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Biodrying for mechanical-biological treatment of wastes: a review of process science and engineering

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Abstract

Biodrying is a variation of aerobic decomposition, used within mechanical-biological treatment (MBT) plants to dry and partially stabilise residual municipal waste. Biodrying MBT plants can produce a high quality solid recovered fuel (SRF), high in biomass content. Here, process objectives, operating principles, reactor designs, parameters for process monitoring and control, and their effect on biodried output quality are critically examined. Within the biodrying reactors, waste is dried by air convection, the necessary heat provided by exothermic decomposition of the readily decomposable waste fraction. Biodrying is distinct from composting in attempting to dry and preserve most of biomass content of the waste matrix, rather than fully stabilise it. Commercial process cycles are completed within 7-15 days, with mostly $H_2O_{(g)}$ and CO_2 loses of *ca*. 25-30% w/w, leading to moisture contents of < 20% w/w. High airflow rate and dehumidifying of re-circulated process air provides for effective drying. We anticipate this review will be of value to MBT process operators, regulators and end-users of SRF.

Keywords

Biodrying; Mechanical-biological treatment; Solid recovered fuel; Biomass; Composting

Abbreviations

APC	Air pollution control
CV	Calorific value
EC	Energy content
MBT	Mechanical-biological treatment
MC	Moisture content
MSW	Municipal solid waste
NVC	Net calorific value
OFMSW	Organic fraction of municipal solid waste
SRF	Solid recovered fuel
RDB	Rotary bio-dryer
VS	Volatile solids

1. Introduction

Biodrying (biological drying) is an option for the bioconversion reactor in mechanical-biological treatment (MBT) plants, a significant alternative for treating residual municipal solid waste (MSW). Waste treatment plants defined as MBT integrate mechanical processing, such as size reduction and air classification, with bioconversion reactors, such as composting or anaerobic digestion. Over the last 15 years MBT technologies have established their presence in Europe (Binner, 2003; Haritopoulou and Lasaridi, 2007; Ibbetson, 2006; Juniper, 2005; Neubauer, 2007; Pires et al., 2007; Stegmann, 2005; Steiner, 2005, 2006), with 6,350,000 Mg a^{-1} of residual waste currently treated in Germany alone (Kuehle-Weidemeier, 2007). MBT is emerging as an attractive option for developing countries as well (GTZ, 2003; Lornage et al., 2007; Pereira, 2005; Raninger et al., 2005; Tränkler et al., 2005).

To our knowledge, the term “biodrying” was coined by Jewell et al. (1984) whilst reporting on the operational parameters relevant for drying dairy manure. Here, the term “biodrying” denotes: (1) the bioconversion reactor within which waste is processed; (2) the physiobiochemical process, which takes place within the reactor; and (3) the MBT plants that include a biodrying reactor: “biodrying MBT,” hereafter. Typically, the biodrying reactor within MBT plants receives shredded unsorted residual MSW and produces a biodried output which undergoes extensive mechanical post-treatment. Within the biodrying bioreactor the thermal energy released during aerobic decomposition of readily degradable organic matter is combined with excess aeration to dry the waste (Fig. 1).

This is attractive for MBT plants established to produce solid recovered fuel (SRF) as their main output, because removing the excessive moisture of the input waste facilitates mechanical processing and improves its potential for thermal recovery (Rada et al., 2007b). A major benefit of SRF production in MBT with biodrying is the opportunity to incorporate the biogenic content of the input waste, a carbon dioxide (CO_2)-neutral, alternative energy source (Flamme, 2006; Mohn et al., 2008; Staber et al., 2008), into a fuel product. This produces an SRF low in CO_2 specific emission loading (Heering et al., 1999), mitigating the waste management contribution to climate change. As result, there is high interest in biodrying MBT plants: 20 commercial references are currently operational in Europe, with overall capacity of *ca*. 2,000,000 Mg a^{-1} (Herhof GmbH, 2008; Shanks, 2007).

However, biodrying remains a relatively new technology and published research is limited. Experience from commercial full-scale application of biodrying MBT plants spans only over the last decade. The first plants that became operational were the Eco-deco in Italy (1996) using the "BioCubi®" aerobic drying process; and the Herhof process in Asslar, Germany (1997), using the "Rotteboxes®." Despite having been subject to research (Calcaterra et al., 2000; Wiemer and Kern, 1994), is neither fully understood nor optimised (Adani et al., 2002).

This review presents and evaluates the process science and engineering available for optimal SRF production through biodrying in MBT plants. It places biodrying in context with composting and similar bioconversion applications. Experience from full-scale biodrying in commercial MBT plants is also included. A separate publication that compliments this is in press, covering the assessment of SRF quality, and mechanical processing necessary to be coupled with biodrying for SRF production in MBT plants (Velis et al., in press). In order to understand the science and engineering of biodrying processes adequately, it is necessary to make reference to commercially available technologies and the grey literature. Technologies are described according to the manufacturer or trade name. The authors have no interest in promoting or endorsing specific technologies.

2. Biodying for MBT in context with similar bioconversion drying applications

Biodrying reactors use a combination of engineered physical and biochemical processes. Reactor design includes a container coupled with an aeration system; containers can be either enclosed (Fig.1), or open tunnel-halls, or rotating drums (Fig. 2). On the biochemical side, aerobic biodegradation of readily decomposable organic matter occurs. On the physical side, convective moisture removal is achieved through controlled, excessive aeration. Whilst the general reactor configuration and physiobiochemical phenomenon is similar to composting, the exact way in which it is operated is significantly different.

Composting is a widely studied and largely understood natural process, controlled for specific objectives within waste management. It refers to the aerobic biodegradation and stabilisation of mixed organic matter substrates by micro-organisms, under conditions that allow development of thermophilic temperatures (de Bertoldi et al., 1996; Epstein, 1997; Haug, 1993; Insam and de Bertoldi, 2007). During multiple cycles of biodegradation, a widely diverse population of micro-organisms catabolises substrates through complex biochemical reactions to satisfy metabolic and growth needs, gradually leading to mineralisation of organic substances (Richard, 2004). The most important parameters that affect composting are substrate composition, carbon-nitrogen ratio (C/N), oxygen content, substrate temperature, MC, hydrogen ion concentration (pH), aeration and the matrix characteristics of mechanical strength, particle-size distribution (PSD), bulk density, air-filled porosity, and permeability (K). Their influence on composting systems has been discussed elsewhere (Diaz and Savage, 2007; Haug, 1993; Schulze, 1961; Richard, 2004).

Biodrying as a variation of composting has been described for applications, other than MBT, including the composting of high MC materials, such as manure (Choi, 2001; Richard and Choi, 1997; Wright, 2002), and of sludge from pulp and paper wastewater treatment intended for combustion in wood-waste furnaces (Frei et al., 2004a; Frei et al., 2004b; Navaee-Ardeh et al., 2006; Roy, 2005). Ragazzi et al. (2007) investigated at bench scale the co-digestion of dewatered and treated sewage sludge with municipal waste.

Research relevant to biodrying has been also conducted for near-ambient grain drying for food preservation (Brazier, 1996; Nellist and Brook, 1987), and for the combined drying and storage of forest residues (Nellist et al., 1993). Near-ambient air drying (or bulk storage drying) uses the flow of air through harvested grains or forest residues in deep beds to dry and preserve them (Nellist, 1998). Matrix temperatures up to 5ºC above ambient are reached. The critical operational and state parameters are matrix-related (MC, equilibrium MC, safe storage time, and pressure resistance to airflow) and air-related (airflow rate and psychrometric properties, *i.e.*, properties referring to the thermodynamic and physical relationship between air and water vapour, such as relative humidity, temperature, etc). Careful management of the process and suitable climatic conditions are critical for successful near-ambient air-drying.

Biodrying differs from composting and near-ambient air drying in terms of the objectives of each process. Composting produces a humus-like “compost” that can be beneficially and safely applied to land, subject to regulatory approval. Composting is also used to stabilise the biodegradable organic material of MSW prior to landfill disposal, minimising leachate and landfill gas formation. Near-ambient air drying: (1) dries grains or forestry residues before storage to prevent spoilage; (2) achieves low specific energy consumption; and (3) reduces the risk of over-drying, as opposed to heated dryers, by using air temperatures close to the ambient level (Nellist, 1998; Nellist et al., 1993).

In contrast, the biodrying reactor aims to pre-treat waste at the lowest possible residence time in order to produce a high quality SRF. This is achieved by: (1) increasing the energy content (EC) (Adani et al., 2002) by maximising removal of moisture present in the waste matrix and preserving most of the gross calorific value of the organic chemical compounds through minimal biodegradation; (2) facilitating the incorporation of the partly preserved biogenic content into the SRF; and (3) rendering the output more suitable for mechanical processing by reducing its adhesiveness.

Secondary benefits are also achieved. Biodrying renders the material more suitable for short-term storage and transport both by partially biostabilising it and by reducing its MC below the necessary threshold for biodegradation to occur. Partial sanitisation of the output is also accomplished (Adani et al., 2002; Calcaterra et al., 2000; Rada et al., 2005; Sugni et al., 2005; Wiemer and Kern, 1994); for the bulk of the biodried product sanitisation to high standards is not necessary, because most of it is not intended to be applied on land but to be thermally recovered.

Table 1 summarises process objectives and typical parameter values for biodrying and similar bioconversion technologies. Notwithstanding that technology transfer could be feasible, wide differences are evident. Hence, uncritical extrapolation of results to different reactor designs, scales, substrates, and operating regimes may be misleading.

3. Biodrying process science fundamentals and engineering

3.1. Operating principles of biodrying: drying

Drying technology generally reduces the MC of a matrix by the application of heat, causing water to evaporate into the air phase (vapour), and produce dried outputs of desired characteristics (Dufour, 2006). Drying phenomena have been widely researched (Hall, 2007). However, the micro-scale mechanisms of drying are highly complex and not fully understood (Konovalov, 2005). Drying technology has been developed within the scope of food, agricultural, pharmaceutical, pulp and paper, and many other industries (Mujumdar, 2004, 2007). For environmental engineering applications, dryers using external sources of heat have been used for refuse-derived fuel (RDF) drying (*e.g.*, rotary cascade and thermopneumatic) (Manser and Keeling, 1996) and sludge dewatering (Chen et al., 2002).

In biodrying, the main drying mechanicsm is convective evaporation, using heat from the aerobic biodegradation of waste components and facilitated by the mechanically supported airflow. The MC of the waste matrix is reduced through two main steps: (1) water molecules evaporate (*i.e.*, change phase from liquid to gaseous) from the surface of waste fragments into the surrounding air; and (2) the evaporated water is transported through the matrix by the airflow and removed with the exhaust gasses. Limited amount of free water may seep though the waste matrix and be collected at the bottom of the biodrying reactor as leachate.

3.2. The drying phenomenon

In biodrying, air convection and molecular diffusion are the main transport mechanisms responsible for moisture flow through the matrix (Frei et al., 2004b). Air convection, induced by engineered airflow through the matrix, is almost exclusively responsible for the water losses. Here, air carries the water evaporated from the surface of matrix particles (free moisture) with which is in contact. Removal of water content from the waste matrix (desorption) by convective evaporation is governed by the thermodynamic equilibrium between the wet waste matrix (solid state) and the air flowing through the matrix (gaseous phase). Mujumdar (1997) provided an extensive list of the psychrometric properties (thermodynamic and transport phenomena related) of the air pertaining to drying. Pakowski et al. (1991) reported the engineering properties of humid air.

Whilst no relevant research particular to biodrying is available, relative science has been summarised elsewhere for the cases of drying of foods (Basu et al., 2006), grains (Mujumdar and Beke, 2003) and wood (Krupinska et al., 2007). The vapour-carrying capacity of air is limited at each T_{air} and reached at saturation point, after which condensation occurs. At a given level of relative humidity (rH) of air (rH_{air}) the mass of water vapour the air can hold increases with the temperature. rH_{air} has been used in near-ambient drying modelling to estimate the distance from saturation point of inlet air, *i.e.*, can be simplistically perceived as a surrogate measure of its drying potential.

For desorption to happen the rH_{air} has to be lower than the equilibrium relative humidity (ERH_{air}), *i.e.*, the rH_{air} value at which the MC of air-vapour mixture (MC_{air}) is in equilibrium with the MC of the matrix (MC_{waste}). This is also expressed as the equilibrium MC of the waste (EMC_{waste}) and depends on temperature and pressure (Mujumdar, 1997). The inverse phenomenon may also happen, where air of sufficiently high humidity moistens the matrix particle surfaces (adsorption), case evident in inverted aeration configurations of biodrying reactors (Fig. 2.A) (Frei et al., 2004b; Sugni et al., 2005).

The rH_{air} and EMC_{waste} relationship can be expressed through equilibrium moisture curves called sorption (adsorption/desorption) isotherms. They are temperature dependent, reflecting the temperature dependence of rH_{air}. In principle, experimentally identified and/or mathematically simulated desorption/adsorption isotherms for biodrying of residual waste matrices could potentially be used to model and optimise the drying process, practice established in the wider drying research and engineering. For instance, for grain drying, some of sorption isotherms exhibit an S-curve shape and a hysteresis effect appears between adsorption and desorption (Basu et al., 2006).

The form in which the water is present within the solid fragments of the matrix has a decisive influence on the drying phenomenon. Different regions of the sorption isothermal curves correspond to drying involving moisture present in different states (*e.g.*, free or capillary, bound, etc), governed by different physical mechanisms, as described elsewhere (Basu et al., 2006; Brazier, 1996; Mujumdar and Beke, 2003; Tsang and Vesilind, 1990). Air convection may eventually dry the surface of the particle, reaching the hygroscopic limit, *i.e.*, leaving no surface areas saturated with water, resulting in less water to evaporate. For further drying, additional moisture has to migrate from the particle interior (bound moisture) to its surface, process governed by diffusion mechanisms (Roy et al., 2006); *e.g.*, during the drying of hygroscopic porous media, such as wood (Stanish et al., 1986).

3.3. Energy balance of biodrying reactors

The energy necessary for evaporation to occur (vaporisation latent heat, or enthalpy of vaporisation) and any additional if the hygroscopic limit is reached, is provided mainly by aerobic biodegradation. In contrast conventional drying employs external sources of heat. The aerobic decomposition of organic mater by micro-organisms is an exothermic biochemical transformation that can rapidly raise matrix temperatures to the thermophilic range. In composting, maximum temperatures of 50-62°C for small-scale systems or up to 70ºC for larger reactors have been reported (Richard, 2004). Roy et al. (2006) reported average rates of energy production due to bioconversion at 23-29 W kg_{DM}^{-1} during biodrying of pulp and paper mill sludge. This energy usually constitutes a sufficient source for drying, despite heat losses from convection, radiation and sensible heating of both the outlet air and any discharged leachate. A small part of the significant external energy needed for aeration is converted to heat flow through the frictional losses caused by the mechanically supported flow of air through the waste. In near-ambient grain drying, this results in an anticipated typical rise in the grain temperature between 0.5ºC and 2ºC (Nellist, 1998); however, the rise may vary according to the exact ambient atmospheric and matrix conditions.

Results of heat transfer studies have established the ability in commercial, large-scale applications to control heat losses and subsequently matrix temperature through increased aeration. For the industrial-scale and fully enclosed Herhof-Rottebox® cells (Fig.1) conduction by aeration (and hence water evaporation) was found to contribute more than 75% to the heat transfer (Weppen, 2001). This indicated limited heat losses by conductance through vessel walls and open surfaces. Instead, the most significant heat fluxes were attributed to sensible heat removed by ventilation, energy storage by change in sensible heat of matrix and vessel, and micro-organism needs. This result is in agreement with similar investigations in composting operations (Bach et al., 1987; Themelis, 2005).

3.4. Process design, monitoring and control

Optimal biodrying can be achieved through effective reactor design and conditioning of the input material, combined with suitable process monitoring and control. Control can be exercised by adjusting the level of operational variables (suitable to directly manipulate), informed by process state variables (suitable to monitor and evaluate). Typical design and operational choices involve:

1. matrix conditioning through mechanical pre-processing, *e.g.*, comminution and/or mixing, affecting the physical properties of the matrix, such as the resistance to airflow;
2. type of containment of waste matrix, *e.g.*, in enclosed boxes (or "bio-cells") (Fig. 1) or piling in tunnel windrow systems, affecting drying mechanisms including insulating effect and degree of compaction;
3. use of mixing/agitation/rotation of the waste matrix in dynamic reactors to homogenise it, *i.e.*, achieve uniform conditions: *e.g.*, by rotating drum reactors (Fig. 2.B) (Bartha and Brummack, 2007; Bartha, 2008; Skourides et al., 2006); however, most of the existing commercial designs are static;
4. aeration system design: inverted aeration systems have been tested (Fig. 2.A), intending to reduce gradients experienced in prevalent unidirectional desings (Frei et al., 2004b; Sugni et al., 2005);
5. management of the aeration rate of the waste matrix, by control of the inlet airflow rate (Q_{air}), to remove water vapour and off-gasses and control state process parameters, such as substrate temperature and oxygen availability;
6. external systems for controlling the psychrometric properties of the inlet air (*e.g.*, temperature, due point, relative humidity), by cooling and dehumidifying of the process air to enhance its capacity to hold water vapour, combined with partial process air recirculation; and,
7. residence time within the reactor, affecting the degree of completion of biochemical and physical processes.

Application of process control engineering in biodrying is challenging. The main difficulty is the two-fold role of the waste matrix, being both (1) the mass to be dried, and (2) the substrate supporting the microbial activity, which in turn provides for the source of heat necessary for the drying. Another difficulty is the inherent high heterogeneity of the residual waste, compared with, for instance, food grains. These main differences impede direct technology transfer from other control applications.

However, control for biodrying could potentially benefit from the recent advances in general drying technology and composting applications. Control engineering for drying technology is applied mainly in the food industry, but also increasingly in painting, pharmaceuticals and paper/wood applications, and has advanced with the application of open and closed loop optimal controllers. However, generally first principle models of drying are still lacking outside the food industry (Dufour, 2006). Software packages for drying have been developed (Devahastin, 2006; Gong and Mujumdar, 2008; Kemp, 2007; Menshutina and Tadeusz, 2001; Wang et al., 2004).

Both simple and complex process control strategies are employed in commercial bioreactor systems treating biodegradable waste. Ward et al. (2008) reviewed control systems for anaerobic digestion reactors: their general suggestions, including the importance of *in situ* on-line monitoring and control, largely apply to all waste treatment technologies. For composting aeration systems, the emphasis is upon providing sufficient oxygen (O_2) for aerobic biodegradation (de Guardia and Rogeau, 2008), whilst simultaneously meeting the requirements of the process air clean up. A general list of control approaches for composting aeration can be found in Haug (1993). Commercially available computerised systems developed for composting complex aeration control have been reviewed by Goldstein (2006).

Theoretically, many process state variables can be used for biodrying monitoring to inform the control of operational variables, such as airflow rate. However, this demands substantial understanding and modelling of the process science which has not yet been achieved. Leonard et al. (2005) examined the effect of inlet air temperature, superficial velocity and humidity on the drying kinetics of convective drying of wastewater sludge in a microdryier using a 3^3 factorial design experiment. The inlet air temperature had the greatest influence. Roy et al. (2006) suggested that for biodrying process control purposes the outlet air temperature should be used – not the average matrix temperature, as is often the case with biostabilisation.

Certain commercial applications use advanced control systems, including control loops. Bartha (2008) developed a fuzzy-logic process control system for a biodrying rotating drum reactor. A Herhof European patent for continuous bio-cell biodrying opts for control of the air supply so that the CO_2 content in the exhaust air is kept within a range of 0.05-0.4% v/v (Hansjoerg et al., 2004). Segmental air supply is blown through a floor plate and automatically adjusted by on-line measurements of heat quantity, exhaust air and matrix temperatures, air permeability of matrix, and CO_2 exhaust concentration. Process air is cooled and dehydrated by a heat-exchanger, and re-circulated until a certain CO_2 limit is met.

3.5. Matrix physical-mechanical properties

Biodrying is heavily dependent on the physical process of convective evaporation, so it can be assumed that physical-mechanical matrix properties are critical for process optimisation. Scholwin et al. (2003) stressed the importance of physical-mechanical properties of waste matrices for effective process modelling and control in the case of organic substrate composting. The relevant parameters that could impact on effective bioconversion were grouped into three classes, related to material, packed bed and flow pattern. Understanding of relevant issues has been advanced for composting substrates (Barrington, et al., 2002; Das and Keener, 1997; Richard et al. 2004). Properties such as MC, air-filled porosity, permeability, mechanical strength, and compaction of matrix, have the potential to affect the resistance to flow of air and, in turn the level of airflow rate necessary for effective biodrying. Some of these properties could be beneficially conditioned by pre-processing the biodrying input to the bioreactor. Currently, the pre-processing strategy in most biodrying MBT plants is limited to coarse shredding, *e.g.*, at 300-150 mm maximum particle size.

3.6. Aeration system type

Mechanically supported aeration of waste is critical for biodrying. It provides a mass and energy flow media, enabling: (1) water content removal; (2) heat-transfer redistribution, removing excessive heat and, adjusting the matrix temperature; and (3) O_2 delivery to meet the stochiometric demand for aerobic decomposition.

Extensive research and experience on aeration is available for composting operations (Keener et al., 2005; Keener et al., 1997; Sesay et al., 1998), but limited for biodrying. In composting, positive and negative pressure, hybrid, inverted and re-circulating airflow designs have been implemented. Chiumenti (2005) has shown that with static piles, as used in tunnel designs, negative pressure aeration achieves more homogeneous air distribution, reducing the problem of preferential air paths that may create anaerobic pockets. In enclosed bio-cells, the usual configuration is positive pressure, forcing air through the matrix flooring and collecting off-gasses through openings located at the top.

Air management in biodrying varies according to reactor design and process complexity. The bottom of a commercial biodrying bio-cell (Herhof Rottebox®) is divided into 12 parts enabling airflow to vary in each segment, facilitating control of matrix temperature (Nicosia et al., 2007). Air partial recirculation systems are often used in biodrying to reduce the volume of off-gasses requiring treatment; especially if air pollution control (APC) is accomplished through high cost equipment, such as regenerative thermal oxidation (RTO), necessitated by stringent legislative requirements in Austria and Germany (Breuer, 2007).

3.7. Uneven drying and solutions

One-way airflow through the waste matrix in static bed systems (*e.g.*, enclosed halls) has been shown to cause gradients in the vertical profile of process state variables in both composting and biodrying. The uneven drying is also well known in grain drying, where a drying zone is established around the air supply.

VanderGheynst et al. (1997) investigated temperature and moisture profiles of an in-vessel pilot-scale reactor composting synthetic food waste with initial MC 45% ar and 55% ar. They observed maximum temperature differences to occur together with significant MC differences; and differences in maximum temperatures in the vertical ($\Delta T_{\max}$) to be less than for higher aeration rates ($\Delta T_{\max}$ = 32°C at 0.06 l $\min^{-1}$ $kg_{\text{initial DS}}^{-1}$ and $\Delta T_{\max}$ = 29°C at 0.6 l $\min^{-1}$ $kg_{\text{initial DS}}^{-1}$).

In bench-scale biodrying experiments, matrix temperature differences as high as 30°C from the top to the bottom of a 800 mm high container have been observed during the initial high-microbial activity phase (Adani et al., 2002; Sugni et al., 2005). The T_{matrix} values converged as the biodegradation ceased (Fig. 3), but the moisture gradient persisted. In turn, these gradients lead to heterogeneous biodried output. Sugni et al. (2005) speculated that air flowing through the lower layers of the matrix had already reached saturation point and hence could not remove additional moisture. This could be in agreement with the higher temperature measured at this layer, as the limited heat removal would result in a higher matrix temperature. However, it is worth considering the possibility of moisture accumulation in the lower layer due to gravitational flow of free water. Whilst some authors do not consider (Adani et al., 2002; Sugni et al., 2005), or exclude (Navaee-Ardeh et al., 2006) this possibility, in both commercial biodrying systems based on halls (*e.g.*, Eco-deco) or bio-cells (*e.g.*, Herhof), a small amount of leachate is collected (Herhof Environmental, Undated).

In order to overcome the uneven drying of grain matrix recirculation or continuous flow mixing systems are used. For biodrying, alternative aeration systems and non-static designs have been proposed to overcome gradient formation aiming at a homogenised output. Two types of improved designs are (1) rotating drum reactors (Bartha and Brummack, 2007; Bartha, 2008; Skourides et al., 2006) and (2) inverted airflow designs (Fig 2). Sungi et al. (2005) experimented with reactors that simulated daily inverted air flow by up-side down turning of the reactor. They observed a mitigation of the matrix temperature gradient (Fig. 3) and a more homogeneous content in terms of moisture and energy, compared with the unidirectional flow. However, this arrangement did not achieve early convergence with the ambient temperatures as in the unidirectional experiments, indicating the necessity for a prolonged residence time; and the impact of solid and moisture substrate flows introduced by the turning of the reactor remain uncertain.

Frei et al. (2004b) tested a sophisticated three perforated pipe, inverted airflow system for biodrying of a sludge/wood mixture (Fig. 2). This system employed a central conduit either pumping or pulling air, whilst the other two pipes were on invert airflow, and operated at a set-point airflow rate of *ca*. 42.5±3.4 $Nm^3 h^{-1}$ (*ca*. 25±2 scfm (standard cubic feet per minute)). The configuration was criticised for removing water from the wet portion and depositing it in the dry portion of the matrix; this then favoured biodegradation rather than biodrying (Navaee-Ardeh et al., 2006): Inverting the airflow led to a drop in relative humidity of the outlet air for the next 10-20 h, indicating that the matrix was re-wetted by the humid inlet air. This was accompanied by increased matrix temperatures (Fig. 3), possibly reflecting a rise in biodegradation activity due to partial restoration of MC. However, as this phenomenon was more acute during the earlier period when the substrate was relatively wet, it is less important for residual waste treatment, because of the much lower MC of the residual waste substrate (initial *ca*. 40 w/w ar) compared with the pulp sludge (final *ca*. 40 w/w ar). Exhaust air became saturated once matrix temperature exceeded *ca*. 40°C.

The biodried output resulting from the same experiment (Frei et al., 2004b) was generally homogenously dried. However, the lower part of the matrix was slightly drier, a result converse to the effect observed by Sugni et al. (2005), who used a different process of inverted flow. Frei et al. (2004b) attributed the differentiated drying of the lower layer to preferential airflow within the matrix via the shortest routes between the inlet and outlet air ports. Drying of the matrix led to a significant increase in matrix permeability resulting in lower pressure across the matrix, reducing the preferential flow in the lower part of the reactor (Hoffmann, 2005). A continuous vertical reactor configuration with segmented air flows reducing downwards (from the upper inlet to the lower outlet) was proposed as a potential solution for less preferential drying (Navaee-Ardeh et al., 2006).

In a pilot-scale rotating drum (Fig 2.B) (Bartha, 2008), temperature differences among the T_{out} and various points within the reactor were evident, but smaller compared with other static single-direction flow designs (Fig 3).

3.8. Aeration rate and air properties

Aeration rate is the main operational variable used for process control in biodrying, both in laboratory (Adani et al., 2002; Navaee-Ardeh et al., 2006; Sugni et al., 2005) and commercial applications. The inlet airflow rate can be manipulated to control matrix temperature, in turn affecting the air dew point and biodegradation kinetics. A high airflow rate is necessary for the production of a sufficiently high in calorific vale (CV) SRF, through preserving most of the biogenic content. In a comprehensive study Adani et al. (2002) used static, adiabatic reactors fed on the fine fraction of shredded MSW (Ø < 50 mm). Trials were conducted on set-points of middle layer matrix temperature, controlled manually by adjusting the airflow rate. It was established that high airflow rate is necessary for effective and fast drying, result in agreement with Roy (2005). However, further studies with the same sample revealed a low reproducibility of EC and CV, these properties being highly dependant on the laboratory employed to measure them (Sugni et al., 2005).

The oxygen stochiometric demand for aerobic decomposition is satisfied by O_2 provided by the high aeration rate necessary for effective drying (Epstein, 1997; Rada et al., 2007a; Themelis, 2005). According to Epstein (1997) the aeration rate necessary for moisture removal in composting is 6-10 times higher than that necessary for biological activity. Rada et al. (2007a) measured the O_2 concentration in the process outlet air at above 15% (generally >20%). Use of air recirculation systems results in low O_2 concentration in the inlet air: the rotary drum reactor tested by Bartha and Brummack (2007) was operated with O_2 concentration up to 3% v/v.

In biodrying, optimisation of the drying potential of the input air can be achieved by adjusting its psychrometric properties. This is attained through (1) dehydration of the exhaust air by cooling in a heat-exchanger and cooling tower and (2) subsequent partial recirculation of it after mixing with ambient air, achieving an input air mixture of the desirable temperature and absolute humidity (Herhof Environmental, Undated) (Fig.1).

3.9. Moisture content and losses

MC of the waste matrix is the single most important variable for evaluating the performance of biodrying processes. In waste management the MC is typically measured by gravimetric water content methods and expressed as a percentage of water for the wet weight of the material (wet basis: ar) (Tchobanoglous et al., 1993). A more accurate biophysical parameter relevant to the microbial activity is the water matric potential, denoting the energy with which water is held in a sample against the force of gravity (Miller, 1989).

In biodrying, the MC can be reduced from *ca*. 35-55% w/w ar (Thomé-Kozmiensky, 2002) to 20-10% w/w ar. During aerobic biodegradation around 0.5-0.6 g of metabolic water is produced per g of VS decomposed (Miller, 1989, 1991). However, water losses during biodrying are much greater than the gains of metabolic water, resulting in a dried matrix (Nakasaki et al., 1987b; Richard, 2004). Water losses can be estimated using values of airflow rate and inlet-outlet air conditions, *i.e.*, absolute humidity (Richard, 2004). Mass balance of MC should include both metabolic water gains and evaporation-convection losses. Rada et al. (2007b) consider overall weight losses of 25% w/w as typical. The authors, in test-scale biodrying experiments with artificial MSW of high-moisture input (MC: 50% w/w ar) and 50% w/w organic material, reported similar time dependent curves for both the water and VS losses, with most losses attributable to moisture removal (ratio of weight losses between VS and condensed moisture: 1:7). The drying rate in sludge biodrying was reported to correlate mainly with airflow rate and outlet air temperature, which in turn was found to depend on the degree of biological activity close to the air outlets (Navaee-Ardeh et al., 2006; Roy, 2005).

MC critically influences the dynamics of biodegradation during composting. Optimal moisture conditions for composting range significantly, change during the process (either increase or decrease) and vary with substrate (Richard and Choi, 1997; Richard et al., 2002). Regan et al. (1973) reported an optimal MC range for cellulose degradation at 50-70% w/w. Relevant overviews for waste substrates have been provided by Epstein (1997), Richard (2004), and Linag et al. (2003). Liang et al. (2003) used factorial design experiments to investigate the influence of temperature and MC on microbial activity, measured as O_2 uptake rate (mg g^{-1} h^{-1}) during composting of biosolids, showing that MC is more influential than temperature. In practice, biodegradation may stop during biodrying, or its rate may be significantly reduced, due to complete decomposition of readily biodegradable VS (degradation effect), or, more possibly, due to water stress where low moisture conditions inhibit microbial activity and movement (drying effect) (Griffin, 1981; Miller, 1989).

For biodrying processes, the minimum MC below which the biodegradation process is inhibited has not been identified. The rate of heat production by microbial activity can be anticipated to decline as the MC of the matrix approaches the water stress limit, affecting the drying mechanism. From composting studies it is evident that below 20% w/w very little or no microbial activity occurs (Haug, 1993).

3.10. Air and matrix temperatures for optimal biodrying

Conflicting evidence is available for the temperature range that optimises drying. Whilst some modelling studies for aerobic biodegradation indicate highest moisture removal at matrix temperatures at or slightly above the peak of biodegradation rate, experimental evidence supports maximum drying for much lower temperatures, which delay biodegradation. We speculate this contradiction can partly be attributed to confusion concerning the temperature referred to or measured, which could include the varying or set-point, biodegradation reaction, air outlet, matrix average or in various points within the matrix. Further, results from composting models rarely allow for high or constant airflow rates, typical in biodrying. Comparative interpretation of results is not helped by the wide variety of units used for reporting aeration rates.

Most evidence indicates that comparatively effective heat removal can be achieved by higher aeration rates resulting in lower matrix temperatures (Adani et al., 2002; Skourides et al., 2006; VanderGheynst et al., 1997), with an optimal T_{waste} as low as *ca*. 45ºC.. In batch-scale biodrying of pulp and paler sludge Roy et al. (2006) reported higher drying rates (volume of removed moisture per time) for higher airflow rates; the curves of the T_{out} and Q_{air} followed the same trends.. This is in agreement with Adani et al. (2002) who achieved best drying results for the highest specific airflow rates they used (0.023 $\mathrm{m^3\ kg_{TS}^{-1}\ h^{-1}}$) allowing for a mid-layer matrix set-point temperature of 45ºC, whilst they even higher airflow rates for more effective drying.

Skourides et al. (2006) investigated the agitated biodrying of the organic fraction of municipal solid waste in a semi-industrial rotary drum. Similarly, results showed maximum drying rate achieved for the highest aeration rates used (120 $\mathrm{m^3\ h^{-1}}$), leading to lower final MC levels (20% w/w from an initial 40% w/w) with a shorter retention time (< 7 d). This agrees with results reported by Macgregor et al. (1981) for field-scale, open static pile composting of sewage sludge and wood chip mixture, aerated by a blower and two perforated ducts system at the pile base. Lower set-point substrate temperatures (45ºC, as compared with 55ºC and 65ºC) achieved by longer blower operation, resulted in more effective drying (from 75% w/w to *ca*. 20% w/w, as compared to *ca*. 40% w/w, respectively).

However, a model of semi-batch stationary composting based upon heat and mass balance, and validated with laboratory and commercial scale experiments on mixtures of dewatered sewage sludge, seed and rice husks, reached conflicting conclusions (Nakasaki et al., 1987a). The optimal MC removal (from 60.3% w/w to 44.8% w/w) was achieved at a set-point substrate temperature of 60ºC with an average specific airflow rate of 0.0143 m^3 h^{-1} $kg_{initial}^{-1}$ after 150 h of operation, whilst a minimum set temperature of 50ºC demanding the highest average specific airflow rate of 0.0164 m^3 h^{-1} $kg_{initial}^{-1}$, reduced MC only to 48.6% w/w. The model predicted that the optimum temperature for biodegradation coincided with the optimum temperature for drying, a result verified for a series of biodegradation kinetics models examined by Richard and Choi (1997). However, this model enabled varying airflow rates, a condition which does not correspond to usual biodrying practice. Jewell et al. (1984) reported maximum moisture removal rates at 46ºC, but maximum degradation at 60ºC, whilst studying biodrying of dairy manure.

Most commercial biodrying processes operate in the temperature range of 40-70ºC for outlet air T_{out}, for most of the residence time (Herhof Environmental, Undated; Juniper, 2005). A typical temperature profile for the Nehlsen process is available (Juniper, 2005). Herhof Rottebox® applies a staged T_{out} control, consisting of four phases over one week: (1) start up and biomass acclimatization: 40ºC; (2) degradation: 40-50ºC; (3) sanitisation and drying: 50-60^{0}C; (4) cooling to room temperature 60ºC to ambient T (Nicosia et al., 2007).

3.11. Microbial activity

Microbial processes during biodrying should be suitably harnessed for the generation of the heat necessary for effective drying, along with limited biodegradation of waste substrates. Substrate temperature T_{waste} is the most critical factor affecting the microbial growth (Miller, 1996), because, *inter alia*, provides ideal conditions for proliferation of certain types of micro-organisms, *e.g.*, mesophilic or thermophilic. In turn, this affects the type of organic matter that can be degraded. In composting, at $T_{\text{waste}} > 60$ºC cellulose and lignin are largely preserved, as the thermophilic fungi die-off, but waxes, proteins and hemicelluloses are readily metabolised by spore-forming bacteria and actinomycetes (Lester and Birckett, 1999).

The wider influence of substrate temperature on composting microbial population dynamics has been discussed elsewhere, including Miller (1996), Epstein (1997), and Liang et al. (2003). Overviews of microbial community dynamics, including group succession and utilisable substrate for different process stages and temperature ranges, can be found in Marshall et al. (2004) and Insam and de Bertoldi (2007). However, biodrying of MSW is operated within a MC range typically lower than the optimal composting and the T_{waste} profile is managed differently: therefore, biodegradation behaviour may be atypical compared with composting research results (Adani et al., 2002).

During biodrying of a high MC matrix of pulp and paper sludge, Roy et al. (2006) identified three separate drying stages, which correlated with microbial population growth periods: (1) acclimatisation of microbes resulting in an exponentially increasing drying rate; (2) exponential decrease of the drying rate due to insufficient availability for nutrients for microbe consumption, and (3) constant drying rate, corresponding to the fluctuations of the Q_{air}. If a similar dynamic applies to the much drier substrates of residual MSW it would indicate that after some point biodrying is less dependent on the microbial activity, increasingly impeded by water stress; becoming, instead, just a physical process (air convection). It is not clear how this would affect the energy balance of the process.

3.12. Degree of biostabilisation at process completion

Fast and effective biodrying, optimised for SRF production, can be achieved at the expense of a low degree of biostabilisation for the organic substrate. Because the thermal energy for drying results from the decomposition of organic matter, a degree of biostabilisation is anticipated to have occurred at the end of the process. Regarding SRF product quality, the desirable degree of biostabilisation will generally be low, as this would preserve carbonaceous matter, reserving CV and biogenic content. Conversely, where the SRF is not used immediately, biostabilisation to a limited degree is desirable, because this would reduce any potential storage and environmental problems caused by further biodegradation.

There is evidence that the degree of substrate biostabilisation is inversely correlated to a fast-rate, producing high EC output biodrying (Adani et al., 2002). Adani et al. (2002) showed in comparative laboratory tests that the highest airflow-rate enabled the fastest SRF production (*ca*. 150 h), along with the highest EC. Using lower airflow rates, the process took more than 250 h to complete and the end occurred because of sufficient biodegradation of readily decomposable organic matter., This resulted in much higher losses of VS, leading to much lower final EC, rendering it unsuitable for SRF production.

A further experiment under different process parameters showed that microbial activity ceased after about 200 h, as verified by the final temperatures, which converged with ambient values (Sugni et al., 2005). Thus, under controlled laboratory conditions, fully enclosed biodrying can be effectively completed within 8-9 d.

However, Rada et al. (2007a) in test-scale biodrying of high MC input (MC_{waste} *ca*. 50% ar) observed longer times for the process completion of up to 4 w, using increased aeration over the time (*ca*.11.5 $Nm^3\ kg_{MSW}^{-1}$ after two weeks of treatment and *ca*.14.5 $Nm^3\ kg_{MSW}^{-1}$ after four weeks).

3.13. Biodrying configured for biostabilisation

Some advocates of biodrying consider it feasible to use biodrying reactors for effective intensive composting, based on the similarities between biodrying and in-vessel composting. This capability would theoretically enable the process to be adapted for stabilising organic material intended for landfill, thereby achieving regulatory compliance. Such an operating mode could be adopted until a robust market for SRF was secured, as market availability is challenging under current conditions (Juniper, 2005; Maunder, 2005). However, further evidence is required before such process resilience can be guaranteed.

Regarding full-scale reactors, the Eco-deco biodrying plants in Corteolona and Bergamo, Italy have previously operated with the objective to minimise biodegradability, producing a fully biostabilised output (Juniper, 2005). Scotti and Minetti (2007) presented Eco-deco data from the Montanaso plant showing the ability of the process to operate in “*high speed process management*” mode, intending to achieve a higher level of weight loss in fewer days (typical weight loss of 28% w/w ar of input waste reached in *ca*. 5 d instead of *ca*. 14 d; final losses of *ca*. 38% were achieved in 14 d). The authors argue, but have not quantified, that such an operational mode leads to higher final stability for the biodried output.

However, it is evident that biostabilisation demands a very different operational mode than biodrying. Rada et al. (2007b) based on respirometric index measurements argued that a biodrying operation mode is capable of achieving only partial final output stability, compared with biostabilisation through composting. Input waste of 50% in organic content reached 500 mg O_2 kg_{TS}^{-1} h^{-1} after *ca*. 200 h residence time (typical limit in Italy(Scotti and Minetti, 2007): at < 1000 mg O_2 kg_{VS}^{-1} h^{-1}).

3.14. Modelling of biodrying processes

Limited modelling attempts for MBT-related biodrying processes exist in the peer-reviewed literature. However, composting processes have been extensively modelled (Mason, 2006; Mason and Milke, 2005a; Mason and Milke, 2005b). Particularly relevant are attempts to model moisture-dependent aerobic biodegradation (Higgins and Walker, 2001; Pommier et al., 2008); however, evaporation phenomena were excluded. Brazier (1996) reviewed modelling efforts for near-ambient drying and developed a validated simulation model from first principles. The wider modelling and simulation research on grain drying has been reviewed by Parde et al. (2003). Nakasaki et al. (1987a) modelled a generic composting process to explore the relationship between aeration and drying, reaching results that contradict recent biodrying experiments.

Rada et al. (2007a) provided initial biodrying modelling results focusing on simulation of lower heating vale (LHV) (or net calorific value, (NCV)) dynamics, volatile solids (VS) consumption, waste MC dynamics, and nitrogen compounds release. The overall loss in EC of the input waste matrix was 3% w/w and most of the change in the NVC was accomplished within the two first weeks of the process. The energy produced from the bio-oxidation of the readily decomposable VS was dominant in the energy balance, compared with the enthalpy of the input at ambient *T*.

Nicosia et al. (2007) combined both experimental data and theoretical calculations to provide simplistic mass and energy balances for a fully operational biodrying bio-cell. The process losses (37% w/w of input) were simulated with 80% accuracy, stressing the importance of more accurate estimates for matrix biochemical composition and actual amount of heat generated during biodegradation. Frei et al. (2004b) modelled the matrix pneumatic behaviour of their complex inverted airflow configuration for biodrying of paper and pulp wastewater. Navaee-Ardeh et al. (2006) adopted a stepwise approach to model at an introductory level a vertical continuous biodrying reactor for sludge drying, with perpendicular forced aeration diversified within four compartments. Bartha (2008) extensively modelled properties of a bench-scale rotary drum biodrying reactor, including its biodegradation behaviour, for process control purposes.

4. Commercial biodrying-MBT applications

Commercial, proprietary applications of biodrying within MBT plants are described. Indicative flow-sheets for some of these plants can be found in the related MBT review (Velis et al., in press). Following sections provide comparative data on operating parameters from commercial biodrying processes in full-scale plants summarised in Table 2 and Table 3. Almost all data have necessarily been collected from the grey literature supplied by process providers.

4.1. Technology provider: Eco-deco

Eco-deco is an Italian company that developed biodrying in the mid 1990s and operates 10 plant plants in Italy, the UK, and Spain with an overall capacity of *ca*. 900,000 Mg a^{-1} (Shanks, 2007). The core biological process is marketed as

“BioCubi®” in Italy, and the overall plant as the “Intelligent Transfer Station (ITS)” under licence by Shanks in the UK (Juniper, 2005). Scotti and Minetti (2007) provide a recent account of the commercial reference plants of Eco-deco.

Eco-deco plant configurations differ according to the available options for outputs. They are fully enclosed and equipped with air pollution control systems. Various process flow-lines have been described in detail elsewhere (Cozens, 2004; Environment Agency, 2007; Juniper, 2005). Waste input is shredded to *ca*. 200-300 mm, with the aim of homogenisation and size reduction to improve efficiency of subsequent aerobic fermentation. Biodrying occurs in an enclosed hall, with comminuted input automatically stockpiled by crane in adjoining windrows. These are divided for process control purposes into a virtual grid that provides on-line data to a computerised control system.

Air suction is applied through the waste matrix, through the vents of a pre-cast perforated floor and is directed to the air pollution control system. The airflow rate is automatically adjusted depending on the exhaust air temperature. Various optimal temperature ranges have been reported in the literature, namely 55-70ºC (Juniper, 2005); 50-60ºC (Environment Agency, 2007); and *ca*. 65ºC (Cozens, 2004). Residence time within the biodrying unit is 12-15 d.

4.2. Technology provider: Entsorga

The technology is marketed as “H.E.BIO.T.®,”(“High Efficiency Biological Treatment”) (Entsorga, Undated). Entsorga will be commissioning a MBT plant to treat 60,000 Mg a^{-1} at Westbury, UK (Hill, 2005). No data on the exact process configuration and anticipated performance are yet available in the public domain.

4.3. Technology provider: Future Fuels

Future Fuels have recently applied for an international patent of a biodrying method (Hood et al., 2008), building upon pilot-scale research and development by Skourides et al. (2006). The concept uses an inclined rotating drum ("Rotary bio-dryer," (RBD)) to process a mechanically separated organic fraction of MSW (OFMSW), potentially mixed with selected commercial waste. The RDB is operated in alternate cooling and heating cycles, using consecutive rotating and static intervals, and variable airflow rates. The process control strategy aims to keep the temperature inside the bioreactor optimised for aerobic biodegradation (upper mesophilic to thermophilic range: 40-55ºC). According to the process developers, the RDB can achieve fast and homogeneous drying of the OFMSW, reducing its MC from 35-40% w/w ar to 10-15% w/w ar within 3 d. Table 3 includes further process details.

4.4. Technology provider: Herhof

Herhof developed biodrying in 1995 (Wengenroth, 2005; Wiemer and Kern, 1994) and the first commercial plant to operate was in Asslar, Germany, in 1997 (Juniper, 2005). Herhof operates 8 plants in Germany, Italy and Belgium, with overall operational capacity *ca*. 1,085,000 Mg a^{-1}. Their processes differ slightly, to adapt to local conditions or due to evolving optimisation. Plant configurations have been described elsewhere (Diaz et al., 2002; Herhof Environmental, Undated; Juniper, 2005). The plants are fully enclosed, automated and equipped with APC systems.

Rotary shredders are used for mechanical pre-treatment (Rennerod: < 150 mm; Dresden: < 200 mm). Downstream a magnetic conveyor belt removes the ferrous material. The comminuted Fe-free output is biodried within air- and liquid-tight boxes ("Herhof-Rotteboxes®") with capacity of 600 m^3, receiving around 280 Mg of waste each. Filling/unloading of material and handling of the box lid is handled automatically by crane. The biodrying reactor residence time ranges from 5 to 10 d, with 7 d the most common (Herhof Environmental, Undated; Herhof GmbH, Undated; Juniper, 2005).

The mass losses in the biodrying stage are around 30% w/w input. The initial MC of 42% is reduced to 12% after six days biodrying in the Rennerod facility. APC residue (dust) from the bag-filter (*ca*. 4% w/w input) is pelletised and mixed with the SRF. High effectiveness has been reported for the mechanical post-biodrying at the Rennerod-Asslar plant, with typical purity of the final “Dry Stabilat®” over 99%, *i.e.*, < 1% impurities with a yield of around 50% of plant input. Recovery of the combustible mass content of the input waste is much higher.

4.5. Technology provider: Nehlsen

Nehlsen developed a biodrying process during the mid-1990s in Germany, marketed as “Mechanical Biological Stabilisation” (MBS) and the SRF as “Calobren® The process configuration is similar to Herhof, using biodrying containers with under-flow of partially circulated process air. In the past, plant capacities were lower and the mechanical refinement stage less sophisticated than other biodrying providers (Juniper, 2005). Breuer (2007) reported on recent operation experience of the Stralsund plant. This facility is diversifying its production lines and SRF outputs to secure multiple market outlets.

4.6. Technology provider: Wehrle Werk

The Wehrle Werk system is operated on mixed MSW. It uses mechanical pre-treatment followed by percolation (“Bio-percolat”) and anaerobic digestion, aiming at easily degradable materials (Juniper, 2005). Solid residuals from the percolator are dewatered by a screw press to about 40% MC. This is fed into closed tunnel biodrying reactors with matrix circulation known as "Percotry®." Output MC is reduced to below 15%. Sieving of the biodried output could produce an SRF that is around 35% w/w of input waste. Process losses are around 15% w/w.

5. Conclusions and recommendations

Biodrying for MBT is a versatile bioconversion process that can improve the fuel characteristics of its output, or partially biostabilise it, according to end-use. Few providers of commercial biodrying processes dominate the market, but research and development on process variations is continued. Most of this research is proprietary and has not yet reached the public domain. There are limited experimental results on the physiobiochemical fundamentals and dynamics of biodrying reactors; and few modelling results have appeared.

This said, this review provides a critique of the current state-of-the-art. Evidence suggests that effective biodrying demands different management of process control variables than composting, to fulfil different objectives. High aeration rates and limited biodegradation produce optimally biodried output, for further processing to SRF. Typical process times are 7-15 days, leading to weight loss of 25-30% w/w of the reactor input, mainly $H_2O_{(g)}$ and CO_2 Modification of the psychrometric properties of input air and minimisation of matrix gradients for critical properties, such as MC, are critical aspects of optimisation. Inverted air and rotary drum reactor designs can improve uniformity of treatment and output quality, but they have still to be proven on a commercial scale. Integration into the wider MBT plants flow-line deserves more attention, especially pre-conditioning for optimal airflow through the matrix.

Additional modelling efforts could explain the prevailing process dynamics and evaluate the relative role and contribution to drying of the bio-conversion *vs.* the physical mechanism of aeration. Process control can be improved. Suitability of state and operational process variables used for process monitoring and control respectively should be further investigated. Knowledge transfer from the traditional drying applications can be sought for both modelling and control purposes.

Research should seek to examine the possible trade-offs in process performance, enabling optimisation in line with site-specific desired output quality and wider process objectives, eventually further increasing market confidence in biodrying MBT plants.

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Nomenclature

Symbol type	Symbol	Explanation
Properties	EMC	Equilibrium moisture content
	ERH	Equilibrium relative humidity
	Q_{air}	Inlet airflow rate
	K	Permeability
	m	Mass
	MC	Moisture content
	O_2	Molecular oxygen
	rH	Relative humidity
	T	Temperature
Subscripts	air	Air flowing through waste matrix
	inicial	Initial plant or process input values
	max	Maximum value
	MSW	Municipal solid waste
	out	outlet (exhaust) air
	TS	Total solids
	VS	Volatile solids
	waste	Waste matrix
General	%	Percent
	Ø	Diameter
	Δ	Difference
	®	Proprietary
Selected units	ar	Reporting basis: as received (*i.e.*, wet)
	d or DM	Reporting basis: dry matter
	d	Days
	Mg	Mega gram (or ton)
	Mg a^{-1}	Mega gram per year (or tpa: ton per annum)
	Nm^3	Normal cubic meters
	Scfm	Standard cubic feet per minute
	Rpm	Rotations per minute
	w	Weeks
	w/w	Weight fraction or percent
	v/v	Volume fraction or percent
	ºC	Degrees Celsius

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List of figures

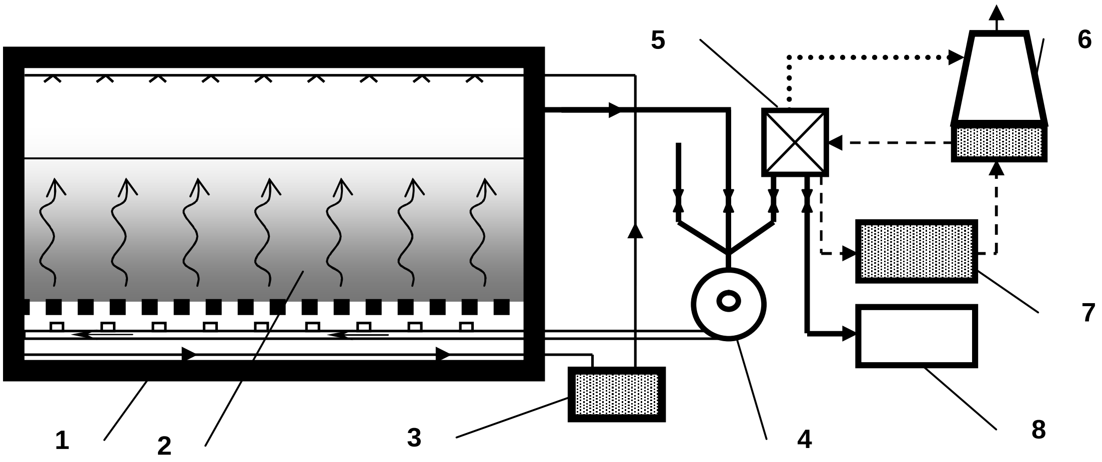
Fig. 1. Schematic of biodrying box with process air circulation and dehydration based on a Herhof system: (1) enclosed box; (2) air forced through the waste matrix, heated by the exothermic aerobic biodegradation of readily decomposable waste fragments; (3) leachate collection and circulation system; (4) forced aeration system with partial air re-circulation, mixing ambient air and conditioned process air; (5) heat exchanger; (6) cooling tower; (7) water (vapour condensate); (8) exhaust air treatment through biofilter or regenerative thermal oxidation (RTO). Appropriate conditions for microbial activity allow for the biodegradation of the waste placed within the bioreactor, providing the necessary heat to evaporate moisture from the waste fragments. Evaporated moisture is removed by the air convection, achieved by forced aeration. The exhaust air is going through various treatment stages that improve its drying capacity (ability to carry moisture) before it is partly re-circulated into the reactor, after being mixed with ambient air. Redrawn from Herhof Environmental (Undated).

Fig. 2. Simplified schematics of bench/pilot scale biodrying reactor designs, among else aiming to mitigate the uneven drying of matrix. Reactor A: static enclosed cell. The central perforated pipe (C2) alternates between blowing and pulling air through the matrix, whilst the peripheral pipes (C2, C3) operate conversely. Reactor B: cylindrical rotating drum with one perforated pipe. Certain monitoring points are shown: T: temperature: 1-7 internal, out: exhaust air; P: pressure; rH: relative humidity; Q: airflow- rate. BL: blower. For A1 refer to Fig. 3. Redrawn from A: Frei et al. (2004b) and B: Bartha (2008).

Fig. 3. Various matrix temperatures and process completion times during biodrying bench/pilot scale reactor experiments, reflecting different reactor designs, control mechanisms, operation regimes and matrices. Part A: (i) curves B1-3: bottom, middle and upper layer T respectively of enclosed cell reactor (Adani et al., 2002; Sungi et al., 2005). Airflow direction from upper to bottom layer. T differences resulting in uneven drying; (ii) curves A1-2: rotary drum reactor (Fig.2, reactor B) (Bartha, 2008). Range of temperatures inside reactor walls at T1/3/5/7 points. A1 curve shows T7, almost identical with T_{out} (Fig2). Part B: airflow inversion designs, abrupt T increase denotes inversion of flow: (i) reactor as in part 1(i), curves C1-3: bottom, middle and upper layer T respectively (Sungi et al., 2005); (ii) curve D, (Fig2, reactor A), matrix mixture of sludge/wood, average matrix T (Frei et al., 2004b). Redrawn from the above indicated sources.

List of tables

Figures



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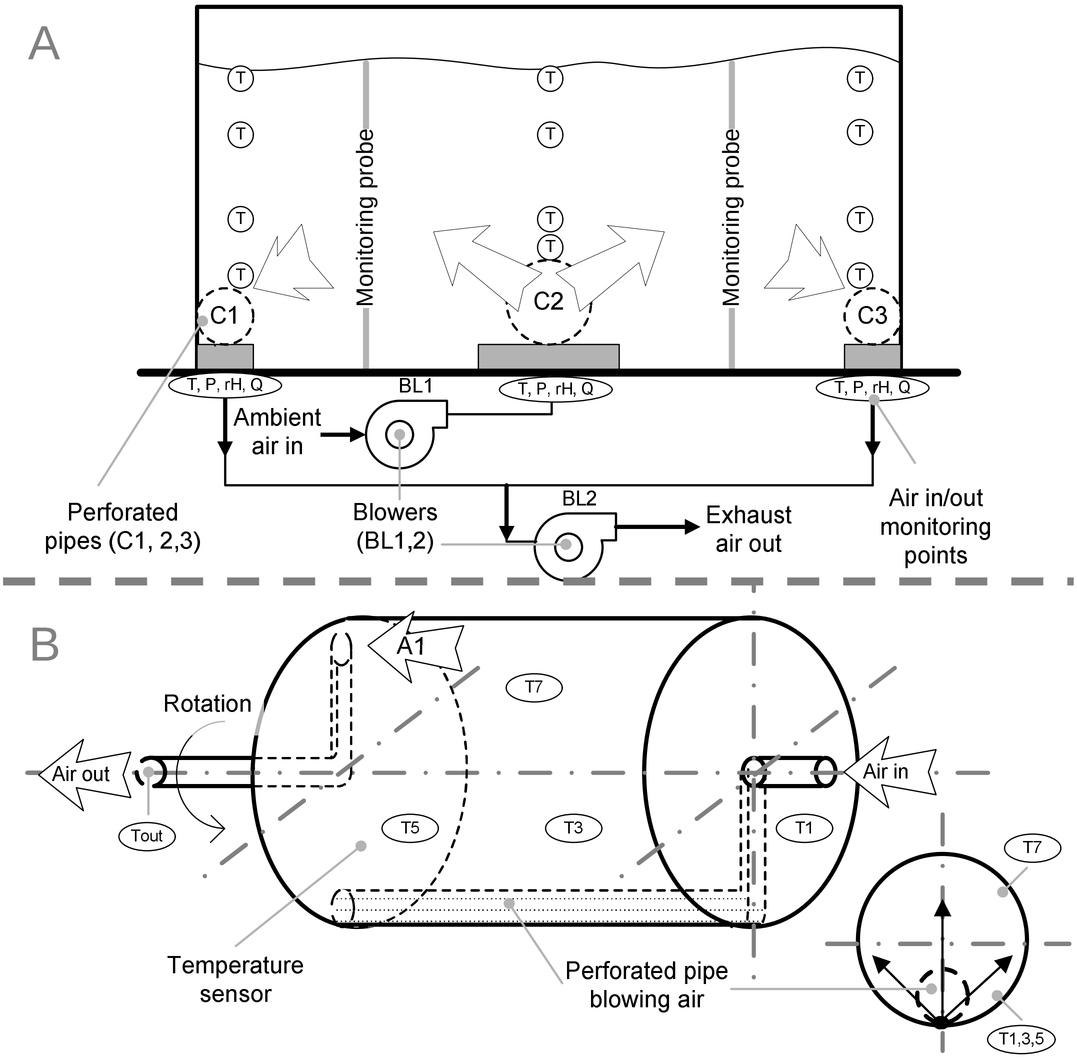

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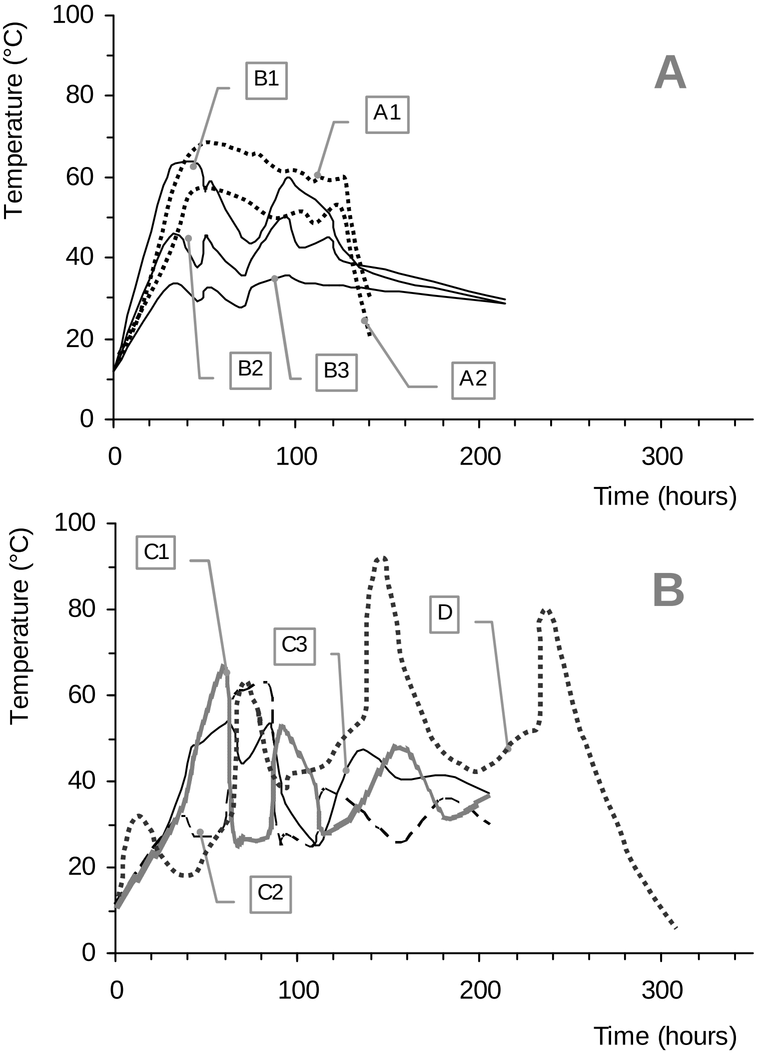

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Tables

Table 1

Objectives and features of biodrying in comparison with other similar drying bioconversion technologies

	Drying process			
Process feature	Composting (intensive) (de Bertoldi et al., 1996; Epstein, 1997; Haug, 1993; Richard, 2004)	Sludge de-watering by composting (Frei et al., 2004a; Frei et al., 2004b; Navaee-Ardeh et al., 2006; Roy, 2005)	Grain and forest residues air-drying (Brazier, 1996; Nellist and Brook, 1987; Nellist et al., 1993)	Biodrying in MBT (Adani et al., 2002; Rada et al., 2007a; Hood et al., 2008; Sugni et al., 2005; Wiemer and Kern, 1994)
Objectives	Production of a compost, largely stabilised material Apply beneficially on-land or dispose of in landfill	Reduce sludge volume Dry and partially stabilise sludge	Food preservation (dry grains before storage to prevent proliferation of spoilage agents, including biodegradation)	Produce a high quality SRF Partially stabilise output and inhibit further biodegradation rendering it suitable for short term storage Preserve biogenic content of substrate Output suitable for subsequent mechanical processing (improve flowability)
Matrix type	Organic waste material	Sludge (biosolids)	Grain harvest Forest residues	Residual unsorted MSW Mechanically separated OFMSW [h]
Degree of reactor enclosure	Outdoors or indoors in fully enclosed cells	Enclosed cells	Outdoors design	Fully enclosed bio-cells/rotating drums or enclosed in-tunnel
Dependence on	Depending on reactor type	No	Influx air T, rH dependent on	Depending on degree of

meteorological conditions			meteorological conditions	sophistication of reactor design
Moisture content management	Limited removal or addition of water to keep MC within optimum range of *ca*. 50-70% w/w ar [a,b]	Reduce MC from an indicative 80 to *ca*. 40% w/w ar [d]	Reduce MC to 14.5% w/w ar [f]	Reduce MC from *ca*. 40% to 20% w/w ar or less
Residence time	10-12 w of intensive decomposition	*ca*. 10 d	Months	Static, commercial designs: 5-15 d Longer for higher input MC [g] Pilot-scale rotating drum: 2-3 d [h]
Airflow rate	Batch systems peak: 4-14 O_2 g_{VS} h^{-1} at T 45-65ºC (under certain assumptions equivalent to: 125-460 m^3 h^{-1} (metric ton of feed solids)$^{-1}$) [c] Continuous systems: average demand *ca*. 1660 m^3 h^{-1} (dry metric ton of feed solids per day)$^{-1}$) [c]	*ca*. 42.5±3.4 Nm^3 h^{-1} (25±2 scfm) [e]		0.023.1 m^3 kg_{TS}^{-1} h^{-1} [i] Increasing over time (for high-MC input): *ca*.11.5 Nm^3 kg_{MSW}^{-1} after two weeks; up to *ca*.14.5 Nm^3 kg_{MSW}^{-1} after 4 weeks [g] RDB cooling cycle: 0.120-0.150 m^3 h^{-1} kg^{-1} [h]

General references are presented in the column titles. Reference to specific values are denoted by Latin letters below

[a] Regan et al. (1973)

[b] Richard (2004)

[c] Haug (1993)

[d] Navaee-Ardeh et al. (2006)

[e] Frei et al. (2004b)

[f] Brazier (1996)

[g] Rada et al. (2007a)

[h] Hood et al. (2008)

[i] Adani et al. (2002)

MBT: mechanical-biological treatment

MC: moisture content

MSW: municipal solid waste

RDB: Rotary bio-dryer

scfm: standard cubic feet per minute

SRF: solid recovered fuel

Table 2

Indicative mass balances of commercial MBT processes using biodrying reactors

	Process provider							
	Eco-deco		Entsorga	Herhof		Nehlsen		Wehrle Werk
Material fraction/ recovery	Frog Island plant (Scotti and Minetti, 2007)	General process (Cozens, 2004; Environment Agency, 2007; Juniper, 2005)	Indicative process (Entsorga, Undated)	Rennerod plant (Diaz et al., 2002)[*,**]	Dresden plant (Diaz et al., 2002)[***]	Rugen plant (Juniper, 2005)[†]	Stralsund plant (Breuer, 2007)	General process (Juniper, 2005)
SRF (% w/w. input)	39	*ca.* 53 49.5 [††]	46-53.5	53	50	*ca.* 55	50.7	*ca.* 35 [†††]
Fe (% w/w input)	2.6	3.3	5-10 [*†]	4	4	4		
Fe recovery (% w/w)				85 [a]				
Non-Fe (% w/w input)	0.3	0.4		1 [a]	1	1	2.3	
Non-Fe recovery (% w/w)				60 [a]			0.9	
CLO [*†*] (% w/w input)	11 (-8 mm)	17 (+20 mm)	5-10					
Sum of mineral fraction (% w/w input)				15	10			
Sum of mineral fraction recovery				95 [a]				
Aggregates (sand, stones, ceramics, porcelain) (% w/w input)	1.6 (+8-20 mm) [†*†]	5 [†*†]		4				
Glass (% w/w				4				

input)								
Batteries (% w/w input)				0.05	0.05			
Losses ($CO_2+H_2O_{(g)}$) (% w/w input)	28.4	Typical: 25 Range: 20-28	29-31.5	30 [**†]	30 [**†]	25-30	16.2	*ca.* 15 [††*]
Liquid effluent (% w/w input)		> 1						
Solid reject fraction (% w/w input)	17.5	17 (+20 mm)	10-15	4 [#]	5 [#]	15	Landfill: 22.7 WIP: 7.4	

General references are presented in the column titles. Reference to specific values are denoted by Latin letters below

[*] Typical approximate values. APC residue/light reject fraction pelletised and used with SRF

[**] 70% residual (high kerbside segregation) 30% commercial

[***] Approximate values. Mass balance not closing: insufficient data. Less kerbside segregation than and advanced post-refinement compared to Rennerod. APC residue /light reject fraction pelletised and used with SRF

[a] Juniper (2005)

[†] Use in cement kilns

[††] Possibly including the processed oversized trommel fraction and rich-in-plastics contaminants of the aggregate fraction

[†††] Various grades

[*†] Both Fe and non-Fe metals

[*†*] Not fully stabilised. Needs further composting to CLO markets or to landfill disposal with low biodegradability

[†*†] Both aggregates and glass

[**†] Partly re-circulated

[††*] Biodrying reactor is fed with a fraction of plant input

[#] Light densimetric fraction + APC residue

APC: air pollution control

CLO: compost-like output

WIP: waste incineration plant

Table 3

Comparison of selected process elements and parameters for biodrying commercial processes

	Process provider					
	Eco-deco	Entsorga	Future Fuels	Herhof	Nehlsen	Wehrle Werk
Process feature	(Cozens, 2004; Environment Agency, 2007; Juniper, 2005)	(Entsorga, Undated; Hill, 2005)	(Hood et al., 2008)	(Diaz et al., 2002; Herhof Environmental, Undated; Juniper, 2005)	(Breuer, 2007; Juniper, 2005)	(Juniper, 2005) [*]
Biodrying reactor type	BioCubi® Windrows in enclosed hall. Downward air suction through matrix	H.E.BIO.T.® Enclosed hall	Rotary bio-dryer (RDB), with internal lifters: circular cylindrical drum Inclined 7º Ø 4 m Length 25 m	Herhof-Rotteboxes® Air and liquid-tight boxes. Upward blowing of circulated de-hydrated air through matrix	Bio-cells, air and liquid-tight	Percotry® Enclosed tunnels with waste circulation
Operational variables (manipulated)	Airflow rate		Airflow rate Drum rotation pH of RDB input: 6.0-8.5, by recirculation of 10-20% w/w of biodried output Heating cycle for T< 40ºC: 30-35 $m^3\ h^{-1}\ Mg^{-1}$ Reactor static for 1-2h; rotating for 10-15 min Cooling cycle, for T>55ºC: 120-150 $m^3\ h^{-1}\ Mg^{-1}$ Reactor rotating at 0.5 rpm	Airflow rate 12 segments in bio-cell bottom [a]		
State variables (to inform control)	Exhaust air T		T: 5 thermocouples, kept within 40-55ºC Exhaust air rH	Heat quantity, matrix temperature, air permeability of matrix, CO_2 exhaust concentration		

Biodrying unit outlet ait temperature T_{out} (°C)	50-70			*ca.* 50 Staged approach, 40-60 [a,**]	Up to 70	
Residence time	12-15 d	14 d	Aeration bay: 14-72 h RDB: 2 d: for MC reduction from 35-40% w/w ar to 15-25% w/w ar 3 d: MC reduction to 10-15% w/w ar	5-10 d	*ca.* 7 d	
Input to the biodrying reactor	Residual unsorted MSW		OFMWS, mechanically separated from residual unsorted MSW			Dry residuals of MSW percolation, dewatered to MC 40% ar
Mechanical pre-treatment	Shredding 200-300 mm	Trommel	Bag splitter Primary shredding to 80-120 mm (Aeration bay) Trommel at 80 mm underflow fed to RDB Metal separation of trommel overflow and secondary shredding at 80 mm, fed to RDB	Hammermill < 200/150 mm	Shredding < 300 mm Single shaft cutting mills suitable for high plastic film content [†]	
Biodrying losses (% w/w)	*ca.* 30			20-28 Typical 30; specific case reported 37 [a]	*ca.* 25 *ca.* 30 of input to the biodying unit [†]	*ca.* 15 of plant input
Liquid effluent	< 1 %			Condensate treated or evaporated		
Process air management	Negative pressure		Possible pre-heating of RBD	Partial circulation for	Partial circulation	

	Selective air-flow treatment		inlet air by air-to-air heat exchanger using heat from aeration bays	biodrier process air Circulation of cleaned fabric filter air Airlocks in discharge area Enclosed conveying	of screening and refining process air after cleaning Negative pressure
Air pollution control	Biofilter for biodrying Fabric-filter for air classification	Biofilter	Biofilter	LARA® RTO Fabric-filter for densimetric separation	Previously biofilter; upgraded to RTO to meet German 30th BImSchV

General references are presented in the column titles. Reference to specific values are denoted by Latin letters below

[*] Mass balance values as percentages of plant 100% input: biodrying reactor is fed with a fraction of plant input

[a] Nicosia et al. (2007)

[**] See section 3.10. for details

[†] Stralsund plant Breuer (2007)

MC: moisture content

MSW: Municipal solid waste

OFMSW: organic fraction of municipal solid waste

RBD: Rotary bio-dryer

RTO: regenerative thermal oxidation