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### Application of circular economy principles in biowaste management

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#### **Abstract**

*In developed countries, biowaste management legislation is changing rapidly over the last 2 decades due to the growing environmental awareness in society. The main benefits from changes in biowaste processing pathways for corporations come from the improvement of the corporate social responsibility (CSR) image. In developing countries, the search for suitable technology is driven primarily by efforts to minimize processing costs. This paper summarizes the current global market situation and techno-economically assesses some promising trends. It is firstly proposed to sort biowaste into 3 different categories and to combine different wastes and methods of their treatment with each other. Applying circular principles and respecting conventional financial indicators seems to be more reasonable than maximizing the added value of products obtained. It is pointed out that applying circular principles and respecting conventional financial indicators seems to be more reasonable than maximizing the added value of products obtained.*

**Keywords:** circular economy; biowaste; techno-economic assessment; valuation

#### **1. Introduction**

The amount of biowaste is growing globally as more households move from low-income to lower- and middle-income class (Turkadze, 2021). Based on historical data, even 2 decades ago it was possible to generalize that large quantity of biowaste was linked to the lifestyles of the most affluent EU (Ignat and Constantin, 2021) and USA citizens (Awasthi et al., 2021), whereas in the USA the main emitter of greenhouse gases was the entire middle class (Goldstein et al., 2020). However, the sharp dynamics of population curves in developing countries (Kircher et al., 2023) and the increased pressure on the energy utilization of biowaste in the EU (Maurya and Misra, 2023) have caused that India and China tend to be the main producers of biowaste at the moment (Gul et al., 2022). In heavily populated countries, underdevelopment, poverty and corrupted public authorities are often cited as the main reason for irrational biowaste management (Mutatkar, 2020; Wang, 2020). The identification of new and perspective technologies that could minimize negative environmental impacts and turn the costs associated with biowaste management into profits are thus intensively in demand all over the world (Marousek et al., 2023a). However, most of the technologies proposed recently focus rather on obtaining products with the highest possible added value, without assessing the entire economics of the process and the technical context, including water

and energy consumption. For the sake of clarity, this review paper divides biowaste into 3 basic types: type (A) (biowaste composed mainly easily biodegradable organic matter with substances based on sugars, starch, easily hydrolysable hemicellulose etc.); type (B) (liquids rich in phosphate and nitrogen substances) and type (C) (hardly biodegradable organic matter composed of cellulose with a higher degree of crystallization, lignin, etc.).

Biowaste is still unsorted in most countries and the overall mixture obtained contains type (A) biowaste the range from 1 to 40 %; type (B) biowaste usually only in a concentration up to 1% and the type (C) biowaste in the range of 1 to 70%. The type (A) biowaste represents a valuable intake for most microorganisms and thus its level in the biowaste is almost constantly decreasing over time. Type (A) biowaste includes mainly food waste and post-harvest residues (straw, corn cobs, etc.). The type (A) is often refined into sugary hydrolysates which are subsequently used in the feed industry and, with an increased degree of hygiene, also in the food industry. Concept of these procedures was reviewed by Zhou et al. (2021). It is worth pointing out that sugar solutions can be fermented into a whole range of organic compounds (such as alcohols) that can be used as fuels (Wang et al., 2020). However, current research and development in this direction does not yet inspire hope for price competitiveness with fossil fuels.

The type (B) biowastes with reasonable levels of nutrients are hard to find as concentrations of key substances tend to be variable and chemically unstable. Most often, these are digestates, slurry, fermentation residues, whey and the like. These can be refined into ammonium sulfate; phosphate fertilizers; complex fertilizers; seed coating products and others. As recently reviewed by Deng and Dhar (2023), many alternatives to precipitation technologies can be used to capture phosphorous compounds, but emerging sorption technologies have an advantage in that the captured nutrients are more easily accessible to plant nutrition (Kopecky et al., 2020). As reviewed by Wu and Vaneeckhaute (2022), ammonia stripping is among the most frequently investigated ways to recycle nitrogen from wastewater, but the economic viability of this technological pathway is problematic. To make matters worse, (B) is often present in complex molecules at low concentrations which often require high energy cost for their release (Skare et al., 2021).

As far as type (C) biowaste is concerned, these are usually bulky and their processing can be energy-intensive (Zheng et al., 2021) which makes the products obtained problematically price-competitive (Akbari et al., 2021). Common type (C) biowastes include bark; sawdust; pruning; waste wood and similar waste materials with a high proportion of lignocellulose. The most common method of refining is pyrolysis, which transforms these feedstocks into gaseous, liquid and solid residues. In addition to energy use, the usual products include charcoal; tar; technical gases and biochar, while each of these outputs can be further refined into a spectrum of products with higher added value. Following the above, the development of conventional biowaste technologies is thus linked with public incentives into acquisition of modern technologies (Simkova et al., 2022); encouraging of corporate social responsibility (Habek et al., 2019); subsidizing energy prices (Yao et al., 2022) and legislation tightening (Gavurova et al., 2019).

The exponential growth of humanity, coupled with volatility of global economy and escalating trade tensions, underscores the urgent need for heightened food production and innovative solutions at the nexus of the food industry and biowaste management (Zeller et al., 2020). Increasing recognition of biowaste valorization's pivotal role in environmental sustainability is driving the implementation of stringent regulations and financial incentives to promote environmental protection, albeit met with reluctance from major economic powers fearing competitive disadvantage (Delgado et al., 2020). Addressing such challenges necessitates an interdisciplinary approach, with recent advancements in self-learning algorithms poised to substantially contribute to solving techno-economic issues (Kliestik et al., 2023). While agricultural subsidies dominate the environmental policy landscape in developing countries, environmental legislation in developing countries remains nascent. This dynamic necessitates the development of biowaste valuation technologies that are both ecologically sound and economically viable (Dvorsky et al., 2023). Achieving exceptional financial performance in this arena demands surpassing established technologies and leveraging synergies, with emphasis on consistent biowaste

quality and access to cost-effective waste energy sources. Stakeholders are actively pursuing economically viable technologies to enhance biowaste's value, focusing on nutrient recovery and organic matter enrichment. In connection with the above, the application of circular economy principles in biowaste management is a high priority of contemporary engineering.

## 2. Methodology

Patent (European Patent Office, United States Patent and Trademark Office, Japan Patent Office and Google Patent search tools) and Research (Cambridge Journals, EBSCOhost, Emerald Premier, Encyclopedia Britannica, IEEE Xplore, IOPscience, nature.com, Oxford English Dictionary, Oxford Journals, ProQuest Central, ProQuest EBook Central and ScienceDirect search tools) databases were searched via indexing tools for the following keywords (and its combinations): organic matter; hydrolysis; biowaste; nutrient regeneration; biowaste; circularity and valuation. Top 20 papers and patents from each database were reviewed for relevance. The identified technologies were subject to legislative and techno-economic considerations.

## 3. Results and Discussion

### 3.1. Established valorization methods

Over the past century, advancements in agricultural practices have led to a remarkable 3 fold increase in crop yields across various commodities. The increments in animal and fish production are two to four times more efficient than those reported a century ago. The remarkable advancements in agricultural productivity owe their success to a multifaceted approach encompassing traditional agricultural fields such as breeding, agrotechnics, and agrochemistry, particularly combined with applications stemming from industrialization; automation and robotization which are lately even booted by use of artificial intelligence (Kliestik et al., 2024). Despite remarkable advancements, global food systems still face significant challenges (Stehel et al., 2018). In developed countries, around 5% of fruits and 2% of vegetables are wasted, a figure that doubles or triples in developing regions. When it comes to animal products, the waste issue is almost consistent globally. It's estimated that over 2% of meat from livestock and poultry is wasted, along with nearly 3% of fish products. This waste is largely attributed to limited markets for byproducts like tongue, wings, lungs, heart, runners, kidneys, fins, or spleen for human consumption, particularly in developed countries.

The cost affordability of food varies extensively among countries as never before in extant records (Strunecky et al., 2021). As a result, health systems in rich countries face problems linked with obesity and related diseases while other countries cry for help because of malnutrition from food deprivation (Kopecky et al., 2020). However, intensive agricultural production that is driven by short-term profit is being accompanied by deforestation; a decrease in wildlife; soil erosion and loss of fertility;

contamination of water bodies with agrochemicals, and the release of greenhouse gases. Following the above, there is a general consensus that global food demand will further increase by more than 40 % in 2050 relative to 2020 (Tian et al., 2021). However, limited water and land resources altogether with climate change impacts do not match with increased food demands. Existing models indicate that the growth rate of crop production will slow down, the yield of main crops will stagnate, and biodiversity losses and environmental degradation will intensify. Critical situations can be expected, particularly in protein supply for human nutrition. It seems that the meat production (particularly poultry; pig; veal and fish) would not be able to increase sufficiently in the future to fill the meat gap demand due to lacking feed production and insufficient land area even though abandoned farmland is used in developed countries (Hall, 2018). In addition, to crops and livestock, the oceans are the critical source of protein, supplying one third of global meat demand. However, its overexploitation would probably take its toll and limit further accessibility of ocean protein. Finite food sources necessitate both to find out the alternative means of production as well as decrease its wasting. Higher efficiency in animal husbandry amended by the progress in genetic engineering of livestock (Lee et al., 2020) or production of artificial meat might solve the meat demand only partially because, in the end, all of them have a high demand for energy and nutrients.

The overwhelming majority of reviewed documents agrees that the main schism is that the contemporary food production industry has deeply incorporated unsustainable elements into its daily operations in the pursuit of increased profits (Habek, et al., 2019). On the other hand, given that plethora of unsustainable moments have been incorporated into the daily activities of all mankind, there are several options with untapped potential. Better processing of biodegradable waste (including that from landfills or sewage treatment plants) is widely agreed to be the biggest opportunity with many technological solutions available and under development. The increasing wealth simultaneously with natural humankind's greed to gather resources is, most probably, not to decrease in coming years. Currently, over 52 % of the overall global municipal waste is food waste, whereas, calculated per person, the vast majority of waste is mainly produced by less technologically developed countries (Xue et al., 2017). Avoidable losses occur due to inefficient food processing, inadequate preparation techniques, suboptimal logistics, and improper storage, including the expiration of shelf life and similar factors. It was highlighted that in undeveloped retail and consumer stages of developed countries, over 41% of food is wasted. In contrast, developing countries generate eight times more food waste in the early stages of the food supply chain compared to developed nations (Dvorak et al., 2018). It is anticipated that in the coming years, Asia will generate more than 520 million tons of biowaste. Consequently, the valorization of biowaste presents a colossal economic and environmental challenge, its resolution jeopardized by various socio-economic factors, particularly in developing countries.

There is a broad consensus regarding the high energy potential of food waste. However, when selecting the ap-

propriate technology, three key concerns should be considered based on the current state of knowledge. Firstly, it is crucial to distinguish between easily and less easily decomposable organic matter. Secondly, one should bear in mind that certain technologies might hinder the subsequent regeneration of nutrients. When it comes to processing more easily biodegradable waste, numerous technological options exist. In developed countries, biowaste is commonly processed through anaerobic digestion, which produces biogas for electricity, or it undergoes composting to create a soil conditioner (distinct from fertilizer due to its low levels of nitrogen and phosphorus readily available for plant nutrition). However, both of these publicly supported technologies come with significant drawbacks. In many countries, the residual material from anaerobic digestion of biowaste is subject to stringent regulations, and its disposal onto arable land is often economically unfeasible. The alternative, aerobic composting, entails converting food waste into humic compounds or stabilizing it with a soil mixture to create organo-mineral associates. Nevertheless, composting has substantial disadvantages, including significant loss of organic carbon as CO<sub>2</sub> (Svajlenka and Marouskova, 2023) and substantial nitrogen loss, which amount to as much as 62%, during the composting process. Moreover, the resulting compost contains minimal quantities of labile organic compounds strongly impairing its fertilizing properties. The primary advantage of compost lies in its ability to enhance the qualitative aspects of soil organic matter and improve soil's air and water management. However, the economic evaluation of these benefits can be challenging. In developed countries, farmers' demand for compost is generally low because achieving a demonstrably quantifiable fertilizing effect requires the application of substantial quantities of compost to the fields, resulting in disproportionately high costs. Although the obligation to operate sewage treatment plants has significantly improved the quality of water bodies in developed countries, the related legislation has set the rules so controversially that the management of sewage sludge is not sustainable. In its present state, critical phosphorus is mostly precipitated by iron or aluminum salts into minerals such as struvite or vivianite, which is the cheapest way of its capture. However, these minerals integrate phosphorus so firmly into their crystals that it is difficult for living organisms to access. A better way is when phosphorus is captured by sorption processes on charred waste, but current legislation is still not adapted to this technological leap. In addition to minerals, sewage sludge still contains significant amounts of hardly biodegradable organic matter (Brabenec et al., 2021). Its decomposability can be increased physically (intracellular disintegration) or thermochemically (steam explosion) so that it can be used by anaerobic digestion consortia for additional biogas production or, for example, by insects.

However, recent literature and patent documents suggest that the most profitable method for evaluating biowaste with higher labile organic matter content is through insect utilization that can be turned into valuable source of protein and fat. The attention is currently turned to growing insects for mass consumption (van Huis et al., 2013). The idea of insect utilization is old, honeybees (*Apis mellifera*) and silkworms (*Bombix mori*) supply mankind for more

than three thousand years. Larvae and adult insects are part of diet in many communities at the Africa and Asia due to high energetic content value. The high nutritional value and exceptionally high protein content (Rumpold and Schluter, 2013) connected with high resource efficiency to convert organic matter into protein (Nakagaki and DeFoliart, 1991). The efficiency of protein production via insect might be higher than that of any recently cultivated livestock. This approach offers a promising solution to counter pessimistic forecasts of future protein shortages (Wang et al., 2020) especially considering the projected doubling of protein consumption (by 196 %) by 2050 (Berners-Lee et al., 2018). While the previous solution was seen in lowering the protein consumption and adjusting the diet structure with a preference for a plant-based diet, the new option would be to use insects as feed or directly for human consumption (Marousek et al., 2023b). The necessary change in biowaste utilization might be its management by biological means.

Mass intensive insect rearing will be needed for large-scale production at levels dwarfing the current wild-harvest and small-scale production (Berggren et al. 2019). Food safety agencies all around the world tends to allow production of yellow mealworm (*Tenebrio molitor*), locusts (*Locusta migratoria*) and house crickets (*Acheta domesticus*) for human consumption lately. Including these ones, many other insects such as black soldier fly (*Hermetia illucens*), common housefly (*Musca domestica*), lesser mealworm (*Alphitobius diaperinus*), banded cricket (*Grylloides sigillatus*) and field cricket (*Gryllus assimilis*) are being approved as feed especially for poultry, aquaculture, pets and pigs. The mealworm beetle (*Tenebrio molitor*) is commonly used for research purposes, and its larvae, yellow mealworm has the reputation of promising feed for majority of farmed animals. Mealworm cultivation is well established on a semi-industrial scale, being easily reared on oat flakes. Every 1 kg of raw mealworm larvae contains some 8.8 kJ, nearly 210 g of protein and 230 g of fat respectively (EFSA, 2021a). Commercial projects produce between 110 and 460 g of insects per 1 kg of biowaste, with conversion efficiency correlating most strongly with the nutritional value of the biowaste (Vochozka and Marouskova, 2018). Vast number of substrates was assessed for the production of mealworm, however, as its name suggests, larvae prefer similar food sources to humans. Flakes of various compositions showed the highest efficiency with a conversion ratio around 11 % (Rumbos et al., 2020). Beer yeast, pastry remains, spent grains and potato steam peelings showed the best efficiency (nearly 29 % conversion) in mealworm rearing (van Broekhoven et al., 2015). Other studies revealed that mealworm larvae fed on low-energy biowaste had the conversion feed efficiency below 1 % (Tan et al., 2018). The mean larvae development time ranged between 95 and 122 days independently on the diet. Migratory locust (*Locusta migratoria*) is infamously known to make huge swarms affecting extensive areas in warm climates, particularly in Africa. Locusts in nature feed on green parts of graminoids as different grass species, reeds, and cereals. However, as their population grows, they transition from a solitary phase to a gregarious phase, leading to insect plagues that can devastate not only legumes but also other plants. Prod-

ucts from locust larvae have high crude protein content between 43% and 54%, a well-balanced amino acid profile (EFSA, 2021b) and a production cycle within 21 days. Moreover, existing know-how on rearing and commercial scale for pet food or even human nutrition is well established. House crickets (*Acheta domesticus*) are spread worldwide in warmer areas. At 30–35 °C crickets can pass the entire cultivation cycle within 20 days (Clifford and Woodring, 1990). House crickets are omnivorous, feeding on leaves, seeds, fruit, other live or dead insects, including cannibalization (Sorjonen et al., (2019). House cricket rearing shows to be the techno-economical optimum for valorization of soya byproducts and barley leftovers. Two other crickets (banded cricket - *Grylloides sigillatus* and field cricket *Gryllus assimilis*) of tropical origin might be used in feed production. The other species of crickets are currently accepted for feed production. Common housefly (*Musca domestica*) is a commensal insect associated with humans worldwide. Its larvae can thrive on a wide range of decaying biowaste. Housefly larvae are considered as a solution to process manure produced by concentrated animal facilities around the globe (Miranda et al. 2019). Housefly rearing can reduce nitrogen concentration in manure by 23 up to 77% and recover up to 25%, of dry matter (Roffeis et al., 2015). Lesser mealworm (*Alphitobius diaperinus*) is a tropical insect that thrives in warm, humid environments. It is one of the most common insect pests in commercial poultry farms feeding on poultry manure, spilled feed, and other organic material. However, mealworm might serve as a vector for many pathogens that cause serious diseases, such as *salmonella*, *escherichia*, and various viruses. Nevertheless, mealworm can also be used as an aquafeed ingredient, turning the insect from a noxious pest to a valuable nutrient source (van Broekhoven et al., 2015).

All the reviewed literature agrees that the black soldier fly (*Hermetia illucens*) has currently the highest industrial potential for mass rearing because its larvae are the easiest to separate from biowaste on a commercial scale. The larvae of black soldier fly are capable to develop on various biowaste (preferably fermented cereals; manure and food waste) while converting 15 up to 48 % of it into its body in usually less than 5 weeks (Ganda et al., 2019; Rehman et al., 2017). The metabolic residues of black soldier fly larvae are called frass and there is a big demand for these on the decorative flower market (Gligorescu et al. 2020). Converting 1 kg of biowaste into black soldier fly and frass to reduces release of NH<sub>3</sub> nearly 205 times and N<sub>2</sub>O over 980 times in comparison to composting (Pang et al. 2020). The high efficiency of biowaste conversion into insects is usually influenced by optimal feedstock composition, particularly crude protein in formulas was between 30-40%, which is rare even in some of the most energy-rich types of biowaste. The highest efficiency of biowaste conversion (above 41 %) was reported for mealworms. The black soldier fly larvae maximal biowaste conversion match to most efficient insects. Gärtling and Schulz (2022) summarized the nutrient content in frass from literature and industrial producers of black soldier fly products. Data from 24 sources (dry matter of frass ranged from 67 to 79 %) showed that total nitrogen (N<sub>tot</sub>) was on average 3 % of dry matter, with C<sub>tot</sub> : N<sub>tot</sub> ratio of 14.7.

The level of phosphorus P was usually between 1 and 2%, while the potassium level was usually half of that. The magnesium and calcium content are usually around 1%. These values are close to old manure, and it can be argued that frass from black soldier fly can be understood as soil improver with some long-term fertilization capabilities (Schreefel et al., 2020). As low as the content of mineralized nutrient is in frass is (in comparison to established mineral fertilizers) given the current societal trends, frass is a highly marketable commodity and many commercial projects are finding success with it in the hobby and gardening segment (Anyega et al. 2021).

The other promising alternative are fungi. Fungi are considered a viable alternative to produce high-quality protein that can be further used to substitute meat (Bonny et al. 2017). However, producing stable-quality fungal protein from biowaste appears to be extremely challenging. The main constrain is the quality assurance due to natural fungal inoculum in biowaste that would produce harmful mycotoxins due to inconsistencies in feedstock properties which are a common source of contamination vectors (Xing et al. 2019). To evade this issue, all the food waste must be deeply sterilized with high energetic costs. Regarding pyrolysis, all the economic and technological considerations across the reviewed documents indicate that the potential of pyrolysis processes remains largely untapped, particularly if it is part of a complex refining process. There is a broad consensus that the production of char or biochar represents the viable technology for treating hardly degradable solid biowaste. Nevertheless, from an economic point of view, it should be noted that it is necessary to look for biochar applications that are more lucrative than its energy use otherwise producers will prefer to sell it as energy commodity. Pyrolysis of biowaste often needs significant energy investment since many biowaste feedstocks are excessively wet or contain high levels of minerals, necessitating external energy sources. Currently, the most cost-effective method for producing biochar is based on the approach proposed by Stehel et al. (2020), which involves pyrolyzing fermentation residues from biogas plants and utilizing waste heat from a cogeneration unit that burns biogas for electricity. This concept involves using the low-potential waste heat from the combustion engine and the pyrolysis chamber to dry the mechanically dewatered fermentation residues, while the hot flue gas from biogas combustion contributes to the energy balance of the pyrolysis chamber.

The resulting biochar consists of crumbly pyrolytic structures with a carbonaceous nature, intended for use in plant production, soil enhancement, nutrient recovery, and environmental engineering in general. In addition to its agronomic benefits and soil improvement characteristics, all the reviewed documents have consistently concluded that the properties of biochar make it an outstanding tool for carbon sequestration. Its high porosity reduces material density, making it suitable as a substitute for sand in the production of lightweight concrete (Marousek et al., 2023a). The substantial porosity of biochar also makes it an excellent sorbent, capable of filtering microorganisms present in liquid forms of organic matter without further treatment. However, it should be noted that during the py-

rolysis process, the majority of nitrogen is converted into a mixture of pyrolytic gases, and no economically sustainable technology has yet been defined for regenerating these gases into chemical forms suitable for fertilizing agricultural crops. Therefore, it is recommended to recover nitrogen into ammonium nitrate or sulfate before using the feedstock as raw material for the pyrolysis process (Menkveld and Broeders, 2018). From an environmental perspective, equipping the chimney of the pyrolysis unit with a water filter is advantageous, as it captures the finest soot particles and allows them to be further used for special applications.

Following the biochar production, it can be employed to recover phosphorus. To enhance the sorption capacity of biochar while maintaining cost-effectiveness, it is advisable to activate biochar using calcium fertilizers (Figure 2). As far as activation by calcium fertilizers, the highest phosphorus sorption rates are reported for biochars made from coconut shells and hardwoods, which are materials where high porosity can be expected. However, taking into account the economic side of the matter, the best results are nowadays achieved with feedstocks such as digestates or distillery stillages, the production price of which is many times lower. The cost of this activation is negligible, as calcium is an essential component for crop production. Subsequently, the modified biochar can effectively capture phosphorus in forms readily accessible for plant nutrition.

### 3.2 Assessment of type (A) biowaste management methods

As far as the processing of type (A) biowaste (containing rather organic matter that is more easily hydrolyzable by usual enzymes at normal conditions) is concerned, anaerobic digestion is the dominant technology in the field for several decades already (Bencooova et al., 2021), whereas biomethane (purified biogas) is the latest trend which expands the possibilities of biogas use into transport, industry and other sectors, including injection into ordinary gas pipelines. The European biogas sector is the fastest growing in the world and currently generates more than 21 billion m<sup>3</sup> of gas (both biogas and biomethane) and nearly 300 000 jobs (europeanbiogas.eu). For the year 2030, a target of 35 trillion m<sup>3</sup> has been set. Nevertheless, if mainly the purposefully grown phytomass was used to produce such a high amount of biogas, this could have negative environmental and economic consequences in the long term. It seems advantageous to diversify the feedstock and also process the type (A) biowaste so that less agrochemicals are used. However, biowaste of type (A) is most often based on lignocellulose, whose natural biological decomposition in an anaerobic environment usually takes more than 2 months. Nevertheless, the residence time in the fermenter is a key technical indicator that demonstrates direct financial implications since it can prolong the return on investment payback period of usual biogas station (1 MW of electricity + 0.8 MW of heat; investment of 2 M€) by 1 up to 3 years (Vochozka et al., 2018). For economic reasons, biogas stations processing biowaste of type (A) most often install technologies of deep disintegration of plant matter such as steam-explosion, milling,



Fig. 1: *Jean pain* composting represents a low-cost method of heat production whereas a pile (4x4x4m) of type (B) biowaste can serve for family home or small business all winter long. The right section of the image shows an infrared image, where scan "A" indicates temperatures in the center of the pile (discharged to the house) are satisfactorily above 40°C and scan "B" indicates that after coming from the house heating circuit, the process fluid is returning at a temperature below 20°C.

pressure shockwaves or enzymatic hydrolysis (Marousek et al., 2013a, b). Repeated attempts were made to use (A) in composting. However, the demand for composts is low and allows only minimalist profits (Murindangabo et al., 2023). A wide range of fermentation technologies can be found in the literature, which demonstrated the possibility of turning type (A) biowaste into hydrogen (Sarangi and Nanda, 2020); alcohols (De Buck et al., 2020); organic acids (Tsapekos et al., 2020) and other reactants such as aldehydes. Although all these products are usually of high value, the whole concept is hardly economically viable (costly reactants, high energy requirements etc.) which casts a negative light on other biorefining technologies in general (Pavolova et al., 2021). Groeneveld et al. (2021) pointed out that the biotransformation of type (A) biowaste via insect rearing has promising financial potential. The obtained larvae can be used not only as feed with a high content of valuable feed substances but can also be processed into a whole range of products based on protein and fat (Marousek et al., 2023c). *Jean pain* composting (Fig. 1) of type (A) biowaste has an ever-growing fan base since it allows to produce low-potential heat (40 to 70 °C) for 2 up to 5 months and is thus one of the cheapest sources of heat in the temperate and climatic cold zones. A summary of the above findings is shown in Table 1.

### 3.3 Assessment of type (B) biowaste management methods

Regarding the valuation of biowaste with a significant share (B), it is worth noting that there is currently a shift from precipitation technologies (such as production of struvite, vivianite and like) that were designed in the last century to modern sorption-based technologies (Priya et al., 2022). Modern sorption technologies most often use biochar as a sorbent, which is usually made from biowaste type (C), so there are different synergies between different wastes. It is worth remembering that biochar is a way of

carbon sequestration, which can represent additional economic synergies. Even the modern sorption technologies for (B) type biowaste processing, however, do not show good profitability (Bartos et al., 2021), because as regards phosphorus, they compete with imports of fossil minerals (Simkova et al., 2019) and as regards the regeneration of nitrogenous substances, they compete with Fischer-Tropsch synthesis (Chen et al., 2021), whose production costs depend primarily on the prices of catalysts (Novakova et al., 2022; Rowland et al., 2021) and especially energy (Vochozka et al., 2020a).

### 3.4 Assessment of type (C) biowaste management methods

Incineration is the traditional way to deal with the type (C) biowaste. Although the demand for energy is constantly growing (Vochozka et al., 2020b), modern methods of type (C) biowaste regeneration are also coming to the fore. Recently, many research activities have been devoted to pyrolysis and torrefaction, especially in connection with use in agriculture (Ghorbani et al., 2023) and civil engineering (Marousek et al., 2023b). In this segment as well, countless technologies can be found that allow the type (C) biowaste to be refined into a whole constellation of commodities with high added value, such as Bishenol A (Shah et al., 2021); furfural (Sherif et al., 2021), pigments for pains (Bhakare et al., 2020); sorbents (Binh et al., 2022) and many others. However, simulation modeling by digital twins of material and energy flows (Valaskova et al., 2024) indicate that such refining pathways do not tend to improve the corporate performance (Valaskova et al., 2023). However, customers remains skeptical of biowaste refining because, unlike fossil fuels, the type (A) biowaste is hardly available in constant quality throughout the year.

**Table 1.** A simplified summary of economic and environmental perspectives with regard to the current state of the global market.

Feedstock	Technology	Products	Economic sustainability	Environmental sustainability
A	hydrolysis	sugars	good	high
A	fermentation	alcohols	unsustainable	N/A
A	fermentation	biogas	good	good
A	biocatalysis	aldehydes	good	good
A	composting	compost	low	good
A	pyrolysis	biodiesel	unsustainable	N/A
A	fermentation	hydrogen	unsustainable	N/A
A	Jean Pain	heat	good	high
A	fermentation	organic acids	good	high
A	rearing	insects	high	high
B	precipitation	phosphate minerals	unsustainable	N/A
B	sorption	phosphates	good	high
B	mixing	ammonium sulfate	low	high
B	mixing	ammonium nitrate	good	high
C	pyrolysis	charcoal	low	high
C	pyrolysis	tar products	low	good
C	combustion	energy	low	good
C	pyrolysis	gases	low	low
C	pyrolysis	biochar	good	high
C	combustion	ash	low	good
C	pyrolysis	cement substitutes	good	high

#### 4. Conclusions

In order to improve the economy of biowaste management it is proposed to sort biowaste according to the quality of organic matter and nutrient content into several basic categories (analogous to solid waste, where metals, paper, plastics, etc. are sorted, for example). Furthermore, it is advisable to deviate from the complex refining of products with the highest possible added value and choose refining pathways with regard to the variability and year-round availability of biowaste with established indicators of financial performance in mind.

Insect rearing and Jean Pain composting appears to be the most efficient methods of the type (A) biowaste management at the moment. Fungi cultivation hold promising potential for the near future, yet the challenge lies in mastering the technology to ensure both robustness and the elimination of toxic metabolites in mass fungi production. Regarding the type (B) biowaste, sorption of phosphate on biochar and refining of ammonium nitrated seems to be the most promising at the moment. However, both technologies still face some challenges as far as mass commercialization is concerned.

Regarding type (C) biowaste, the most reasonable valorization technology is pyrolysis, whereas use of the most profitable use seems to be production of specialized biochar applications and cement substitutes.

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