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Food waste valorisation and techno-economic analyses through simulation's software: a literature review

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Abstract

The valorisation of food waste and losses is pursued to cope with the increasing amount of wastages produced along the whole food supply chain, in order to achieve value added products such as animal feed, molecules and compounds for the cosmetic and pharmaceutical sectors, bio-fuels and energy. Due to the variety of different losses, wastes and processes to obtain value added products, an important engineering activity is required to convert laboratories results to real plants for industrial production. Process flow simulation software, such as SuperPro Designer®, are then currently used to pursue techno-economic-analyses and feasibility studies of these kind of industrial bioprocesses. Modelling and optimization of process conditions will allow systems scale-up thus leading to a maximization of the production. Therefore, an analysis of the current applications of these types of software, will allow the reader to understand how to model these processes and evaluate which will be those already designed at an industrial level or that still remain nowadays at a lab scale. With the aim of understanding the state of the art of the software implementation, a literature review has been carried out. This work deals with then a survey about technologies for food waste valorisation into energy or value-added products, including biofertilizers, biofuels, bioplastics, and chemicals, with also a focus on biological and thermal treatments.

Keywords: Food Waste; Techno-economic assessment; SuperPro Designer; Food losses; Valorisation.

1. Introduction

The increasing attention towards the environmental sustainability (Cui, Weng, Majeed, Zahid, & Shahzad, 2022) and the duty of human being toward our planet in term of pollution reduction, led to constant research in how to treat the waste. (Nyairo, Hasegawa, Fujimori, Wu, & Takahashi, 2022). Nowadays, energy consumption strongly depends on fossil fuels which own the 80% of the energy source (Schernikau & Smith, 2022), causing greenhouse gasses (GHGs) emission (Amjith & Bavanish, 2022), consumption of non-renewable resources (Chien, Hsu, Ozturk, Sharif, & Sadiq, 2022), increase of extraction costs (Ladero, et al., 2022) and an expensive market of fuels (Geissler & Maravelias, 2022). A valuable solution lies in the field of food waste and losses valorisation, which can represent a precious source of energy allowing a decrease of the global amount of waste. Food Waste (FW), i.e., "the mass of food lost or wasted in the part of food supply chains leading to edible products for human consumption" (Kharola, et al., 2022), can be found all along the food supply chain, within food cultivation, harvesting, processing and distribution (Yadav, Singh, Gunasekaran, Raut, & Narkhede, 2022). As far as, FW has different material composition, it can be classified with five different elements, i.e. carbohydrates, proteins, extractives, lignin, and lipids (Xu, et al., 2022). The FW valorisation can led to different achievable outputs, such as soil conditioner, solid fuel, liquid biofuel, or electricity (Awasthi, et al., 2021) through different methodologies, such as: (i) biological treatment, (ii) thermal treatments and (iii) landfilling (Caldeira, et al., 2020). Authors refer to these processes as Waste-To-Energy (WTE), if the aim is to recover the energy from waste in the form of heat, electricity, or fuel. This work will review the actual implementation of simulation software aiding the WTE technologies (WTEt), with a focus on the process simulation software able to provide a process flow diagram (PFD) and carry out a techno-economic analysis (TEA). The first section describes the methodology adopted to perform the literature review. Section 3 shows the main outcomes , while Section 4 presents discussions and conclusions about them.

2. Methodology

With the aim of reviewing the literature about each category of WTEt aided by simulation software, such as SuperPro Designer, a search has been launched via Scopus, i.e. a database of peer-reviewed literature. The keywords have been selected considering their relevance to the topic, such as "SuperPro designer", "food", "waste", and "valorisation". Figure 1 shows the main outcomes by running the research with different keywords. In particular, the first two keywords return 299 documents. Then, 172 documents have been found with the combination of SuperPro Designer and food, while by filtering the sample with the keyword "waste", documents decrease to 111. The final refines of the research, made by adding the keyword valorisation or valorization combined with the main food waste treatment, returns 22 documents for the biological treatments, 7 for the thermal and 1 document that includes the keyword landfilling.

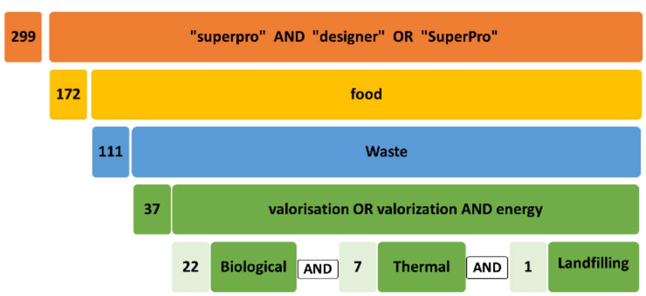

Figure 1 Research result on Scopus for different keywords

3. Results

3.1. Descriptive statystics

Among the articles found with the refined research, only 15 documents, over the 30 previously selected, meet the topic of this work. The results are shown in Table 1. The selected articles propose a huge variety of studies in the waste valorisation treatments to produce value-added products and biofuels, or processes able to convert waste into energy. A particular mention has to be dedicated to biorefineries which include different processes characterized by a cascade use of waste to product both value-added product and energy (Zhao, Jiang, Li, & Wang, 2016). Aforesaid studies, has a common denominator: the use of simulation software, such as SuperPro designer, to assess the feasibility of industrial processes that have been previously tested by laboratories and research centres. This work shows a systematic literature review starting from 2014 to 2022, developed with the same process simulation software. As mentioned, the sample is composed of only 15 relevant works, so not many statistical analyses can be performed. However, trying to describe the collected papers, it must be noticed that the number of works is increasing during the time (Figure 2).

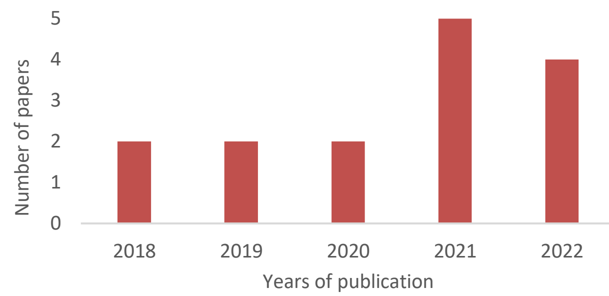

Figure 2 Results of publications over years

Moreover, the address of the main author was taken as a reference to geographically collocate the work: as can be noted in Figure 3, Malaysia and Colombia are the main countries of publications, followed by North America and South Asia.

Figure 3 Results of the geographically distribution of the papers

The selected studies have been categorized by considering the main waste treatments technologies, starting from the biological and thermal ones that are described in the next sections. On the other hand, even if landfilling was firstly investigated, no relevant results have been found on this topic.

3.2. Biological treatment technologies

The biological methods suitable for the treatment of FW can be divided in two categories: (i) alcoholic Fermentation (AF) and (ii) Anaerobic Digestion (AD). AF, also known as ethanol fermentation, is an anaerobic process in which sugar is converted into CO_2 and ethanol. AD is instead a reliable technology for obtaining bioenergy from FW, that enables a distributed production of biogas to avoid costs of long-distance transportation of high moisture content biomass. In this context, the simulation model proposed by (Cheong, et al., 2022), finds out an optimum in biomethane production by slightly increase the hydraulic retention time (HRT), i.e. the average time in which the digester holds the substrate, in this case composed by sewage sludge and FW (Fernando-Foncillas & Varrone, 2021). (Tiong, et al., 2021) modelled a PFD and carried out a process optimisation for similar technology in which palm oil mill effluent was adopted as co-substrate with FW to optimize HRT for biomethane production, while (Mahmod, Jahim, Abdul, Luthfi, & Takriff, 2021) adopted the same software in a double stage process able to extract both biohydrogen and biomethane, by adopting a TEA based approach. (Achinas, Leenders, Krooneman, & Euverink, 2019) carried out a comparison between three different waste feedstocks, such as sugar beet pulp, cow manure and grass straw, and carry out a TEA demonstrating the effectiveness of investing in plant for heat and electricity production by grass straw digesting. (Canizales, Rojas, Pizarro, Caicedo-Ortega, & Villegas-Torres, 2020) carried out a feasibility study and a modelling of a bioreactor which produce biogas from sugar cane vinasse, useful as fuel for turbo-gas, at its maximum capacity, to produce up to 20MW to generate electrical energy. Regarding the AF, (Gómez, Nobre, Teixeira, & Sánchez, 2022) adopted an approach based on both TEA and nutritional analysis demonstrating that plantain agro-industry waste, due to its low nutritional values, should be used as feedstock in biogas production instead of dairy cattle feeding, in particular the high content of moisture shows its effectiveness in producing a prebiotic compound such as isomalto–oligosaccharides, and can be adopted in a biorefinery pathway, to produce bio-ethanol and single cell proteins. (Mabrouki, et al., 2022) study's proposes the adoption of cheese whey with a content of lactose higher than 45.9g/l, as biorefinery feedstock in order to extract cheese butter, bioethanol through AF and biomass as secondary product. (Vučurović, Bajić, Vučurović, Jevtić-Mučibabić, & Dodić, 2022) carried out a TEA for a biotechnological process which convert spent sugar beet pulp into bioethanol. This study proposes a comparison scenario for the usage of the raw material under examination, as animal feed or as fuel for heat production, results obtained report higher return of investment in the second scenario. (Ozturk, et al., 2021) proposed a feasibility study to scale-up a laboratory process, which involve the usage of cooked rice in a two-steps fermentation process for bio-butanol production. (Fredsgaard, Hulkko, Chaturvedi, & Thomsen, 2021) examined the feasibility of a biorefinery pathway for synthetic kerosene production which involve Salicornia sp. via insect digestion for sugar to lipids conversion. (Shafinas & Rosentrater, 2020) proposed various options to FW landfilling modelling, by using three commercial scale different scenarios for FW fermentation for ethanol production. (Demichelis, Fiore, Pleissner, & Venus, 2018) modelled a PFD of both AF for biogas extraction and AD for lactic acid production from generic FW by comparing three different scenarios, in particular a standalone process for lactic acid or biogas only, and a third scenario, called integrated biorefinery where, by coupling both processes, it is possible to decrease the digester volume required for biogas extraction with a concurrent decreasing of energy demand and waste generation.

3.3. Thermal treatments

Biochemical methods, such as AD, shows their limits in converting lignocellulosic biomasses, producing mainly biogas and some digestate (mainly used as fertilizer), and involves slow process which may takes days, weeks, or months to be completed. Thermochemical conversion methods have some advantages if compared to biochemical conversion like easily converting all organic materials, producing multiple and complex products, requiring very short reaction times (typically seconds or minutes), and having high conversion efficiency. Incineration is a technology that includes conversion and combustion of waste materials into heat and energy. Within the thermal treatments adopted, we found some articles which involves thermal hydrolysis and pyrolysis. (Pang, et al., 2021) referred to pyrolysis as a common WTEt. Their study presented a simulation model and TEA for pyrolytic behaviour of different biomass by highlighting the relation between biomass composition and possible pyrolytic products, such as biochar from lignin-based biomass, or bio-oil from feedstock with a high cellulose contains or biogas from hemicellulose. Other studies suggested the adoption of integrated biorefinery, whit both biological and thermal treatments, for the self-sustainability achievement. In the context of biorefinery process to produce biojet fuel, (Li, Mupondwa, & Tabil, 2018) carried out a profitability analysis for an industrial plant able to produce hydro-processed renewable jet through thermal hydrolysis, and Hydro-treated Depolymerized Cellulosic Jet thought pyrolysis, starting from camelina oil. (Hemalatha, Sarkar, & Venkata Mohan, 2019), modelled a closed loop biorefinery which involve the cultivation of Azolla pinnata, that naturally retains C02 and, with its material composition, can provide value added products such as protein, carbohydrate and, lipids and biohydrogen though acidogenesis and pyrolysis products from pyrolysis. Furthermore, the wastewater from the azolla cultivation can be reused for the dilution of the acidogenesis process.

4. Conclusion

Nowadays, a lot of attention is paid to the environmental sustainability of the food industry sector. Researchers are finding alternatives to valorise the big amount of waste that is generated along the food supply chain. At high TRL level many times process flow simulation software have been used to purse techno-economic-analyses of possible process, aiming to scale-up the systems. Among these software, SuperPro Designer is one of the most used. Based on these premises, a literature review on Scopus database has been carried out to analyse the state of the art of the software implementation to valorise food waste. The number of retrieved papers is limited, but the results shows that the topic is gaining interest over time, in some Asiatic and American countries. The techno-economic analysis shows that FW-based biorefineries exhibit higher economic feasibility than lignocellulose- and ethanol-based biorefineries due to the high-value products obtained from the compounds presented in the FW, such as extractives and proteins. In general, the economic viability of biorefineries will increase by focusing on obtaining high-value biobased products rather than low-value products, such as fuels or heating sources, and using all components of these feedstocks. This aspect is absent in lignocellulosic biomass, making FW a more advantageous feedstock. As the current biorefinery is heavily focused on ethanol and lignocellulose, feedstock diversification through the utilisation of FW creates opportunities for new products and chemicals in addition to conventional ones. However, the proposed solutions have been assessed based on research laboratories and pilot-scale plants outcomes. A better connection between research and closer collaboration between academia and food processors, manufacturers and distributors is crucial to create practical and viable solutions. Alignment between companies interested in producing biobased industrial products and consumer stakeholders is crucial to make significant progress in the valorisation of FW. Finally, favourable policies could be helpful to make this happen.

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Table 1 Literature Review from 2022 to 2014

Author and year of publication	Feedstock	Co-product	TECHNICAL TREATMENTS	Software outcomes
Gomez j.a. Et al. (2022)	Unripe plantain fruit	Fermented block for biorefinery	AF	Process simulation
Cheong w.l. Et al. (2022)	Kitchen FW and sewage sludge	Bio-methane	AD	Process simulation; Process optimisation; Tea
Mabrouki j. Et al. (2022)	Cheese whey	Bio-ethanol	AF	Process simulation; Four production scenario; Tea; Energy analysis.
Vučurović d. Et al. (2022)	Spent sugar beet pulp	Bio-ethanol	AF	Process simulation; Process optimisation; Tea
Tiong j.s.m. Et al. (2021)	Palm oil mill effluent	Co-substrate with FW for AD	AD	Process simulation; Process optimisation; Tea
Pang y.x. Et al. (2021)	Biomass	Bio-oil from cellulose; bio-gas from hemicellulose; Bio-char from lignin	Pyrolysis	Process simulation; Tea
Mahmod s.s. Et al. (2021)	Palm oil mill effluent	Co-substrate with fw for ad	AD	Process simulation; Process optimisation; Tea
Ozturk a.b. Et al. (2021)	Cooked rice	Bio-buthanol	AF	Process simulation; Production scenario comparison; Tea
Fredsgaard m. Et al. (2021)	Salicornia sp.+hermetia illucens	Hydro-processed esters and fatty acids synthetic paraffinic kerosene (hefa-spk)	Fermentation	Process simulation; Tea
Canizales l. Et al. (2020)	Sugarcane vinasse	Bio-methane	AD	Process simulation; Tea
Shafinas muhammad n.i. Et al. (2020)	FW	Bio-gas	Fermentaion	Process simulation; Production scenario comparison; Tea;
Achinas s. Et al. (2019)	Sugar beet pulp, cow manure, and grass straw)	Biogas	AD	Process simulation; Production scenario comparison; Tea;

Hemalatha m. Et al (2019)	Azolla+spent wash (distillery wastewater)	Hydrolysis for biohydrogen and volatile fatty acids (vfa). Pysolysis for bio-char, oil, gas	Acidogenesis, photosynthesis, hydrolysis and pyrolysis	Process simulation; Production scenario comparison; Tea;
Demichelis f. Et al. (2018)	Fw	Lactic acid (la) and biogas from fermentation	Hydrolysis or fermentation, mesophilic ad	Process simulation; Production scenario comparison; Tea;
Li x. Et al. (2018)	Camelina oil	Biojet fuel	Thermal hydrolysis; pyrolysis.	Process simulation; Tea