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Vea, Eldbjørg Blikra; Romeo, Daina; Thomsen, Marianne

Published in:
Procedia CIRP

DOI:
10.1016/j.procir.2017.11.062

Publication date:
2018

Document version
Publisher's PDF, also known as Version of record

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Citation for published version (APA):
Biowaste valorisation in a future circular bioeconomy
Eldbjørg Blikra Vea, Daina Romeo, Marianne Thomsen*
*Department of Environmental Science, Aarhus University, Frederiksbergvej 399, DK-4000, Roskilde, Denmark

Abstract
The biowaste refinery concept has received significant attention in recent years as a sustainable alternative to the petroleum refinery, exploiting the biowaste for producing high value bioproducts. However, waste-based biorefineries mainly apply homogeneous waste streams from agriculture and food processing as feedstock. This paper presents the state of the art of mixed-biowaste biorefinery concepts. We identified 20 studies that use the organic fraction of municipal solid waste (OFMSW) as feedstock, producing enzymes, bioplastics, biopesticides and other high value products. Valorisation efficiency (output product per kg OFMSW) and potential revenue by valorising the OFMSW into different products (Euro/ton OFMSW) was analysed for the identified studies. It was found that enzymes have the highest potential revenue followed by biopesticides and bioplastics. Developing biorefineries applying OFMSW as feedstock presents a promising opportunity for moving up the waste hierarchy by coupling the waste and production sector in a future circular bioeconomy.

Keywords: Circular economy; biorefinery; municipal biowaste valorisation; valorisation efficiency

1. Introduction
One of the major challenges humanity faces today is the increasing generation of solid waste. This is a result of the linear economy and a growing urban population. Circular economy has gained attention as a key concept for developing closed-loop technical and biological cycles [1]. In a closed-loop system, also referred to as cradle-to-cradle concept, materials are either recycled indefinitely with no degradation of their properties or returned to the natural ecosystem with no harm to the environment [2].

Rethinking our economic system and implementing circular resource management systems will help mitigate the pressing problem of urban waste management and the limited availability of resources. The scarcity of resources will increase in the future and the ability to recover and manage these resources will become essential for a sustainable global economy [3]. A coupling between waste and production sectors is needed to secure a sustainable development; this can be obtained by applying waste fractions as input to industrial production systems according to the concept of industrial ecology. This paper addresses such coupling with the focus on biowaste and its transformation to resources.

In EU in 2015, 241 million tonnes of municipal solid waste were generated [4], whereof 40-60 % is organic waste [5]. Organic waste has high moisture and salt content, leading to rapid decomposition and unpleasant odours [6]. Moreover, it can generate greenhouse gas emissions, leachate and sanitary problems if not managed properly. However, it also represents a great resource for renewable energy production and for providing added-value products such as organic fertilizers, biopesticides and bioplastics [3, 5, 7, 8]. Technologies that apply biomass as a feedstock for producing bio-based products are referred to as biorefineries. Waste-based biorefinery concepts using side streams from agriculture or food processing e.g. from bakeries and breweries have received significant attention in recent years. Although a number of review papers have been published on biorefinery of...
biomass from agriculture and food processing waste, e.g. [7, 9, 10], a review of studies with a specific focus on OFMSW as feedstock is still missing. Furthermore, research should also focus on identifying the most optimal food-waste biorefinery output products and processes from an environmental and economic point of view [11].

This paper will focus on organic fraction of municipal solid waste (OFMSW) as feedstock to biorefineries and its role in a future bio-based circular economy. It will contribute with reviewing existing OFMSW biorefinery concepts with the objective to deliver an overview of the valorisation efficiency and potential revenues of different valorisation pathways of OFMSW. This goal is fulfilled by 1) identifying studies that apply the OFMSW as feedstock to produce high value products (i.e. beyond bioenergy and fertilizer) 2) addressing the conversion efficiency (return of bio-based products into the economic system) of the identified studies and 3) analysing potential revenues for future biowaste biorefinery systems.

2. Method

A literature review was conducted to identify research applying mixed organic waste streams from households, restaurants and canteens (i.e. OFMSW) as feedstock for biorefineries. The scope of the review was limited to literature reported in English and published after 2010. The review only concerns the OFMSW (defined as mixed biological waste from households, restaurants and canteens). In other words, the review does not include homogeneous organic side streams from food processing or agricultural waste. The most common valorisation processes of OFMSW include the production of energy fuels (ethanol, methane and hydrogen) [12] and organic acids extracted from volatile fatty acids (VFA) [13]. However, this review only considers studies going beyond these already established biorefinery technologies, and considers the whole valorisation process from OFMSW to high value biomaterials (e.g. from OFMSW to VFAs further converting the VFAs to bioplastics via PHA accumulating mixed cultures).

Scientific literature is identified through the search engine Scopus applying key words such as “high value products”, “organic waste”, “food waste”, “bioplastics”, “biorefiner”, “organic fraction of municipal solid waste” and “PHA”. The conversion efficiency (e.g. kg output product/kg OFMSW input) of each study was estimated based on data available in the studies and applying conversion factors from literature where necessary. The unit of the conversion efficiency depends on the type of products produced. The potential revenues of the identified products per dry weight (DW) input feedstock (Euro/tonnes OFMSW DW) were estimated from the valorisation efficiency (kg output/kg input) and data on market prices.

3. State of the art of a bio-based circular economy in Europe

3.1. Strategies and legislation – moving up the waste hierarchy

The waste hierarchy established in the Waste Framework directive (EU directive 2008/98/EC) is the main policy for waste management in EU. The waste hierarchy promotes waste preventions as the highest priority followed by reuse and recycling. In terms of biowaste, incineration with energy recovery is still a usual practice in EU. If incinerated with energy recovery, the opportunity to extract valuable bioproducts is lost [12]. Furthermore, the high water content prevents an increase in incinerator temperature resulting in lowered reduction and destruction efficiency and hence risk of increased formation and emission of persistent organic pollutants [14, 15]. Thus, biowaste incineration should be prevented as far as possible and its management should be shifted further up the waste hierarchy to recycling and re-use of the biowaste resource for bio-based production.

Strong policies and supportive regulatory instruments are needed to further decrease the generation of biowaste and increase the re-use and recycling of materials. In 2014, the European Union introduced a circular economy strategy aiming to push the dominant linear economic strategy of “take, make and dispose” towards a more circular resource management approach. Targets of 70% reuse and recycling and eliminating landfill by 2030 are proposed [16]. The circular economy strategy goes beyond the waste hierarchy by designing circular resource flows at regional and global level and between industries [17]. The circular economy strategy brings the waste hierarchy and the bioeconomy together [16], where the bioeconomy concentrates on the conversion of renewable carbon reserves from agricultural or forestry biomass and organic wastes into different products and materials [18]. Transition to a circular economy will require changes in the whole value chain; in product design identifying new methods turning waste into products, new business and market models and changes in consumer behaviour [16]. These systemic changes will be relevant for converting biowaste into a resource including the sorting habits of the consumers and new market models for the use of the new products.

3.2. The biorefinery concept

The concept of biorefineries encompasses integrated bio-based industries valorising the whole biomass applying a range of different technologies [19]. A biorefinery is analogue with the petroleum refinery where crude oil is segregated into various products such as fuels and raw materials for petrochemical industry [20]. The biorefinery concept based on mixed feedstock such as OFMSW (including restaurant and kitchen waste) is less developed than applying homogeneous feedstock from industry and agriculture. Due to the mixed nature of OFMSW, the composition is complex and is chemically composed of starch, cellulose, protein, fats, lipids, and other organic matter [6]. A biorefinery process can be adapted to handle specific feedstock-related problems, but variations in the feedstock properties may be challenging [21]. This can explain why the use of OFMSW in biorefineries is less studied. Nonetheless, this review identified 20 studies applying the mixed OFMSW as feedstock for the production of high value products (Table 1).

No industrial scale OFMSW biorefineries were identified. The lack of industrial scale facilities is also recognised for food processing and agriculture waste biorefineries [8, 9].
Three studies producing potential high value products other than bioplastics, biopesticides and enzymes were identified (Table 1). These studies produced probiotic in animal feed, graphic carbon and plasticizers. In the following sections, the studies in Table 1 producing bioplastics, biopesticides and enzymes will be discussed based on product produced, methods used and the valorisation efficiency.

3.3. Bioplastics produced from OFMSW

In addition to being produced by a non-renewable and environmentally burdensome resource, the use of petroleum-based plastics has led to problems in the management of solid waste. Bio-based and biodegradable plastics such as polyhydroxyalkanoates (PHAs) provide an interesting alternative. However, the substrates used in the established industrial PHA production are sugar-based compounds with a high market value. This makes the use of low-value-substrates such as the OFMSW interesting [27].

We identified seven studies producing bioplastics by synthesizing organic acids from OFMSW (Table 1). In general, the results obtained are promising, however the process needs to be further optimised [22–24]. With the exception of [23], all studies applied similar procedures; first the OFMSW was

<table>
<thead>
<tr>
<th>Refere nee</th>
<th>Method and experiment set-up</th>
<th>Main product</th>
<th>Side stream valorisation</th>
<th>Valorisation efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>[22]</td>
<td>(i) acidogenic fermentation (ii) Culture enrichment (C. necator CCGUG 52238) (iii) PHA production in fed-batch reactor (7 L)</td>
<td>PHA</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>[23]</td>
<td>(i) acidogenic fermentation producing lactic acid (ii) lacticide synthesis by zinc oxide nanoparticle as catalyst (250 ml flask) and purification (iii) PLA polymerisation (iii) PLA fibre production</td>
<td>PLA fibre</td>
<td>No</td>
<td>115.0</td>
</tr>
<tr>
<td>[24]</td>
<td>(i) acidogenic fermentation and H2 production (4.5L reactor) (ii) Culture enrichment (10/13L reactor) (iii) PHA production (4.5 L reactor)</td>
<td>PHA (PHB and PHV)</td>
<td>H2, wastewater remediation</td>
<td>93.3, 115.0</td>
</tr>
<tr>
<td>[25]</td>
<td>(i) dark fermentation and bioH2 production (1 L reactor) (ii) Culture enrichment (aerobic mixed) (iii) PHA production in 4 sequential batch reactors (250 ml) in aerobic and anoxic microenvironments</td>
<td>PHA (PHB and PHV)</td>
<td>H2</td>
<td>-</td>
</tr>
<tr>
<td>[26]</td>
<td>(i) acidogenic fermentation (500 ml flask) (ii) culture selection (E. coli pmDTM2) (iii) PHA accumulation in fed-batch reactor (2L)</td>
<td>PHA (PHB polymer type)</td>
<td>No</td>
<td>22.4</td>
</tr>
<tr>
<td>[27]</td>
<td>(i) acidogenic fermentation (2 L reactor) (ii) culture selection (C. necator H16 PHB) (iii) PHA accumulation (1.5 L reactor). Continuous feeding.</td>
<td>PHA (PHB polymer type)</td>
<td>No</td>
<td>27.4</td>
</tr>
<tr>
<td>[28]</td>
<td>(i) acidogenic fermentation (0.36 m3 continuous reactor) (ii) culture enrichment (3 L sequencing batch reactor) (iii) VFA rich effluent used for PHA production adding propionate (500 ml flasks)</td>
<td>PHA</td>
<td>No</td>
<td>23.9</td>
</tr>
</tbody>
</table>

| Bioprosticides | | |
|-----------------|----------------------------------|------------------|-------------------|
| [29]            | Semi-solid fermentation (200 - 250 ml flasks) | Bacillus thuringiensis | 9.30E+14          |
| [30]            | Solid state fermentation (SSF) (15 L reactor) | Bacillus thuringiensis | 1.60E+14          |
| [31]            | Anaerobic digestion (AD) followed by SSF (10 L reactor) | Bacillus thuringiensis | 2.63E+12          |

| Enzymes | | |
|-----------------|----------------------------------|------------------|-------------------|
| [33] Aspergillus niger C-5 used in SSF | Cellulase | No | 1.95E+05 |
| [34] Aspergillus niger NS-2 used in SSF | Cellulase | No | 9.08E+04 |
| [35] Trichoderma reesei and Aspergillus niger in SSF | Cellulase | No | 1.14E+05 |
| [36] Two-stage solid AD using the mutant eubacterium strain Cellulomomas flavigena PR-22 | Xylanase and Cellulase | No | 3.07E+06 |
| [37] Production of holocellulases from the cellulosytic microorganisms Cellulomomas flavigera PR-22 and Trichoderma reesei MCG 80 | Holocellulases | No | - |
| [38] Aspergillus niger UV-60 used in SSF | Glucoamylase | No | 1.84E+06 |

| Other | | |
|-----------------|----------------------------------|------------------|-------------------|
| [39] Liquid, semi-solid and solid state fermentation tested at both aerobic and anaerobic conditions. Bench scale (15 kg kitchen waste) | Probiotics in animal feed | N | 2.65E+10 |
| [40] AD with low temperature microwave plasma and purification. Tranforming biogas to highly graphic carbon and renewable H2 | Graphitic carbon (GC) | H2 | 0.5%GC, 0.2% H2 |
| [41] Oxidation of double bounds of methylated unsaturated fatty acids with in situ generated peroxyformic acid | Plasticizer | Fatty acid methyl esters | 52 (g/kg dw) |

*Calculation based on PHA per dry cell weight (g PHA/g DCW), DCW per liter (g DCW/L) and COD per liter (g COD/L), assuming 0.9 g COD/g dw food waste, and 0.5 dissolved COD (CODs) [48].Applied conversion factor 0.63 TSS/TS from [25].Applied density of the OFMSW of 1.052 kg/L [49].

Calculation based on produced digestate from OFMSW of 0.862 TSS/TS, a biogas potential of 120 m3/t/on food waste, and biogas in normal conditions (density 1.15 kg/m3) [50].Applied conversion factor 0.228 dw/ww of food waste [48]. Applied conversion factor 0.228 dw/ww of food waste [48] and 0.01 kg food waste/L water [37]. Applied conversion factor 130 g lipids/ kg food waste [51].
fermented followed by a culture selection (the PHA-producing species). Lastly, the liquid effluent containing the organic acids of the initial fermentation was combined with the microbial culture, producing and accumulating PHA. All studies produced the polymer PHA (polyhydroxyalkanoates) consisting of it co-polymers PHB and PHV. However, the studies differed in terms of microbial cultures and size.

Moreover, the studies tested different strategies when optimizing the process and increasing the efficiency of PHA production. E.g. different regimens for feeding the fermentation liquid were tested in Hafuka et al. [27], revealing that a continuous-feeding regime had the highest yield. Wu et al. [28] found that enriching PHA-accumulating cultures with propionate-rich substrates increased the PHA production. Amulya et al. [24] tested different operating conditions on enrichment and PHA production finding that the cycle length is an important factor for PHA production and composition. However, further research should focus on analysing other strategies for enhancing the yield.

Two studies aimed to valorise side-stream products (H₂) and provide additional service of waste water remediation [24, 25]. These are the only studies that present a biorefinery concept for bioplastic production of OFMSW as feedstock. This shows that the concept is still in its early stages where most studies focus on optimising the output of the main material.

The valorisation efficiencies were successfully estimated for five studies ranging from 27 – 115 g/kg OFMSWDW. The application of zinc oxide nanoparticles as catalyst for the synthesis showed to produce the highest yields (115 g/kg OFMSWDW for PLA fibre and 128 g/kg OFMSWDW for PLA) [23]. This was also the first study applying mixed food waste as raw material in PLA production. However, considering that this study was a lab-scale study, the results are not directly comparable with the results from the bench-scale studies.

3.4. Biopesticides produced from OFMSW

*Bacillus thuringiensis* (Bt) is one of the most commonly used and studied biopesticides. Despite various applications (e.g. in agriculture, forestry and public health sectors), its conventional production is constrained due to expensive raw materials, high equipment investment and complicated operational procedures. Thus, producing Bt from OFMSW biorefineries represents a competitive and promising alternative.

We identified three studies producing Bt (Table 1). Zhang et al. [29] produced Bt through semi-solid fermentation and retrieved a higher valorisation efficiency (CFU/kg OFMSWDW) than the studies applying solid state fermentation (SSF) [30, 31]. In a SSF reactor, the growth of microorganisms occurs on the solid substrate without free water. SSF provides some advantages compared to conventional submerged fermentation, including higher fermentation productivity and product stability, and lower pollutant emission. However, due to high sugar content in the substrate, it shows low mass-transfer efficiency and substrate inhibition [29]. Thus, by increasing the water content of the substrate to reach a semi-solid state fermentation, a higher efficiency is obtained. However, in the considered studies the semi-solid fermentation was conducted only on a lab scale, and the SSF experiments on bench scale. Hence, the productivities are not directly comparable.

One study tested the effect on productivity of sterile and non-sterile conditions at a lab scale, observing no significant differences between the experiments. This is important for further up-scaling, considering the high costs of the sterilisation process [31].

3.5. Enzymes produced from OFMSW

Enzymes are protein molecules that catalyse biochemical reactions, such as the hydrolysis of cellulose to glucose. In a biorefinery, the use of enzymes is fundamental for the production of biofuels and bulk chemicals, since it determines the efficiency and velocity of the reactions involved in the process.

However, the conventional chemical production of enzymes is expensive mainly due to the high costs of the substrate used to cultivate them [33]. The use of OFMSW as substrate to produce these enzymes is therefore an important step towards more cost-efficient biorefineries.

Several studies [31–37] use mixed food waste as raw material for the production enzymes through SFF by microorganism and fungus (Table 1). Low cost and optimised growth media for enhanced production of complete cellulase system on zero cost mixed food waste was obtained. The rate of release of sugars from OFMSW was similar to that of commercial enzyme preparation.

4. Potential revenue of OFMSW-based production and future perspectives

Figure 1 presents the potential revenue of OFMSW-based production of the products for which the valorisation efficiency were calculated in Table 1. It was found that enzymes produced from the OFMSW have the highest potential revenue (from 1.2 million to 88 million Euro/tonne OFMSW), followed by Bt (from 14 thousand to 4 million Euro/tonne OFMSW). Bioplastics showed to have a less significant potential value (95 to 580 Euro/tonne OFMSW). It was assumed that the activity of the enzymes and Bt is not altered when transforming and transporting the crude products to the market. This is a rough assumption and can explain the extremely high revenues for these products. However, it also indicates that adequate design of production and transformation phases, to preserve the enzymatic and entomotoxic activities, could guarantee high revenues per unit of treated OFMSW. The industrial implementation of the OFMSW valorisation is a critical point for the large-scale development of OFMSW biorefineries.

Moreover, operational costs and environmental impacts and benefits from substituting fossil-based products have to be considered as well. Only then the whole economic and environmental value of the products and the application of OFMSW as a resource can be characterised. However, further research and development is needed before a complete assessment of the economic and environmental costs and benefits of the cascade utilisation of OFMSW and associated bioproducts can be characterised. This is left as a key limitation in this study, but should be a research objective for future studies.
The research was performed as part of the DECISION (Decentralised valorisation of biowaste) project (www.decision2020.eu), funded by the European Union’s Horizon 2020 research and innovation program under the grant agreement N° 689229 and the Graduate School of Science and Technology at Aarhus University.

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