An integrated, modular biorefinery for the treatment of food waste in urban areas

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ABSTRACT

Innovative and decentralized biorefineries are needed in urban areas to contribute to local resource efficiency. In this case study a biorefinery (waste-to-resource-unit, W2RU) is introduced for bioconversion of food waste using heterotrophic microalgae to protein-rich biomass, and for simultaneous extraction of high-value chemicals pigments (e.g., astaxanthin, β-carotene, lycopene, lutein, or riboflavin), vitamins (e.g., retinol, tocopherol, or ascorbic acid), and flavonoids from food waste. The W2RU is a compact and fully automated systems, which is applicable to recycle various biological waste streams. It consists of a module for the extraction of valuable compounds from wasted food. Remaining material will be sent to hydrolysis and hydrolysate applied as nutrient source in heterotrophic microalgae cultivation for production of protein-rich biomass. Such an approach can be integrated in urban infrastructure and the simultaneous production of various products from high-value chemicals to proteins revealed beneficial environmental impacts.

1. Introduction

Food waste accumulates in urban areas at consumer level, e.g., canteens, in considerable quantities and is converted into low-value products by conventional processes such as composting, anaerobic degradation or incineration [1]. The chemical potential in the form of functionalized molecules as well as essential trace elements, vitamins, and nutrients, which were built up in food production at high resource cost, are mostly lost in the conventional utilization processes [2]. Recycling strategies, which maintain functionalized compounds and meet the continuously increasing demand for food without exploiting planetary resources and to achieve a circular economy, however, are urgently needed.

An innovative biorefinery is considered here as a modular process for bioconversion of food waste using heterotrophic microalgae to protein-rich biomass, and for simultaneous extraction of high-value chemicals from food waste. Such a modular and transportable biorefinery can improve raw material efficiency and environmental impact [3] of global food production as an effective and innovative waste utilization process. Such a waste-to-resource-unit (W2RU) should be compact, fully automated, and applicable in a targeted manner to recycle various biological waste streams. Food waste can be "fed" to the unit via "pick--up-and-delivery" service or direct drop-in. The products, protein-rich algal biomass and specialty chemicals, can be regularly transported to local manufacturers such as the feed, food, or chemical industries, as well as to marketplaces. This case study introduces to W2RU as innovative biorefinery, which can be applied decentralized in urban areas and contribute to local resource efficiency.

2. Modular waste-to-resource conversion

The W2RU presented here is an example of how the knowledge-based use and recombination of biological and technical methods may mitigate environmental and supply problems in urban areas (Fig. 1). The process preserves and generates raw materials for local value creation (raw material efficiency). In the future, this could reduce the urban demand for food produced in other regions and countries. Correspondingly, less food must be produced under intensive land use and transported over long distances to cities, which contributes to environmental sustainability. Organic matter nutrients (nitrogen and phosphorus) do not have to be exported through central composting facilities to the surrounding areas of cities, where only a minor part of consumed crops is being produced. The modules integrated in W2RU are 1) extraction of high-value chemicals, 2) hydrolysis of food waste and 3) use of recovered nutrients in heterotrophic microalgae cultivation and eventually product formation from protein-rich algal biomass.

2.1. Extraction of high-value chemicals

Food waste is usually comprised of a large share or even pure plant material [4]. It is a resource for complex chemical compounds relevant for further use in food, chemistry, or other industrial purposes, and thus, a cascade valorization by extracting valuable components from primarily plant-based biomass before hydrolysis will extent the usability of biomass. However, mixed biomass, e.g., food waste, can be a challenging object for the extraction due to physical composition and mixtures of compounds (e.g., phenolics, lignocellulose, isoprenoids, or pigments), which are prevalent and can be extracted constantly and purified. In the W2RU, a green, solvent-free extraction process using solid phase extraction is considered [5]. Either the solid compounds are removed from the liquid by centrifugation or filtration and the liquid phase is passed through a solid phase (gravity- or pressure driven), or the solid adsorber phase is added to the biomass suspension and mixed to allow a passive diffusion of the target compound into the solid phase. The solid phase adsorbs the compound of interest, which can be re-extracted by smaller amounts of solvents or with physical means (e.g., distillation or

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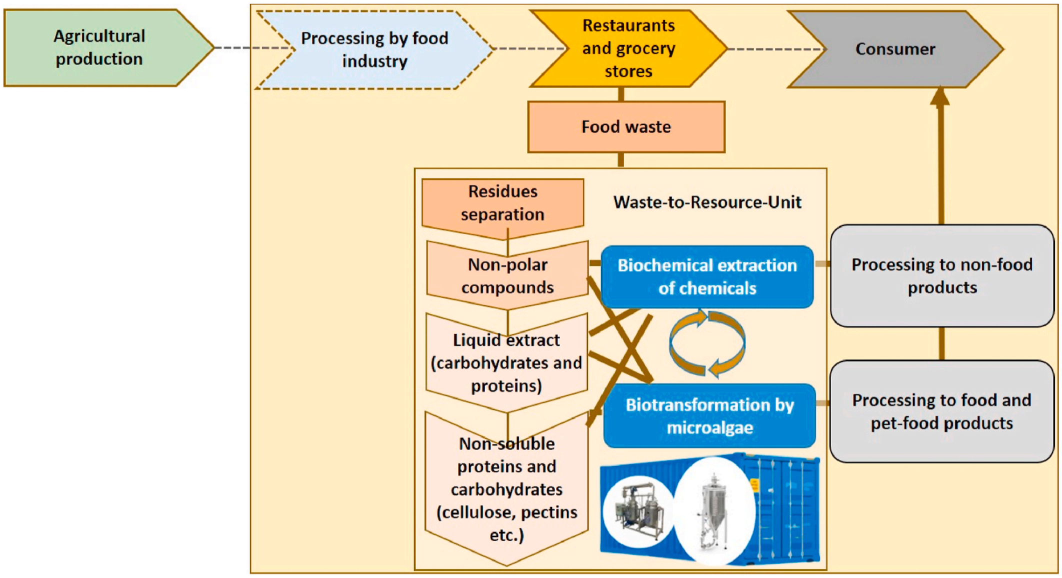

Fig. 1. Scheme of the integration of the waste-to-resource-unit (W2RU) in materials flows.

extrusion). Another advantage of the process is that the solid phases can be stored and transported more safely and cost-efficiently.

Especially from cantina or restaurant food mixtures with a constant share of plant residuals, several classes of valuable components can be extracted [6]. Pigments such as astaxanthin, β-carotene, lycopene, lutein, or riboflavin are of commercial interest. Besides pigments, antioxidants like vitamins (retinol, tocopherol, ascorbic acid) or phenolic compounds including flavonoids are highly abundant in biomass and likewise interesting for commercial purposes. Phenolics are somehow present in any plant-derived biomass because of the cell-wall component lignocellulose. Lignin components are a source of aroma substances like vanillin though they can further serve as building blocks for the chemical industry [7]. After extraction the remaining material can immediately sent to hydrolysis to make nutrients for the cultivation of microalgae available.

2.2. Hydrolysis of food waste and use of hydrolysate in heterotrophic microalgae cultivation

In various studies it has been shown that heterotrophic microalgae can be grown in presence of hydrolyzed organic materials. The requirement is the presence of carbon, nitrogen, and phosphorous sources. All compounds are basically obtainable from wasted organic material. For instance, food waste consists of 30–60% carbohydrates, 5–10% proteins and 10–40% (w/w) lipids, and to a lesser extent of polyphosphates [8]. Carbohydrates (predominantly starch), proteins, and polyphosphates can be converted by biological and/or chemical methods into sugars, amino acids, and phosphate, respectively [8]. The recovered nutrients can then be used as feed in heterotrophic microalgae cultivation [9,10]. Due to the presence of starch, it is recommended to skip rough chemical hydrolytic treatment and to focus on the application of amylases. Studies have revealed the efficiency of amylases in terms of glucose release. The same applies to proteins. The application of proteases without thermal or chemical pretreatment can result in considerable amounts of free amino nitrogen compounds which serve as nitrogen sources in heterotrophic microalgae cultivation [8,9]. Recent studies aimed for making the addition of external enzymes unnecessary and utilizing the hydrolytic potential of microorganisms present in wasted organic material [11]. Particularly the hydrolysis of cellulose and hemicellulose is of importance when vegetables appear at larger amounts and their potential as source of sugars should be utilized.

The potential of heterotrophic microalgae utilized in W2RU is not only the ability to consume nutrients recovered from wasted organic material but to store the nutrients in form of high-value proteins and unsaturated fatty acids in biomass. The microalga *Galdieria sulphuraria* for instance accumulates around 40% proteins when grown in presence of digestate and glucose [12]. The microalgae *Chlorella pyrenoidosa* and *Schizochytrium mangrovei* accumulate linolenic acid and docosahexaenic acid, respectively, when cultivated on hydrolyzed food waste [13].

It should however be admitted that the economic success of algal-based W2RU depends on the ability to cope with contaminations. Most of heterotrophic microalgae are active at moderate pH and temperature conditions. Conditions which are also appropriate for many bacteria and fungi, and thus an energy-intensive sterilization is needed [14]. It is therefore recommended to concentrate on microalgae which grow under extremophilic conditions (e.g., *G. sulphuraria* [12]) and outcompete most bacteria and fungi and allow even a process carried out under non-sterile conditions.

2.3. Products from algal biomass

Microalgae are one of the most interesting sources of biomass for the development of food and feed products. Even though it is known for centuries, the advances in the design of new foods and feeds continue. The demand of protein-rich biomass with acceptable sensorial and nutritional properties as well as lower environmental impact triggered interest in the use of microalgae as meat substitute [15]. From this perspective, heterotrophic cultivation of microalgae is of particular interest as it results not in stable green, but yellowish protein powder, which has higher applicability range as a food ingredient [16,17]. Furthermore, microalgae in many cases could act as foaming, gelatin, and emulsifying agents. Moreover, microalgae have a great potential as economically viable source of high-value colorants (e.g., phycocyanin) and protein biomass for pets [17,18].

2.4. Environmental impact

W2RU has not only the potential to be economically profitable (payments for waste reduction/treatment and product trade) but also environmentally beneficial. Specifically, the application of food waste as a source of carbon and energy in the heterotrophic production of microalgae reduces the environmental impact by 60% compared to classical microalgae cultivation [19,20]. Application of mobile W2RU in urban areas at the place of food waste generation results in reduction of

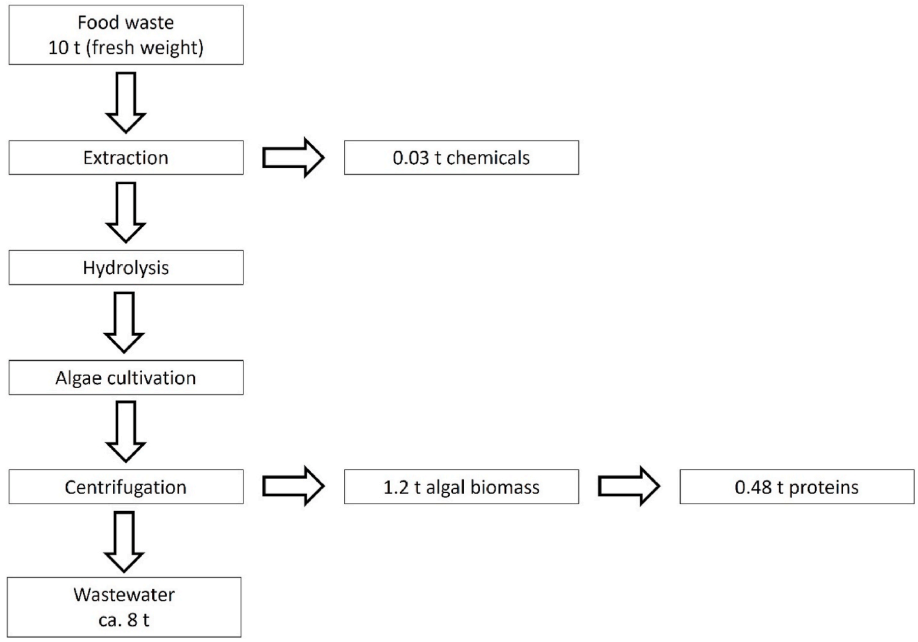

Fig. 2. Quantities of chemicals and algal biomass obtainable from food waste after extraction, hydrolysis, and cultivation of *Galdieria sulphuraria*.

need to transport and process waste, which adds to the benefits of avoided environmental impacts. Further avoided impacts relate to the potential to simultaneously utilize the extracted high-value components from food waste and microalgae (see above). The potential to rely on installed solar panels further contributes to an impact reduction by 10–15% [21]. The proposed heterotrophic cultivation leads to a reduction in food waste in urban areas and the production of protein powder with a carbon footprint of less than 2.25 kg carbon dioxide equivalent per kg powder, making it one of the most environmentally sustainable protein sources.

2.5. Integration in urban infrastructure

The modular biorefinery may be applied decentralized in the urban context. Favorable effects are expected by user awareness in such small circular economy scenario. In wastewater management, sense of ownership and user behavior are improved in decentral reuse systems [22]. Also, individual, or small-community recycling systems for food waste by e.g., (vermi-)compositing do not face sorting problems of central municipal waste collection systems. Thus, a decentralized waste utilization as proposed in W2RU might be realizable.

With 70–90% (w/w) moisture content [23,24] the largest fraction of food waste may be disposed on site by existing sewer systems, reducing logistics above ground significantly. Small-scale waste collection and distribution of treatment products are in line with the transition of urban mobility to micro-logistics as well as trending regional food manufacturers. Application in event logistics, canteens, or campus structures as well as semi-central treatment processes for urban waste operators holds a vast variety of models for innovative urban development and commodity chains, closing the resource loop between disposal problems and demand for high quality materials.

It is estimated that the implementation of a unit in urban infrastructure for the treatment of 10 t food waste (fresh weight) per day requires an investment of around 500,000 €. The operational costs are thereby estimated at around 1,000 € per day. This size would not require large equipment for extraction, hydrolysis, and cultivation but would still allow for significant economic gain. Depending on the waste treated, it is expected that from 10 t of fresh food waste around 0.03 t of chemicals (e.g., pigment such as astaxanthin, β-carotene, lycopene, lutein, or riboflavin), vitamins such as retinol, tocopherol, or ascorbic acid, phenolic compounds such as flavonoids) can be extracted and 1.2 t of algal biomass (dry weight) and eventually 0.48 t of proteins can be produced (Fig. 2). Depending on purity, this may result in a gain of around 3,000 € from the commercialization of chemicals and 12,000 € from algal proteins per day.

3. Conclusions

The use of food waste in food production is a prime example of a circular economy and highly efficient use of raw materials with direct impacts on social, ecological, and economic sustainability aspects. The process can be used locally - creating business opportunities, jobs, and value in the immediate living environment of citizens. Food waste with high water content must be transported much shorter distances, which reduces traffic and emissions. Wastewater can be discharged and treated directly through existing infrastructure. The reduction of odor emissions through rapid bioconversion of waste also improves the quality of life in urban areas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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