of plant nutrients, humic substances, and microorganisms that should be profitable instead of polluting when utilised on cultivated soils.

Parr and Hornick (1992) suggested the necessity to investigate whether composting and co-composting are viable options for alleviating the mounting municipal waste problem. They pointed out that clarification is needed to fix the "value" of organic wastes as biofertilisers and soil conditioners.

Anaerobic digestion of solids is conventionally performed in completely mixed suspension reactors at low concentration (<5-20% total solids), but a recent breakthrough is the development of solid state fermentation at high concentration (20-40% total solids) described by Baeten and Verstraete (1993). The advantages of using high solids are: limited addition of water, which results in smaller reactor volumes, decreasing heating energy requirements, and higher yield of biogas per volume of reactor. The solid end product relies on both anaerobic and aerobic microorganisms, and is referred to as "double bio-process compost" (DP-compost) in contrast to only aerobically treated substrate referred to as "single bio-process compost" (SP-compost).

For the production of fuel gas from solid wastes, reactor capital costs have been identified by Rivard *et al.* (1989) as an important cost factor, partly because of the large reactor volume required for conventional low-solids digestion processes. He also assessed that the maximum sludge solid level was 35-40% solids for active microbial transformation of OM to methane.

Rivard (1993*b*) evaluated digester performance, agitator design, rotation speed, as well as effects of particle size on anaerobic bioconversion. All these results can be adopted when combined processes will be performed. He also compared high-solids (30%) and low-solids (7.3%) fermentation technology by using biochemical methane potential assays. Presented results show that using high-solids performance gave more than 6 times higher biogas production within the same bioreactor volume. It means higher process efficiency and at the same time lower costs for bioreactors. Total solids reduction was similar and bulk reduction was 10.5% in high-solids compared to 2.5% in low-solids reactor.

de Bertoldi *et al.* (1987*a*) suggested that recovering energy by "dual process", i.e. composting and anaerobic treatment for methane production, has to be analysed as well as the impact of both processes on humus quality and on plant response. They also recommended that there is a need to increase efficiency in the composting process, reduce processing time and achieve better quality.

Full scale plants with combined bioconversion, where mainly cow manure with straw is treated, have performed for years in Central Europe (Wolff, 1989). Biogas is used for production of electricity and heat, or can be used as fuel in cars, lorries, or buses. Excess energy from combined process can be sold (Denecke *et al.*, 1995).

Specific research questions

Cultivation of different crops has always fascinated me. To cater for the ever growing world population, the crop production would have to be continuously improved, and thus plant nutrition should be one of the central tasks concerning food quantity, and also quality. Efficient circulation of elements, which are stimulating or indispensable for plant growth and development, is one of the challenges we face to achieve a higher yields and, at the same time, sustainability in cultivation systems.

Cultivation tests were started in 1981 at the Department of Horticulture in Alnarp, Sweden, using different types of bark as part of the growing media for container-grown nursery plants. The aim was to investigate possibilities for using bark as growing media instead of peat. Results of these experiments showed that there was a great difference between the plant response on old bark from different trees and composted bark where mainly spruce bark was used as raw material for composting (Gajdos, 1986). In litterature describing composting of bark are many articles informing about different composting methods, results from cultivation experiments, and experiments dealing with biological control. In research from Norway (Solbraa, 1979*a,b,c,d*), Ohio in USA (Hoitink, 1980; Hoitink and Poole, 1980; Hoitink *et al.*, 1982) and Sweden (Bågstam *et al.* 1974; Bågstam and Svensson, 1976; Bågstam, 1977; Bågstam, 1978*a,b*) were pointed out advantages of proper processing as well as the positive effects of bark compost on plant nutrient supply and on biological control of several pathogenic fungi.

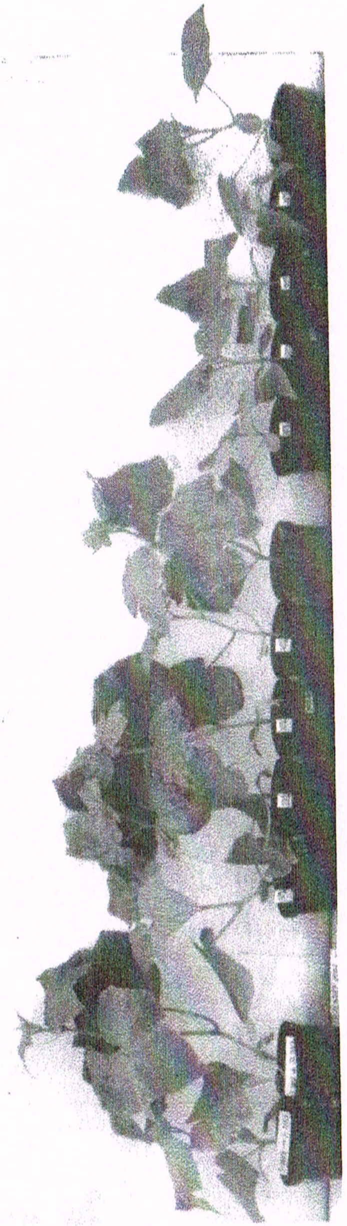

Figure 2. Effects of composts on growth of cucumber plants. Seeds were sown in peat substrate for sowing (S-jord, from Hasselfors) or in peat with various composts. Seedlings were replanted to peat substrate for growing (P-jord, from Hasselfors) or to peat with composts ('cs compost' was made of centrally sorted while 'ss compost' from source separated municipal solid waste).

Both Swedish Association of Waste Management and managers for composting plants, where municipal solid wastes were treated, became interested in cultivation tests for evaluation of compost quality. The REFORSK foundation gave financial support to investigate the suitability of different composts for cultivation needs.

In 1987 and 1989 studies were carried out concerning the effects of compost mixtures on plants in different cultivation tests. Composts from centrally and separately sorted municipal solid wastes were investigated. Various horticultural plants were grown in the peat mixed with composts, such as cucumber (Fig. 2), tomatoes, African marigold, lettuce, lawn grass, radish and garden cress (Gajdos, 1987 and Gajdos, 1989). In sand, moraine and clay soil respectively, amended with composts from municipal solid wastes, cuttings of two *Salix* clones were grown as fuel crops (Gajdos, 1987). Crop response to different composts varied, due to difference of crop requirements on the root environment.

Table 1. Changes of nitrogen during composting in four composting containers (mg/L).

	ROLATE[1]		THERMO-COMPOSTER[2]		SOILSAVER[3]		PLASTIC BARREL[4]	
Weeks	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
4	674	39	329	186	236	306	318	111
8	104	274	158	369	104	226	268	219
10	15	240	8	229	25	295	76	263
17	7	157	7	340	5	167	6	369

[1] ROLATE - well insulated backyard composter from Finland (Fig. 2a).
[2] THERMO-COMPOSTER - partly insulated backyard composter from Switzerland.
[3] SOILSAVER - backyard composter without insulation from Canada (Fig. 2b).
[4] PLASTIC BARREL - covered with lid, with open bottom for aeration.

As the quality of the composts from municipal composting plants does not meet the needs of the cultivated crops, my specific research question was how to improve the composting process to increase the compost quality. Responding to the interest from home-gardeners, an investigation started on composting in different backyard composters (in Sweden called composting containers). A mixture of plant residues (grass clippings and shredded branches and weed plants) was composted in four

a

b

Figure 3. Backyard composters - 'bins' with various levels of thermal insulation. a - bin without insulation (SOILSAWER), b - well insulated bin (ROLATE).

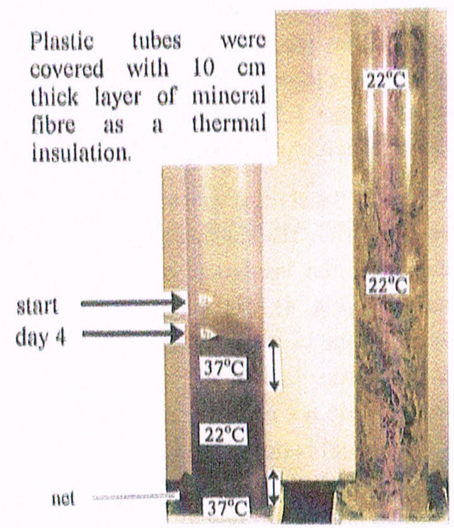

Figure 4. Effect of disintegration of raw material on volume and self-heating of the substrate. a - chopped raw material, b - shredded raw material (mesh openings of 1.5 mm).

types of backyard composters with different thermal insulation. Figure 3 shows two composters, one well insulated and one without thermal insulation containing openings for aeration. Cultivation tests showed that composting in well insulated backyard composters after four weeks gave compost which had more ammonia nitrogen (Tab. 1). When this compost (20 volume %) was mixed with soil (moraine), the best plant growth and development was achieved. Weed plants (*Poa annua*) did not appear as was the case in containers where soil was amended with compost from the simultaneously running less well or non insulated composters (Gajdos, 1992*b*). Results from this investigation indicated possibilities to improve the quality of composts with the aid of insulated containers.

In 1989, a series of insulated boxes of 20, 40, 80, and 160 litres were built. Identical substrate, made of leaves, grass clippings, and shredded old cucumber plants, was used in all of them. That experiment failed because of different technical problems. I realised that to achieve reproducibility of raw material it is necessary to increase the precision in all steps within the system.

Screening experiments on disintegration were carried out in plastic tubes (1 m high and 20 cm in diameter). The tubes were covered with 10 cm thick insulation of mineral fibres (Gullfiber) protected by aluminium foil. As substrate were used two portions containing: potato skin, carrot skin, cabbage leaves, dry leaves, hay, straw, bones (each of 200 g) and egg shells from 4 eggs. One portion was only mixed and placed in the first tube. The other portion was shredded (the mesh diameter was 1.5 mm) and then placed in the second tube. A net covered the bottom of both tubes, and tubes were placed so that air could enter the substrate.

Already at the start, it was evident that the shredded substrate occupied only half of the tube, while the substrate that was only mixed occupied the whole tube. After four days, the insulation was removed and the substrates in both tubes were examined (Fig. 4). The shredded substrate had two warm and dark layers, one in the top about 15 cm high and one at the bottom about five cm high. In the middle, the layer was lighter and cold. Probably the aeration was not sufficient. The oxygen could not reach the middle layer because that microorganisms in the layers at the top and bottom used it. In spite of that the total reduction volume was 5 to 7 per cent four days after the start of the experiment. Actually, the reduction appeared only in layers with the elevated temperature.

To create a suitable mixture that could be used at any time and which would have good reproducibility, different vegetable residues were collected, shredded, and mixed with sawdust and straw. Then the mixtures were processed in insulated boxes and the temperature development was monitored. At that time, the particle

size of the sawdust and straw was up to 8-10 mm and 40-50 mm, respectively. Later, both were shredded and passed through a sieve of mesh size 3 mm. The final particle size was 1.5 mm in diameter. The content of main elements and water in the standard substrate is shown in Figure 5.

When looking for a laboratory system, various insulating materials were used to insulate vessels of different shape, until my colleague, Barbara Biegus, suggested thermoses for laboratory use with a volume of 3 litres (Fig. 6).

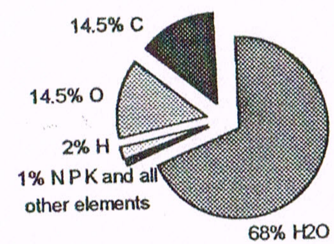

Figure 5. Standard substrate.

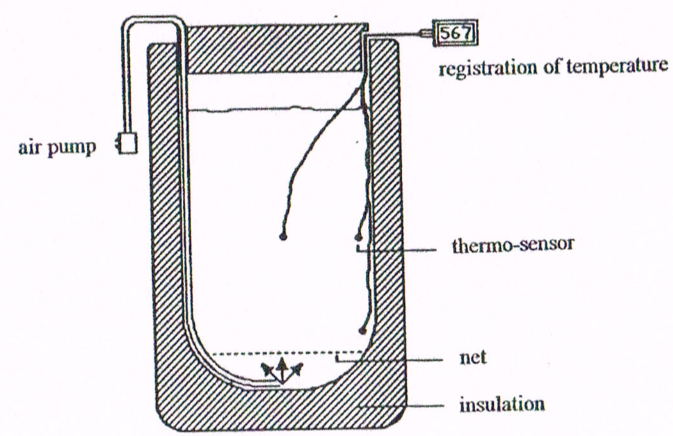

Figure 6. Schematic drawing of a well insulated static bioreactor.

Objectives

The objectives of the present work were:

- To study the response of horticultural crops to composts (Paper I) produced from centrally sorted and source separated municipal solid waste and used as amendments in cultivation media.
- To investigate in laboratory experiments (where two composting methods where developed and a reproducible standard substrate was constituted) some of the most important factors needed for product-oriented composting (Paper II) such as (a) the influence of the additives and the thermal insulation of the bioreactors on temperature and pH development during processing, (b) effects of two different sizes of bioreactors on temperature, pH development, and fresh weight losses, and (c) effects of aerobic and anaerobic processing on the temperature development and on chemical composition of the final product.
- To evaluate current, centralised, open systems in organic waste management, compare it with proposed, local, closed systems (Paper III), and thus give motivation for further improvement of the technology for efficient bioconversion of organic wastes to various valuable products while avoiding emissions.
- To assess possibilities for recirculation of nutrient elements and reuse of bioenergy bound in solid and liquid organic waste by the year 2010 (Paper IV), with regard to needs of novel organic waste management methods producing biofertilisers for sustainable cultivation systems.

Material and Methods

Paper I: Crop response to composts

Composts are mostly used as amendments to cultivation media (soil or substrate). It was investigated how the current composts from municipal composting plants fit crop requirements. It was tested if composts made of source separated (ss) municipal solid waste (MSW) are better suited for cultivation than composts made of centrally sorted (cs) MSW. The ss raw material for composting contained only organic household waste. The cs raw material contained inorganic impurities because the separating method was only used for sorting out "light" waste i.e. dry organic materials suitable for incineration.

Lettuce (*Lactuca sativa*), garden cress (*Lepidium sativum*), ryegrass (*Lolium perenne)*, radish *(Raphanus sativus)*, and African marigold (*Tagetes tenuifolia)* were used as test crops. Their response to composts was studied in an experiment where three cultivation runs, 16 cultivation media, and two fertilising trials were used. Test plants from eight peat-compost cultivation media, which contained 10, 20, 30, and 40 volume/volume % of each compost, were compared with those growing in seven peat-based commercial horticultural media and peat. A liquid fertiliser 'Superba S with micronutrients' was added to one trial in each run. A novel method for calculating compost amendment rate was developed. By this method for mixing compost with peat the reproducibility of the cultivation media and the precision of the performance will be increased.

The tested media were analysed for pH, conductivity, and level of available nutrients at the start and termination of each run. Other parts of the performance such as sowing, watering and fertilising were provided according to horticultural praxis and rules for cultivation under controlled conditions in biotrone. Deionised water was used for watering and leaching was avoided. Observation was made on germination and measurements of available nutrients, fresh and dry matter, and root density at harvest.

Paper II: Composting - microbial transformation

Home composting of plant and food residues has always been the usual procedure for many people. In this work two laboratory methods were developed for studies on improvement of the composting process. The goal was to obtain a final product which will be accepted as biofertiliser of reproducible quality.

In the first method five thermoses were used as well insulated (WI) static bioreactors (SB) and two plastic tubes covered with paper tubes as less well insulated (LWI) SB. All bioreactors had a volume of 3 litres. 800 g of well disintegrated and mixed substrate was processed in each. In the second method well insulated, six sequentially rotated bioreactors were used, three of 3 and three of 18 litres volume in which 800 g and 5.6 kg of substrate was processed respectively. Effects of scaling up could be demonstrated.

Bioreactors were equipped by plastic tubes connected to air blower for aeration of the substrate. A logger with 24 channels was used for frequent temperature measurements during the two weeks of the microbial transformation. The degree of thermal insulation was determined by measuring temperature changes in warm water placed in the bioreactors.

As reproducible standard substrate ecologically grown shredded vegetables (potatoes, carrots and cabbage) were mixed with dry bulking agent of plant residues (barley straw and pine sawdust). This identical substrate was frozen in portions suitable for the batch system. Standard substrate was analysed before processing for total amount of following elements: C, N, P, K, Ca, Mg, S, Fe, B, Mn, Na, Ni, Zn, Al, Cu, Cr, Sr, Rb, Ba and after processing for pH, conductivity and readily available plant nutrients NO_3^-, NH_4^+, P, K, Mg, S, Ca, Na, Cl, Mn and B. The standard substrate was treated with and without additives in static and rotated bioreactors in the laboratory (Gajdos, 1992*b*; Gajdos, 1995*a,b*).

In screening experiments on different particle sizes, the temperature development showed that the process was calmer when sawdust and straw passed through a sieve of mesh size 1.5 mm than of 3 mm (Gajdos, 1992*b*). Therefore, the studies were carried out on the standard substrate with the finer fraction of the bulking material.

Paper III: Holistic approach in bioconversion

Motivation for microbial transformation as the main way for reusing elements and energy bound in organic matter is still missing in our society. Not only all organic wastes, but also all organic residues, by-products and so-called fuel crops can be used as renewable raw material. Efficient bioconversion will lead to increased microbial biodiversity and to ecologically sound conservation of natural resources. In Paper III some of the used methods are practised for Life Cycle Analysis.

A novel approach to ecologically and economically efficient management of organic waste by microbial upgrading for use in cultivation systems is introduced

here as the G&G system. In this completely closed system, mixture of solid and liquid organic materials will be transformed in aerobic or in combined aerobic and anaerobic bioconversion to valuable products while avoiding emissions.

Current management of organic waste is evaluated and compared with future methods which are based on the use of efficient collecting and pre-processing systems, processing by microbial transformation in bioreactors, on suitable post-processing, and on improved application system which have to be adjusted to needs in cultivation systems. Methods and equipment used in G&G system will promote efficient recycling of plant nutrients and efficient use of energy bound in organic materials.

Paper IV: Assessments based on needs of circulation of plant nutrients

The necessities of humans, such as clean air and water, healthy food, and an ecologically sustainable environment, call for changes in the approach for management of solid and liquid organic waste. Investigation of needs and problems which appear in present cultivation systems as well as in current waste management systems formed a base for suggestions for more efficient use of the potential hidden in organic waste. Organic materials in waste have to be treated as renewable raw material. Efficient bioconversion will lead to sustainable waste management and can bring economic and environmental benefits.

Calculations made on economical benefits of current methods in comparison with the suggested methods are based on the assessments of value of nitrogen, phosphorus and potassium in organic solid and liquid waste from the urban area and of usable energy from the renewable sources.