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Bioconversion of organic waste by the year 2010: to recycle elements and save energy

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Abstract

The needs and problems existing in the field of cultivation systems and waste management concerning elements and energy, as well as pollution, health, environment, and economy are described. The lack of reproducible biofertilisers of high quality calls for an efficient use of organic waste as a renewable raw material. Each 100000 inhabitants in Sweden generate organic waste with considerable economic values in terms of nitrogen, phosphorus, and potassium; US$ 600000 from the organic fraction of municipal solid waste and US$ 900000 from human excreta as liquid organic waste, meanwhile only US$ 160000 is recovered from the sewage sludge after the wastewater has passed the wastewater treatment plants. Most of the existing systems for handling solid and liquid waste are of old-fashioned design and cause large losses of nutrient elements. Therefore, pollution of air, water, soil, and vegetation, mainly by emissions from organic uaste, continues. Bioconversion is microbial transformation and upgrading of various organic wastes to products of high value. The elements can be efficiently recycled in completely closed local bioconversion systems with subsystems for collection, pre-processing, processing, and application of end-products. Solid and liquid organic waste from the municipality can provide renewable raw material for manufacturing of reproducible biofertilisers and of biogas. Suggestions are made on how to improve the present situation by the re-orientation of technology. A scenario for bioconversion by the year 2010 is presented. © 1998 Elsevier Science B.V. All rights reserved.

Abbreviations: CS, cultivation systems; IW, industrial waste; LOW, liquid organic waste; MSW, municipal solid waste; NPK, nitrogen, potassium, and phosphorus; OM, organic matter; OW, organic waste; SOW, solid organic waste.

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1. Introduction

The treatment and disposal of wastes, which are mainly of organic origin, is one of the most important problems [1] and greatest challenges facing mankind. Environmental degradation is often caused by mismanagement of wastes [2]. Human health relies on environmental health, which can be measured as air, water and food quality. People have become more environmentally conscious and any kind of system that could contribute to health problems becomes a public issue [3]. Myles [4] wrote that humankind has progressed to the point of having numerous large organic waste streams, thus intensive decomposition systems to match our intensive production systems must be developed.

Most of cultivation systems (CS, defined here to include forestry, agriculture, horticulture, aquaculture, and green urban areas), use petroleum-based, chemically synthesised fertilisers, pesticides and other chemical substances. All these systems also use energy transformed mainly from fossil energy carriers. On the other hand, there is a great amount of plant nutrients and bioenergy (the biochemically bound energy) in organic waste (OW), residues, by-products and fuel crops. These renewable raw materials can be efficiently upgraded in bioconversion systems, plant nutrients can be recycled and bioenergy used.

The production of healthy crops is a basic requirement of modern CS for food and fibre production [5]. Healthy plants can be produced only when human activities respect basic biological rules, for example by proper handling in all steps of OW management. de Bertoldi et al. [6] proposed that compost should be used in different CS in an advantageous manner for the plants.

The existing waste and wastewater management practices are solving the problems associated with OW by use of landfills, incinerators, wastewater treatment plants, and only a small part of OW is treated biologically in systems based on ancient methods. Most of the existing composting and rotting systems entail environmental problems and also are producing composts of insufficient quality and with great losses. Water is one of the most important components of all organisms, therefore it should be protected from pollution and not used as a vehicle for transport of human excreta and other waste materials. Using information from Jenssen and Vant [7], only the purification costs of wastewater (which ought not to be higher than the environmental costs) for removal of phosphorus, depending on the size of the treatment plant, vary in the range of US$ 75–500 per person per year. For the removal of nitrogen (by process of denitrification) the cost per person is nearly double.

Biological treatment of solid, liquid and gaseous wastes is probably the only way that leads to sustainability. All biodegradable wastes can be treated by product-oriented processes of bioconversion in facilities using advanced technology. Regulating and speeding up natural biological processes, for example short-time composting [8], can be one of the steps to achieve an optimal system for processing OW. Composts or biofertilisers of desired quality can be used as (1) growing medium or horticultural substrate [9,10], (2) substitute for peat in a container medium for the nursery plants [11,12], (3) soil improvements that influence the physical, chemical and biological properties of the soil [13], (4) amendments to control soil erosion and maintain land productivity, for example in the mountain environment [14], (5) amendments or media for biological control of soil-borne pathogens [15], (6) mulching to prevent evaporation of water from the soil and/or to disturb and/or delay germination of weed seeds, (7) media for sanitation, as addition of composts, can lower availability of heavy metals for plants [2], and (8) medium to enhance the biological degradation of various chemicals in contaminated soils [16]. Consumers demand to treat sanitary OW without negative impact on the environment, to recycle plant nutrients, and to use a minimum of energy was the driving force for this work.

The first aim of this study was to focus on the great value hidden in organic matter (OM) primarily as plant nutrients and biochemically bound energy from a holistic point of view. The second aim was to give some suggestions on how to treat solid organic waste (SOW), which includes 'wet' and 'dry' OM originating from present, i.e. now living, organisms and products such as food, paper, and furniture, and liquid organic waste (LOW), which include human and animal excreta without water or bulking material, primarily from housing areas. This aim includes the question of how to solve the present situation out of consideration for recycling of plant nutrients, use or save renewable energy, protect human health and the environment and keep a good economy. The third aim was to compare old-fashioned methods of handling OW with the suggested ones.

Used data was collected from reports presented by the Swedish Environmental Agency, the Swedish University of Agricultural Sciences, the Swedish Environmental Research Institute, REFORSK, the Swedish Association of Waste Management, Agenda 21 [17], from personal communications, cited literature, and personal research on bioconversion by composting and cultivation. Closing of loop models was developed using methods similar to ecological energy and material flow models combined with cycles of elements.

The identification and description of needs and problems appearing at the present time is made in the field of plant nutrients and energy. Losses of plant nutrients during current waste management methods and in plants for wastewater treatment are estimated. The old-fashioned methods are compared with the suggested ones, which will be based on efficient bioconversion of OW in systems using modem technology for microbial transformation. For an ecologically sustainable recycling of plant nutrients, a scenario for the year 2010 is presented with attention to a fast development and implementation of technologies promoting the use of biologically based methods for handling SOW and LOW.

2. The need of a holistic view

The ecologically sustainable development of society has its base in various cultivation systems (CS). These are the source of the most important energy for humans: food. The CS produce also industrial feedstocks and have great impact on the environment. Recycling of plant nutrients and efficient use of renewable energy bound in OW is needed, not only for farmers. It should be in the interest and responsibility of the whole society to have an ecologically sound waste management.

The CS need well tailored, reproducible biofertilisers of high quality, which are not available, because the outdated, expensive, and biologically hostile treatment of SOW and LOW. The present needs and problems in the CS (Section 2.1) and in management of OW (Section 2.2) are two sides of the same coin. This results in loss of energy and plant nutrients, emissions which pollute the environment (Section 2.3), and affect human health (Section 2.4), and the economy (Section 2.5). The use of fossil energy carriers can be considerably decreased by the use of OW as source of renewable energy via processes of bioconversion.

The classification of various energy sources in Table 1 briefly explains the differences in terms of by-effects when chemical (burning) and biochemical (microbial conversion) methods of energy transformation are compared. The assumptions

Table 1
Classification of energy sources based on benefit such as the solid and biologically active remainder (biofertiliser), the degree of efficiency in energy transformation, emissions, pollution and produced carbon (C) in carbon dioxide (CO_2)

Source	Fossil			Renewable	
Material	Coal	Oil	Natural gas	Organic waste	
Process	Incineration				Bioconversion
Outcome					
Useful:					
Biofertilisers	–	–	–	–	+ + +
Microorganisms	–	–	–	–	+ + +
Humic substances	–	–	–	–	+ + +
Nitrogen for plants	–	–	–	–	+ + +
Other plant	–	–	–	(+)	+ + +
Nutrients					
Energy[a]	+ + +	+ + +	+ + +	+/+ +	+
Disturbing:					
Emissions	+ + +	+ + +	+ + +	+ + +	(+)
Pollution	+ + +	+ + +	+ + +	+ + +	(+)
kg of C in CO_2/GJ[b]	24	20	14	0	0
Relative values[b,c]	2	1.5	1	0	0

Symbols: –, do not appear; (+), can appear; +, low; + +, high; + + +, very high.
[a] Degree of efficiency.
[b] Impact on the greenhouse effect. Values presented by the Intergovernmental Panel on Climate Change (IPCC).
[c] According to IPCC the relative values which are used in various calculations are misleading.

in Table 1 point out the advantages of bioconversion. The degree of efficiency in energy transformation varies for different energy sources. Fossil energy carriers are often treated by modern efficient methods. Therefore the degree of efficiency can be high. In Sweden renewable sources (wooden waste, packages) are very popular for energy recovery by incineration at present. Unfortunately, incineration degrades all organic compounds and causes emissions, which pollute the environment. Ash from waste incinerators is classified as hazardous waste in some countries and deposition fees are very high. In Switzerland the deposition fee was US$ 914 (1989 value) per ton ash generated from household waste (B. Hjortdal, the head of municipal composting plant in Falkenberg in 1989, personal communication).

The Swedish Association of Waste Management showed that, in 1992, 4.4 TWh energy was generated by incineration and used mainly for heating, while the available amount of energy, in the burned OW, was about 12 TWh. Thus, the energy transformed for use was only about one-third of the energy which was biochemically bound in the OW. The negative impact of incineration on the environment was not evaluated.

Demuynck and Nyns [18] estimated that one-third of the energy that can be recovered by incineration of domestic waste can be recovered as methane gas. In combined bioconversion processes the energy, which is transformed by microorganisms to energy-rich methane, can be transformed to electricity and heat, to only heat, or to fuel for use in engines. Under the assumption that the degree of efficiency by microbial transformation will be 30%, there will still be a great amount of energy bound in biofertilisers, which are the solid remainder of bioconversion of OW. Biofertilisers contain plant nutrients and bioenergy in the not completely decomposed organic material, in newly built humic substances, and in the microbial biomass.

There is very little known about what kind of substances appear on landfills, how they influence water, soil, and vegetation, and how they interact with other compounds inside and outside living organisms. Various heavy metals and anthropogenic substances, such as persistent organic compounds, are hidden in landfills [19]. Source separation of waste and uncompromising restrictions on production, distribution and use of agrochemicals in CS will stimulate the development and implementation of bioconversion, and clean up our polluted environment.

2.1. Cultivation systems

The need of an efficient production of plant biomass for humans and their activities resulted in various more or less efficient cultivation systems. The produced biomass is the basic renewable raw material which is then upgraded to food, feed, paper, furniture, some building materials, etc. After a shorter or longer time of use, all OM become OW, still containing most of the elements, originally bound in organic matter during photosynthesis by energy from the sun. OW should be used as renewable raw material for production of ecologically sound biofertilisers and biogas.

With proper waste-managing practices, energy and plant nutrients will be re-used and applied in cultivation systems. Soil productivity, also called soil fertility, and ecological balance needed for healthy plants can be improved by efficiently closing the loop. In CS, both crops and soil organisms have to be supported with all the essential elements and energy bound in organic compounds. These have been transported at harvest from fields and greenhouses, and are in conventional CS mostly compensated by the addition of inorganic fertilisers, often manufactured with energy from fossil sources. Other agrochemicals, such as pesticides and various soil improvements, are used in addition. This management disturbs the natural balance, probably very often, because the organic compounds are not recycled. The use of inorganic fertilisers should be allowed only when all OW is recycled and there is need to compensate losses, which, with improved technology, can be at a minimum.

The production and application of all artificial chemicals need a great amount of energy, cause pollution and, as Jansson [20] mentioned, make the plant products unsuitable as food and feed. Plant nutrients from source-separated OW can be recovered efficiently by microbial transformation processes in closed systems using bioreactors [21–23]. The bioconversion can be manipulated in many ways, when processing OW, to produce biofertilisers adjusted to various soils and to different crops or their stages of growth and development.

2.2. Waste management

During human activities solid, liquid and gaseous waste are generated. Solid waste is generally divided to industrial waste (IW) and municipal solid waste (MSW). In 1992, 56 million tons of IW were produced in Sweden. Forty-one million tons were from the mining industry, about 2.8 million tons were burnt, some wastes were composted, and more than 10 million tons were dumped. How many tons of IW were in reality of organic origin is difficult to determine. Not included here are residues from agriculture, horticulture and forestry, which are mainly organic. MSW reached 3.2 million tons in the same year. According to studies of the University of Lund, Department of Refuse Handling, up to 80% of MSW is biodegradable (Hedlund, 1991, personal communication). With the assumption that 280 kg of MSW per person per year is of organic origin, the following amounts of plant nutrients are lost: 1.5–4 kg nitrogen, 1–2.5 kg potassium, 0.2–0.5 kg phosphorus, as well as all other elements and energy bound in organic substances. Unfortunately, 50% of MSW was burnt and 45% was dumped, while less than 5% was composted. It is a matter of re-organisation and re-engineering of the old infrastructure, to allow the municipal OSW to be used together with the LOW as renewable raw material, i.e. substrates suitable for microbial transformation.

Liquid wastes are discharged into city sewage systems and the wastewater contains both industrial and domestic waste. The content of OM in industrial wastewater is difficult to estimate. Domestic wastewater includes food residues from dish washing, some skin and hair in bathwater, and human excreta and paper as toilet residues. In Sweden about 6 million inhabitants are connected to wastewater treatments plants. One hundred and ten tons of wastewater is generated per year carrying 0.4–0.7 tons of human excreta (urine and faeces without water) per person. There are 70 kg dry OM in human excreta, which contains 4–5 kg nitrogen, 0.7–0.8 kg phosphorus, about 1.3 kg potassium [24], and other elements both beneficial and harmful for plant growth.

The value of plant nutrients in human excreta, diluted in Swedish wastewater, and which do not return to the cultivation systems, is thus more than US$ 60 million annually. Unfortunately, the cost for treating wastewater can be between US$ 3000 and 9000 million per year, by assumption based on data from Jenssen and Vatn [7]. In wastewater treatment plants, mainly nitrogen and phosphorus are partly removed, while a part of OM is reduced. These costly processes lead to air pollution by compounds containing sulphur and nitrogen. We pay for effluent of ammonia, nitrous oxide and elemental nitrogen, while we have to pay for artificial nitrogen fertilisers, which are produced using fossil energy, when elemental nitrogen from air is used. By current, old-fashioned methods in wastewater treatment plants organic substances and chemicals meet in the sewage sludge. If the use of sewage sludge continues, the arable land will become more contaminated [25]. The working conditions in the sewage system and on wastewater treatment plants are far from healthy. For all of these reasons we have to collect human excreta hygienically, and then use it as energy- and nutrient-rich renewable raw material, together with solid OW or other solid OM.

Gaseous wastes originate to a great deal from gaseous emissions as a result of insufficient management of SOW and LOW. Especially the foul-smelling emissions are mainly products of uncontrolled microbial degradation. Information on exhaust gas from various human activities has neither been systematically collected, nor properly evaluated. Not only gases, but also small particles, microorganisms, and their spores are present in the air during poor disposal methods of collection, transportation, as well as treatment and post-processing of SOW and LOW. Air is polluted especially when primitive methods of composting or rotting in open systems are used.

Considering plant nutrients in uaste, only the three most important elements for plant production, nitrogen, potassium and phosphorus (NPK), are lost annually for between US$ 10 and 15 per capita during existing management of MSW and wastewater in Sweden. None of the other plant nutrients and organic substances hidden in OW, which could positively affect soil fertility, are used in cultivation. The total cost for waste management, including energy consumption and environmental degradation, is nowhere to be found.

2.3. Pollution

There are no data to substantiate the cumulative negative impacts on the environment, for example during collection, transport of waste (including exhausts from cars, damage of roads, noise, vibrations, bad odours and spores of microorganisms from transported waste affecting the air), and by use of biologically harmful

Table 2
Present 'old-fashioned' methods of composting in open, often large, systems compared with suggested future methods where bioconversion is carried out in decentralised, completely closed, automated, and computerised systems in housing areas

	Present open systems	Future closed systems
Raw material	Mixed waste or centrally sorted waste sewage sludge	Source-separated waste mixed with human excreta without water
Treated amount totally	About 5% of solid waste (mostly part and garden waste often mixed with sewage sludge)	100% of all organic waste (organic solid waste together with human excreta)
Collection	Weekly, fortnightly	Daily
Transports	Long	Short
Pollution	Large	Avoided
Losses	Large	Minimised
Retention time	Long	Short
Area	Large	Small
System	Ancient, stiff	Modern, flexible
Equipment	Huge, clumsy	Easily adaptable
Precision	Low	High
Energy use	High	Low
Environmental impact	Negative	Positive
Working conditions	Unhealthy	Clean
Products	Poor, doubtful quality	High, reproducible quality adjusted to cultivation demands
Value of yearly saved NPK/100 000 people (US$)	(?)	ca. 1.5 million
Value of yearly saved bioenergy/100 000 people (GWh)	0	ca. 730

NPK, nitrogen, phosphorus and potassium.

methods. Burning is known as the chemical oxidation of OMs where energy is released very quickly, the living substances are damaged and many life-disturbing compounds arise. Dumped waste causes pollution in the air, on soil and in water. Different chemicals are mixed with OW on the landfills, and may cause microorganisms to mutate into unwanted forms. Therefore it should be obligatory to evaluate how combinations of different wastes will affect the environment in the long term.

A comparison between open and completely closed methods of microbial transformation is presented in Table 2. Present open systems start by collecting waste in ways which pollute and disturb the environment when foul-smelling compounds and spores of microorganisms affect the air. Easily biodegradable OW should be collected in controlled closed systems and treated as soon as possible (or stored in the most suitable way such as cooling or drying), to avoid losses of biologically bound water, unexpected emission of different compounds, and unwanted biodegradative processes.

2.4. Health and environment

Human and environmental health relies on human activities. Environmental degradation is often caused by mismanagement of wastewater [2]. Elliott and Papendick [26] mentioned that burning appears to reduce soil OM. In Europe there are composting plants superbly designed and built by architects and engineers but sometimes the 'compost' produced is so poor that it is directly landfilled [27]. Acid deposition occurs by emissions of sulphur dioxide and nitrogen oxides at rates which exceed the neutralising capacity [28]. This affects the soil surface and its microbial activity, growth and development of plants, and thus all organisms, including humans.

Air, water and food quality is now in focus. People are most concerned about their health, and any kind of system that could contribute to health problems becomes an issue [3]. Air quality issues have no borders, therefore the need to reduce harmful emissions globally, and in the urban areas particularly, calls for new technology alternatives in OW management. This includes collection, transport, and pre-processing of wet and dry OW, which will result in efficient and hygienic upgrading of this renewable raw material to valuable and environmentally safe products.

The new, hygienic and environmentally sound infrastructure will include: (1) waste management (source-separated collection, treatment, and reuse of material and energy); (2) water management (proper supply and discharge, minimising the losses of water and its pollution); (3) transportation (organic fertilisers from urban to rural areas and agricultural products from rural to urban areas, and efficient systems for utilisation of renewable energy (biogas) for generation of electricity and heat or as fuel for vehicles).

Water management in most countries is not sufficient from the environmental, ecological and economical points of view. Migration to urban areas has led to problems connected with OW and water management. The need to conserve and preserve the available water resources, and to safeguard their quality for use in households and for irrigation, calls for a decrease in the use of water as a transport medium. The development of a new infrastructure and sanitation systems with fast collection of human excreta, leading to ecologically sustainable and economically efficient management of OW and wastewater, is of the highest priority.

2.5. Benefits

The organic fraction of source-separated MSW (i.e. SOW) is the most suitable complement to human excreta (i.e. LOW) as bulking material. Both SOW and LOW generates simultaneously and the obtained mixture, after disintegration and proper mixing, is an almost complete substrate for microbial transformation. Water will be protected from pollution by human excreta (0.4% of wastewater), meanwhile organic matter containing plant nutrients will return to cultivated soils. Only grey water will be generated containing small amounts of organic matter, thus the amount of sewage sludge will be minimised. The future wastewater systems without black water will have to treat about 16% less water, will be less expensive, and also will create less gaseous emissions (Table 3).

Based on the assessments in Table 3, the following can be emphasised: the estimated value of the three main plant nutrients NPK, generated yearly in Sweden by 100000 inhabitants, is US$ 600000 in the organic fraction of municipal solid waste, US$ 900000 in human excreta, but only US$ 160000 in sewage sludge because of losses during transport of organic substances through the sewage and by their and plant nutrients reduction in wastewater treatment plants.

An investigation on the effects of sewage sludge, with and without addition of artificial nitrogen, was made on various crops during the years 1982–1989 [29]. It showed the highest increase in yield when sewage sludge was used in combination with artificial nitrogen. In spite of that, the question is whether it is necessary to initially reduce nitrogen, which was bound in OW (inclusive of human excreta), and then add chemically produced nitrogen to the sewage. It should be cheaper and more environmentally friendly to avoid all losses of nitrogen. Therefore, completely closed systems and sub-systems for treatment of OW have to be used.

3. Bioconversion of renewable raw material

Everything from the animal and vegetable kingdom will, sooner or later, decompose in different ways. When we want to manage the processes of bioconversion it is important to take into consideration the liquid OM and the two groups of solid OM: 'wet' and 'dry'. Wet OM are often nitrogen rich, with high water content, and

Table 3
Wastewater, human excreta, organic and inorganic fractions of municipal solid waste (MSW) in metric tons, generated yearly by 100 000 inhabitants in Sweden

	Present situation	Vision for 2010
Total amount of used water (tons)	11 000 000	9 200 000
% of used water	100	84
Wastewater management (tons)		
Grey water	9 200 000	9 200 000
Black water (incl. human excrete)	1 800 000	0
Sewage sludge	11 000	?
Solid waste management (tons)		
Inorganic solid waste[a]	6000	6000
Organic solid waste treated	Conventionally	By bioconversion
	28 000	28 000
Human excreta	0	43 800

Management in present systems is compared with management in systems using efficient bioconversion methods. Grey water, wastewater from bathing, washing, cleaning and wastewater from industries: black water, from WC inclusive human excrete; sewage sludge, generated from wastewater treatment plants where organic substances and plant nutrients are partly reduced.
[a] Inorganic municipal solid waste can be recycled, destroyed or dumped.

should be treated immediately, while fresh, to avoid or stop unwanted decomposition processes, causing unexpected emissions, so-called 'polluting losses'. Otherwise, easily soluble substances will be wasted, and the stored energy will disappear. Dry OM is normally carbon rich, can be favourably stored, and when needed can be mixed in suitable quantities with wet OM. Most OM—we call some of them residues or wastes—can be used as renewable raw materials suitable for bioconversion. The units for local handling of solid and liquid OW from households will work according to the principle of closed loop (Fig. 1).

Biologically, all urban OW, such as that coming from gardens, food residues, paper and human excreta from households, restaurants, commerce, small industries, can be treated in bioconversion systems which can also be modified for rural OWs and residues from agriculture, horticulture and forestry. Even fuel crops (plants grown for utilisation as energy sources for burning) can, by similar methods, be transformed into energy-rich biogas and valuable, reproducible biofertilisers.

To produce biofertilisers suitable for various crops we need to create new systems where all subsystems from collection, through pre-processing, processing, storage, transportation and final products and their applications, have to be handled in enclosed systems with controlled and regulated conditions. All sub-units have to be connected together with quick-couple equipment. The novel systems can work efficiently only when all subsystems are well developed.

3.1. Collection and transport

Fast collection of organic waste is a prerequisite for an end product of good quality. Minimising transport between production of waste and treatment will decrease pollution and increase the possibility to keep the OW fit for pre-processing. This preserves the quality of the collected waste, especially those with high water content and high amounts of readily available compounds.

Collected OW can easily decompose by unwanted processes in dustbins, with the associated odour problems. For efficient collection closed vessels have to be designed. Bengtsson and Svensson [30] recommended to minimise transports as much as possible. In their study, cost and fuel consumption of locally treated park and garden waste (inclusive shredding) dropped to 60 and 16%, respectively, compared with waste transported to regional compost plant.

3.2. Pre-processing

The aim of pre-processing is to create a substrate for efficient bioconversion. To achieve a homogenised and stabilised product, the materials have to be disintegrated before the bioconversion has begun. The energy required for grinding or shredding is well used, since the ground material is more easily handled, mixed, moistened, and saves space before, during and after processing. Grinding can also greatly accelerate composting rate and permit more uniform product [31] (Gajdos, unpublished). The enlarged surface area of the substrate increases availability of oxygen on the surface of all particles, resulting in a greater need of oxygen for the growing microbial population.

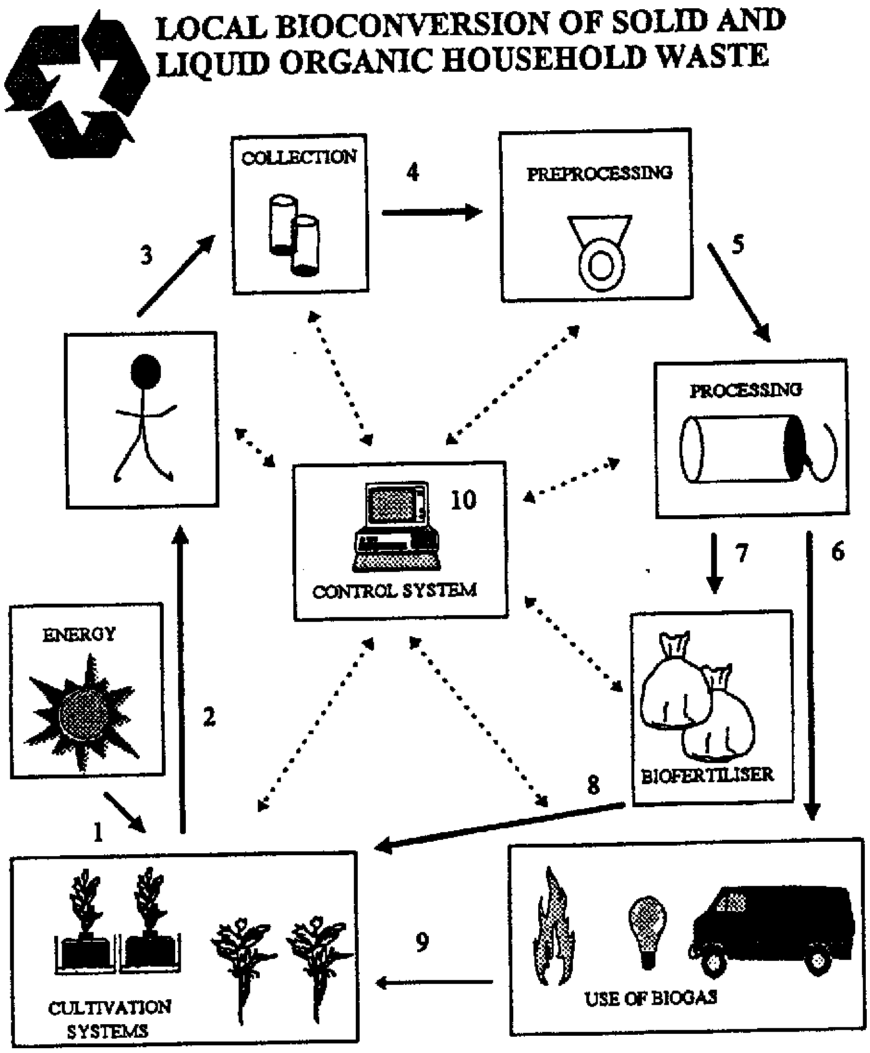

Fig. 1. Model of computerised system for local bioconversion of solid and liquid organic waste from households. The flow of energy and elements. (1) Energy from the sun is used in various cultivation systems and is biochemically bound with elements in organic structures in the biomass; (2) the biomass is used by humans; (3) energy and elements in organic waste are collected in closed equipment; (4) the organic waste is in preprocessing subsystem prepared for treatment; (5) during processing the organic waste is transformed to energy-rich methane in biogas and to biofertilisers, where a part of the energy is still bound in organic structures; (6) biogas can be used for heating, for transformation to electricity and heat ('co-generation') or as fuel in vehicles; (7) energy and elements are in biofertilisers; (8) biofertilisers become the substrate, which microorganisms in various cultivation systems utilise, and thus promote plant growth; (9) biogas can also be used in cultivation systems. The loop is closed and new plants will use the elements from biofertilisers during photosynthesis and with energy from the sun new biomass will be produced; (10) steering and regulation of all subsystems is made by operators who use information from the control system.

Use of suitable additives as bulking material or activators have to be tested for each working unit.

3.3. Processing

Conditions, under which the formation and/or the degradation of various substances take place, are still a large field of research. Steinford and Zane [32] pointed out three principal requirements: nutrient balance, structure and moisture. They also wrote that for hygienisation of the product it is necessary to elevate the temperature to the required levels in the whole substrate, which means that good insulation of the equipment (bioreactor) is important.

Energy balance during aerobic bioconversion is not clearly illustrated. Denecke et al. [33] suggested development of systems where the substrate will be treated in a combined process. The substrate will undergo aerobic and anaerobic microbial transformation, respectively, and the process can go through two or three phases.

By microbial transformation of OM, in local bioconversion units using automated bioreactors and treatment in batches, either biofertilisers (when only aerobic bioconversion is carried out in one phase process), or both biogas and biofertilisers (during the combined process in three phase process [34]) can be produced. The nutrients, required during the whole run, ought to be present in the substrate before the transformation processes start. Missing compounds can be added during each run. For that purpose various organic by-products can be mixed into the organic waste. Activators can be developed and used adequately to increase the efficiency of the bioconversion. Composting systems of simple design are seldom optimised, which results in poor hygienisation of the compost. This may cause emissions into the atmosphere (air) and leachate into the soil and water.

Rates of bioconversion of any biologically based material are dependent upon a variety of factors. In reality, in the beginning pilot scale experiments should be used. In parallel, a part from the actual stream of OW and a reproducible standard mixture [22] should be treated, compared and evaluated. Thus the full-scale bioconversion facility will be built with attention to all factors.

3.4. Post-processing

Biofertilisers are seldom stabilised after the short time of processing, therefore various measures have to be taken to decrease microbial activity or chemical processes involved in decomposition of OM. Preserving methods should be developed to maintain good quality of biofertilisers and avoid emissions. Attention should especially be paid to nitrogen, which appear in biofertilisers in organic (proteins, organic acids, enzymes) and inorganic (nitrate, ammonium) forms, that can be rapidly transformed and lost to gaseous forms (ammonia, nitrogen oxides or elemental nitrogen). To prevent nitrogen losses, various materials can be added to biofertilisers produced in bioreactors. Kirchman [35] recommended use of peat to avoid nitrogen losses from the manure. Packaging system have to support the easy use of biofertilisers during application, as for example in bags adjusted to equipment for planting machines.

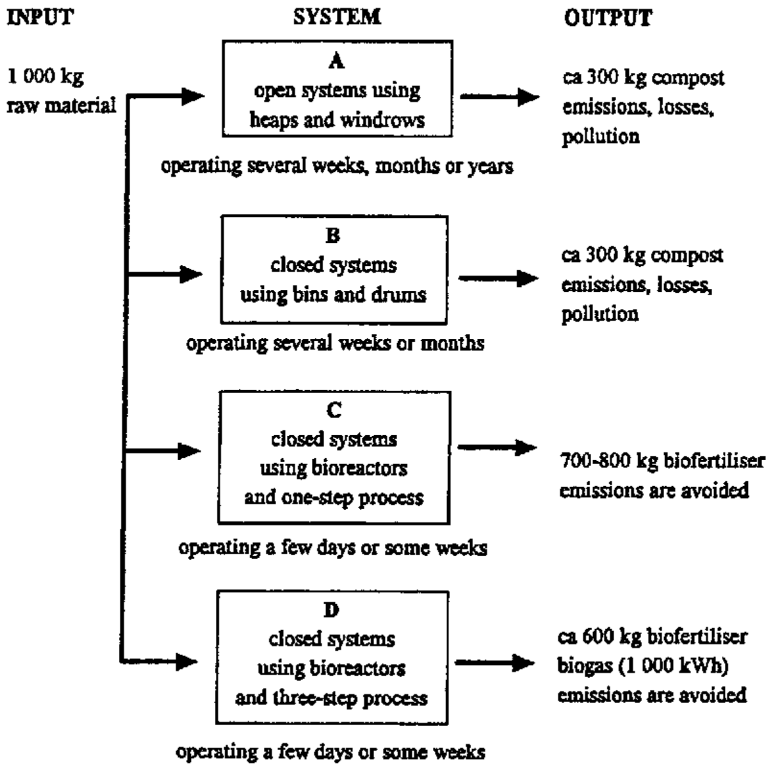

Fig. 2. Open composting systems (A) are compared with closed composting systems (B), with completely enclosed systems of aerobic bioconversion (C), and with completely enclosed systems of bioconversion where both aerobic and anaerobic microbial transformation is used (D).

Post-processing of biogas depends on the purpose of use. Several systems are used, while only one describes use of biogas produced from solid manure in a full-scale plant [36].

3.5. Application of products

Biofertilisers of various qualities may be used for different purposes, such as for different soil types and their changes in biological, chemical and physical properties, for various crops or different stages of plant development, for biological control of plant pathogens, for weed control, and for remediation of damaged soils. Energy from the biogas should be used locally for heating, for conversion to electricity, as fuel in cars, and excess energy can be sold.

4. Re-orientation of technology for treatment of organic waste

An evaluation of four different methods of composting is presented in Fig. 2 and Table 4. For successful bioconversion, changes are needed in methods, systems, infrastructure, and habits of people. Fig. 2 indicates the possibilities to increase the amount of recycled nutrients and reused bioenergy. It shows some advantages that can be reached by modifying or re-engineering the present composting systems and methods.

In the present systems (A and B), the organic fraction of household waste is transformed to products of low value. The suggested future systems (C and D) will be highly efficient ones, ending in valuable products. The facts presented in Fig. 2 are collected from the following sources: (A) a company building composting plants in Germany stated that the raw material is transformed to 30 wt.% compost (Conference in Denmark, May 1995); (B) household waste composted in a drum with capacity for between 50 and 80 households, also results in 30 wt.% compost (K. Persson, composting-consultant, personal communication); (C) in laboratory experiments with bioreactors, 70–80 wt.% biofertiliser were produced from the raw material [22]; (D) based on data from Demuynck and Nyns [18] assumptions are

Table 4
Evaluation of some present (A and B) and suggested future composting methods (C and D) using the organic fraction of household waste as raw material for microbial transformation to products

	Composting systems and methods:			
	A (heaps and windrows)	B (backyards composters (bins))	C (bioreactors, one-step[a] process)	D (bioreactors, three-step[b] process)
Process regulation	+/++	+++	+++++	+++++
Time saving	+/++	+++	+++++	+++++
Space saving	+/++	+++	+++++	+++++
Pollution avoiding	+/++	+++	+++++	+++++
Hygienisation[c]	+/++	+++	+++++	+++++
Nitrogen saving	+/++	+++	+++++	+++++
Energy saving	+/++	+++	+++++	+++++
Energy extraction[d]	–	–	–	+++++
Transport avoidance	+/++	+++++	+++++	+++++

Assessment on degree of efficiency within the frame of biological capacity: – none; from very low + to +++++. +++++ symbolise maximum possible capacity achieved in completely closed systems.
[a] Biofertilisers are produced.
[b] Biofertilisers and biogas are produced.
[c] Inactivation of pathogens and seeds (sanitation).
[d] Biogas as a source of renewable energy.

made that one-third of the energy in the treated substrate can be transformed to energy-rich methane and to between 50 and 60 wt.% biofertiliser.

Changes supporting an efficient bioconversion of solid and liquid OW in local units have to be made in the infrastructure of waste, water, wastewater, and energy management, as well as in packaging, transport, and the application of biofertilisers in cultivation systems.

The assumptions made in Table 4 show the necessity of using basic biological principles. Bioconversion can be used for: (a) biological decomposition of municipal solid waste with the aim to reduce volume and weight of the organic fraction, by methods A and B, which are inexpensive but still with the main goal 'to get rid of' the waste; or for (b) microbial transformation, i.e. upgrading of OM to valuable products, by methods C and D, where organic waste is used as renewable raw material in an ecologically, economically, and socially optimal way.

5. Scenario for bioconversion by the year 2010

The ambitions to carry bioconversion into effect by the year 2010 call for the development of several research and development units. These should vary in bioreactor size and in processing method. Results from all units have to be evaluated and used as a basis for planning full-scale plants (hardware) and for creating the required control programmes (software). The bioreactors available for laboratory use [8,22,23,37] are now ready to be scaled up in order to operate in the research and development units described earlier [37,38].

All solid and liquid wastes, by-products, and residues of organic origin have to be used as renewable raw material for microbial processes and transformed to useful products. The OW has to be kept under controlled conditions in all parts of the closed bioconversion system, i.e. from enclosed waste pits, vessels, or sacks in the collection sub-system using source separation, to the usage of the products. Advanced control systems and modern logistic methods must be used for an efficient product recovery where energy and mass from organic material are transferred with minimum losses.

Microorganisms that transform the raw material have to be supported by technology throughout the whole system. Transports and their negative effects on the environment will be minimised in the locally situated bioconversion units.

The sizes of the bioconversion units have to be adjusted to local requirements. They will vary from small units for educational and family facilities, medium units for a few families and restaurants, to larger plants for food industries, farms, villages, and suburbs. With small modifications, the same methods can be practised on all levels. Jenssen and Vatn [7] wrote that, by using decentralised technologies, undesired constituents are more easily avoided. They also claim that present conventional treatment processes require large amounts of energy and thereby create environmental stress.

Each unit will be constructed so that the processes of bioconversion can be performed under both aerobic and anaerobic conditions. Ecological sustainability will be achieved, while engineering functions with respect to principles and parameters obtained by studies of ecological systems. Teixeira et al. [39] suggested that bioprocess engineering has to use technologies based on living systems. The biotechnology must incorporate the latest advances from many disciplines to protect the environment. "Future waste management programmes should take maximum advantage of resource-efficient approaches to the control of wastes" [17]. Ford [40] wrote that it is wasteful to utilise industrial processes for any reaction that microbes can carry out.

Under assumptions that re-orientation of technology for treatment of organic waste will be of high priority, and the bioconversion systems fully developed by the year 2010, the organic waste which originates from the metabolism of the 8.7 million inhabitants in Sweden, taking into account only the value of the energy and the three plant nutrient elements NPK, will have following impact on the economy: (a) the energy value of the methane in the biogas will be 63.5 TWh, which can be transformed to 19 TWh electricity and 41 TWh heat; (b) the NPK manufacturing costs saved per year will be US$ 130.5 million.

The total effect of produced biofertilisers on soil fertility, crop production, food quality and human health, in fact the effect of the bioconversion on the environment as a whole, such as decreased pollution of air, water, soil, vegetation and other micro- and macro- organisms, the improved balance in the ecosystem, have to be evaluated and added.

6. Concluding remarks

The closing of the ecological loop can be enhanced efficiently by upgrading organic wastes by use of aerobic and anaerobic bioconversion processes, i.e. microbial transformation, to valuable products. At the same time emissions—polluting losses—will be avoided.

All OW (residues, by-products) can be treated biologically, producing economic returns, which can pay for the treatment, save plant nutrients and energy, and help to control pollution.

In product-oriented management of solid and liquid OW, biological systems leading to sustainability have to be used. Especially when treating organic solid and liquid waste from settlements a user-friendly sanitation and clean working conditions are important. The fundamental assumption for bioconversion systems is energy-efficient production of hygienically safe products (biofertilisers) of high and reproducible quality, without infectious pathogens, weed seeds and/or other seeds, and with good compatibility with plants. By modifying the equipment and method within the same unit, additional products, such as biogas, ethanol, proteins or enzymes, can be obtained.

The flexibility of the bioconversion units increases the ability to use OW as a renewable raw material. By choosing the most suitable technology, the units will be not only more environmentally friendly than existing waste management practices, such as incineration or landfilling, but also consumer friendly and more profitable.

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