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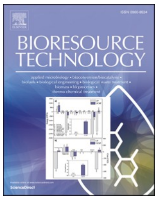

Intensification and biorefinery approaches for the valorization of kitchen wastes – A review

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HIGHLIGHTS

- Kitchen wastes (KW) management can be improved through flexible processes & new technologies.
- Sequential fractionation & valorization of KW within biorefinery approach is encouraged.
- Enhanced efficiency through process intensification can be an attractive alternative.
- New models of regulation and governance are required to promote resource recovery.

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ABSTRACT

Kitchen wastes (KW) are post-consumption residues from household and food service sector, heterogenous in composition and highly variable depending on the particular origin, which are often treated as municipal. There is a need to improve the management of these continuously produced and worldwidely available resources and their valorization into novel and commercially interesting products will aid in the development of bioeconomy. The successful implementation of such approach requires cooperation between academia, industrial stakeholders, public and private institutions, based on the different dimensions, including social, economic, ecologic and technological involved. This review aims at presenting a survey of technological aspects, regarding current and potential management strategies of KW, following either a single or multiproduct processing according to the biorefineries scheme. Emphasis is given to intensification tools, designed to enhance process efficiency.

1. Introduction

Food fractions can be lost or wasted at any step of the food chain, including primary sector, transportation, storage and post-consumption. The terms food loss or pre-consumption wastes often mean the portions discarded during the production, manufacturing, and distribution stages of food supply. The terms food waste or post-consumption wastes define the portion not used in the final food product, thus occurring at consumption level (Kamal et al., 2021; Withanage et al., 2021). However, in many cases the term food wastes has been used to refer to both of them. It has been estimated that 30–50 % of the total food produced is either discarded or not consumed and food losses and waste have a negative environmental impact due to the water, land, energy and other natural resources used to produce them, the post-consumption disposal costs (FAO, 2014; Esteban and Ladero, 2018; López-Gómez et al., 2020) and the contribution to greenhouse gas (GHG) emissions worldwide (De Clercq et al., 2016; Sindhu et al., 2019; López-Gómez et al., 2020). The sustainable management of these wastes represents a challenge from an economic and ecological point of view and their reduction is targeted in the index 12.3 of the United Nations Sustainable Development Goals (Carmona-Cabello et al., 2018; Dou and Toth, 2021; Kamal et al., 2021).

Different approaches, including prevention, mitigation and post-valorization might be proposed for food waste management (Fig. 1). The widely used strategies are based on thermal (gasification, pyrolysis and incineration), chemical or biochemical (composting, anaerobic digestion) transformations (Maina et al., 2017; Sindhu et al., 2019; Wu

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et al., 2021). More recently, the cascading biorefineries for the recovery, recycling and/or generation of high-value compounds have been proposed (Carmona-Cabello et al., 2018; Mahjoub and Domscheit, 2020) to promote a transition to a sustainable bioeconomy (Mahjoub and Domscheit, 2020; Sharma et al., 2021). This circular approach has a positive impact on the environment, and builds long-term resilience, generating business, new technologies and jobs (Sharma et al., 2021).

Kitchen wastes (KW) from households and hospitality sector are biodegradable, highly heterogeneous waste, normally collected by municipal or charter services, accounting for 30–60 % of solid urban residue (Esteban and Ladero, 2018). Food and KW are worldwidely available and could be an excellent source of value-added products (Sindhu et al., 2019) and a good candidate as biorefinery raw material (Carmona-Cabello et al., 2018). The relatively stable temporal composition in most nutrients, of these postconsumption food wastes in comparison to preconsumption food wastes would favor a more effective waste management (Ho and Chu, 2019).

When Pirani and Arafat (2014) reviewed the current status of food waste management for the hospitality sector and food services, they suggested the need of more studies on the implementation of sustainable management. In a more recent work, Dhir et al. (2020) designed a framework to inform future empirical research in this area. Many other reviews have been focused on management strategies of KW, including feed application (Georganas et al., 2020), the energetic valorization (Sindhu et al 2020), and bioconversion into chemicals and biopolymers (Mahjoub and Domscheit, 2020; Sindhu et al., 2020). The chemical, enzymatic and biotechnological processes and the need of a pretreatment of food and KW to value-added products has been updated (Esteban and Ladero, 2018; Sindhu et al., 2019; Torres-León et al., 2021), as well as the exploration of multiproduct processes in biorefineries (Carmona-Cabello et al., 2018).

Overall, KW are often treated as municipal wastes by incineration, landfill, composting, and anaerobic digestion. It is essential to both reduce their generation and to upgrade their treatment to add value within a bioeconomy strategy. In the present review, after an initial survey on the proximal composition of KW, the potential of intensification tools is summarized. Both applications leading to a single product and the biorefinery schemes leading to a variety of products are presented. Emphasis is given on the utilization of efficient flexible technologies based on process intensification to enhance the performance of physical, chemical and biological operations for the valorization of KW. The novelty of this comprehensive review lies in the stimulation of the alternative and efficient valorization of this heterogeneous worldwidely available residue.

2. Composition of kitchen waste

Adequate residue classification and detailed characterization of these feedstocks are needed to define any valorization proposal (Carmona-Cabello et al., 2020; Dhinam and Mukherjee, 2021; Withanage et al., 2021). Analysis from different perspectives can be performed, including the annual variability and the chemical characterization. Qualitative or typological distribution of foodstuff can be informative, i. e., fruit and vegetable, starchy, meat, fish and others (Carmona-Cabello et al., 2020) or raw, cooked, fruit/salad and bread/dessert (Vavouraki et al., 2013). Classification into avoidable (edible before being thrown away), possibly avoidable (if eaten depending on cultural factors, the preparation mode), and unavoidable, has also been considered (Pirani and Arafat, 2014; Withanage et al., 2021). According to the discarding causes, Carmona-Cabello et al. (2020) proposed different categories: out of date and non-processed food due to deficient logistics; surplus processed food, due to a wrong forecast; inappropriate food handling; and discards related to excessive meal portion sizes.

Food waste is the major significant component of hospitality waste, being almost 40 % of the waste from hotels and 60 % of the waste from restaurants, on average, 5–21 % from spoilage, out-of-date or unusable items; 45–65 % from food preparation and 30–34 % from plates (Pirani and Arafat, 2014). Restaurant food waste can be wet (organic/biodegradable) and dry food waste. The first includes customer and preparation leftovers, can account for more than 50 % of the hospitality waste and up to one third of all the food served within this sector (Pirani and Arafat, 2014). The second comprising chopsticks, napkins and food boxes (De Clercq et al 2016; Yu et al., 2018; Jayalakshmi et al., 2009), should be separated before some uses (Pirani and Arafat, 2014).

The portion wasted from household or from food services is highly heterogenous in composition and depends on the particular food service, is inconsistent in production rate and volume, geographically distributed (Engelberth, 2020), includes different mixtures of food (Carmona-Cabello et al., 2018), and the type of restaurant is highly influencing (Pirani and Arafat (2014). In a study assessing the composition monthly during one year with household KW, pre- and post-consumption hotel food waste, wet market food waste and KW from a Chinese restaurant, Ho and Chu (2019) found that the composition of postconsumption food waste was less fluctuating and could be considered a more reliable feedstock for conversion than others. The kitchen and post-kitchen stages are strongly determined by the human factor and the sector diversity difficults generalisations and estimates (Filmonau and Ermolaev, 2021).

Studies on the average composition of domestic, institutional and

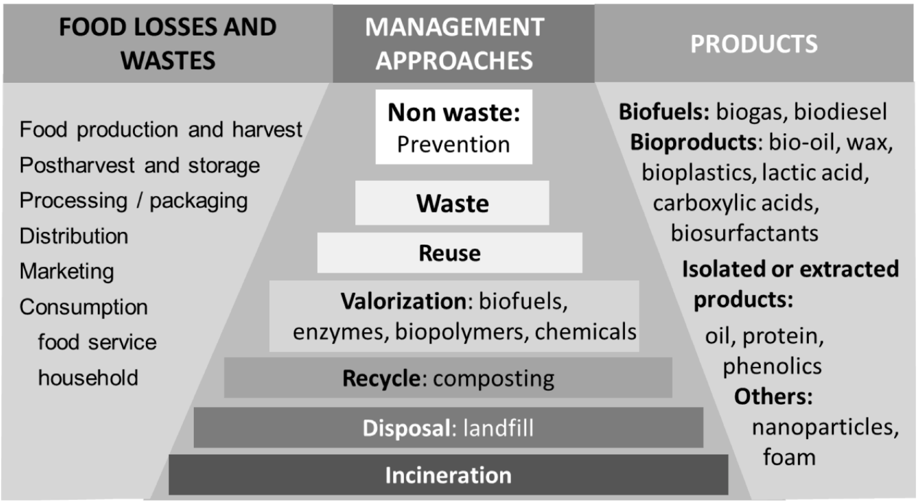

Fig. 1. Origin of food wastes and losses (Kamal et al., 2021; Withanage et al., 2021), management approaches (Dhinam and Mukherjee, 2021) and valuable products (Carmona-Cabello et al., 2018).

hostelry wastes, show that these residues have a pH 4.2–6.7 (Moon et al., 2009; Bibra et al., 2020; Jayalakshmi et al., 2009; Sondhi et al., 2020), and 52–88 % water. This high moisture content may lead to the loss of nutrients during draining, may promote contamination and hydrolytic reactions, and in terms of energy recovery efficiency, reduces the calorific value (Carmona-Cabello et al., 2020). In dry basis they contain mainly carbohydrates, followed by lipids and protein and ash (Wang et al., 2008; Vavouraki et al., 2013; Dhinam and Mukherjee, 2021; López-Gómez et al., 2020). From data in Table 1 and from a database with physicochemical characteristics (Dou and Toth, 2021), a high variability was observed. In some works, data represent the composition of samples collected either daily, or once or twice a week (Vavouraki et al., 2013; Ntaikou et al., 2018), or on random days during periods of four to twelve months (Ho and Chu, 2019), or every month (Sondhi et al., 2020). Usually, for characterization purposes the samples are stored at 4 °C until use in a day or two (Cekmecelioglu and Uncu, 2013), or stored during several weeks (Carmona-Cabello et al., 2019). For applications, conditions should be adequately defined, since during storage the physical structure of KW can change and part of the solid mass could be potentially lost (Degueurce et al., 2020).

Polysaccharide rich fractions are good carbon sources for bioconversion processes. The cellulose, hemicellulose and starch content in restaurant KW depended on the type of restaurant (Carmona-Cabello et al., 2020). These fractions can be efficiently used as feedstock in biochemical processes and starch is also a valuable molecule for paper production, glues and adhesives and biodegradable plastics (Mahjoub and Domscheit, 2020). The liquid and solid lipidic fractions, representing an average of 20 and 81 % (w/w, db) of KW, respectively, are closely linked to the type of sample and to the presence of meats, frying oils, or sauces. The fatty acid profile determines the total unsaturation degree and the type of phase, liquid or solid (Carmona-Cabello et al., 2018). In addition, oils can be also used for the synthesis of surfactants and other oil-based products (Mahjoub and Domscheit, 2020). Significant differences have been found depending on the restaurant and also postconsumption food wastes could exhibit higher crude fat content than preconsumption ones, which are normally not processed (Ho and Chu, 2019). The protein content comes from meat, fish and legumes (Carmona-Cabello et al., 2020), and both proteins and peptides show high potential for their nutritional, functional and biological properties. Part of the N present in protein molecules may be degraded to other

Table 1
Composition of kitchen wastes from household, restaurants and cafeteria, expressed in dry basis, except moisture, which is presented in wet basis.

Kitchen origin	Component (g/100 g dry basis)								
	Moisture	Ash	Total sugars/ Carbohydrates	Lipid	Protein	Hemicellulose	Cellulose	Lignin	Starch	Reference
University cafeteria	80.0	1.3			0.6					Kwon and Lee, 2004
Student cafeteria	75.9	1.2	10.2		3.9				7.1	Ohkouchi and Inoue, 2006
University student restaurant	80.3		59.8	15.7	21.8		1.6 (holocel)	0.8		Tang et al., 2008
Kitchen garbage	81.9–88.0		56.78–67.10	15.1–19.9	13.2–17.1		1.91–2.87		41.4–55.1	Wang et al. 2008
Hostel	83.1		47.6 organic carbon		14.1					Jayalakshmi et al., 2009
Bussiness center cafeteria	81.9	5.0	17.6 red sug	8.3	21.1	14.9 (crude fiber)			30.1 s	Moon et al., 2009
Students dinning hall	88.0	8.0	56.1	18.0	15.6		2.2			Zhao et al., 2009
University food court	64.4	1.8	20.5	8.8	4.5					Cekmecelioglu and Uncu, 2013
University cafeteria	77.4		33.3 sol sug	14.7	14.7					Shen et al., 2013
University student restaurant	81.5	5.9	55.0 (25.0 sol)	14.0	16.9	7.7	16.9		24.0 t 22.3 s	Vavouraki et al., 2013
Household		11.3	33.8 s	11.9	10.5	7.6	18.3	2.2		Matsakas et al., 2014
University dinning hall	84.2		52.3	10.6	18.4					Zhao and Ruan, 2014
University canteen			46.4	30.3	14.9					Tian et al., 2015
Restaurant	86				6.7					den Boer et al., 2016
University canteen	80.9		11.8	3.5	2.5					Li et al., 2016
School canteen	54.0	5.6		5.0	17.0		24.0	1.2	35.0	Chen et al., 2017
University canteen	76.3	5.7			16.3		42.9		40.2	Nishimura et al., 2017
Restaurant			8.5 % free sug	12.9	14.8				33.5	Pleissner et al., 2017
University dinning hall	60.8	5.01		13.6	18.9				42.1	Fung et al., 2019
Household	72.5	5.6		10.6	13.5				12.5	Fung et al., 2019
KW municipality level			43		10.2	3.0	11.0	5.0	16.0	Ntaikou et al., 2018
University dining room	74.1–75.9			17.6–19.1	18.7–21.0		20.8–23.2		35.6–31.9	Yu et al., 2018
University canteen	76.4	5.5	22.4	28.1	17.1				25.1	Peinemann et al., 2019
University canteen	87.6			2.3					80.3	Wu et al., 2019
Cafeteria	71.6	6.3	56.1	6.6	8.7	3.5	18.1		34.5	Bibra et al., 2020
University cafeteria		4.3	49.9		18.3	4.7	3.6	1.1	29.4	Carmona-Cabello et al., 2020
Grill restaurant		4.2	50.9		23.5	8.5	4.1	2.4	28.1	Carmona-Cabello et al., 2020
Italian restaurant		4.6	43.9		19.5	5.1	3.5	1.5	23.1	Carmona-Cabello et al., 2020
Fine dining restaurant		5.3	45.7		21.5	7.4	4.3	1.4	16.2	Carmona-Cabello et al., 2020
Household food		5.2	4.9 red sug	12.3	13.7	11.3	10.3	6.7	10.7; 9.5 s	Prasoulas et al., 2020
Canteen	88.0	11.1	62.0		7.2					Sondhi et al., 2020
Household		14.4		12.7	14.7	10.2	9.8		8.8	Taheri et al. 2021

Starch: t: total; s: solid; red sugar: reducing sugars; sol sug: soluble sugars; NDF: neutral detergent fiber; Hemicellulose: NDF – ADF; Cellulose: ADF – Lignin.

species, NH4 + or NH3, and inorganic species, such as nitrates and nitrites, used as additives can also be found. Nitrogen also plays a key role as nutrient in bioconversion processes. A metal profile with Na, K, Ca and Mg as main components, followed by trace elements, i.e., Zn, Mn and Fe, and traces of heavy metals, namely Cu, Ni and As, were found in food waste (Ho and Chu, 2019; Carmona-Cabello et al., 2020). Some trace elements can be relevant in microbial processes.

3. Pretreatment of kitchen wastes using intensified strategies

Process intensification has emerged as a tool to develop equipment and techniques, leading to compact, smaller and cleaner plants with increased efficiency, products quality, safety and improved control and automation, and also with decreased byproducts formation, capital cost and energy consumption (Vaghari et al., 2015). In a holistic approach process intensification is broader than process integration and is characterized by higher performance for a given unit size. Process intensification is a key objective in designing new plants and rethinking existing units into more precise and efficient ones and can be achieved by minimization, substitution, moderation and simplification of the methods, but also by cutting the number of unit operations or equipments (Tian et al., 2018). Other aspects are in relation to flexible equipment that can be both scaled up and down, offering the possibility of constructing smaller processing plants in developed and developing countries. The substantially decreasing equipment-size/production-capacity ratio, energy consumption, or waste production, results in cheaper, safer and environmentally friendly sustainable processes (Himmelstein et al., 2016). Furthermore, the better performance for a given unit size is also achieved by maximizing the effectiveness of intra and intermolecular effects, coupling and intensified phenomena (Van Gerven and Stankiewicz, 2009).

Process intensification technologies include multifunctional materials (e.g., ionic liquids) and reactors, hybrid separation, alternative energy sources (ultrasound, microwaves, centrifugal fields), application of enhanced driving forces or new modes of production (extreme conditions, low-frequency vibrations, high temperature and high-pressure technologies). Other ecofriendly pretreatment strategies for KW could be freezing and its combination strategies (He et al., 2022), advanced oxidation process (He et al., 2021), alkaline treatment, among others. Nevertheless, several important barriers must be overcome, such as the maturity and economic competitiveness compared to the conventional technologies. In summary, process intensification has been identified as a major tool for the implementation of sustainable processes and should also be considered for the sequential valorization of waste streams (Gallego et al., 2019). Some of the strategies tried in the pretreatment and management of KW are now summarized.

3.1. *Subcritical water*

In the subcritical state, at 100–374 °C, under high pressure to maintain the liquid state, water presents high diffusion, low viscosity, low surface tension and the dielectric constant can be comparable to those of organic solvents. Furthermore, the increased ionic product enhances its ability to act as an acid or base catalyst. Benefiting solubility, mass transfer and reaction kinetics can favor both extraction and reaction; and operating under medium–high pressures result in tuneable processes and more efficient than atmospheric pressure ones. Subcritical water processing has attracted interest due to its simplicity, versatility, and the non-toxic nature of water. The advantages include the faster operation and higher yields in comparison with atmospheric operation and it offers the possibility of directly processing high moisture content biomass without prior drying. There is no general recommendation for the best conditions for hydrothermal treatment of wet waste; they depend on the type, composition, moisture, accessibility, managing costs, biological hazard and local regulations (Marzbali et al., 2021).

Subcritical water is valid both for recovery and for hydrolysis of different fractions (protein, lipid, carbohydrates, phenolics) of biomass from different origin (terrestrial, marine, botanical, animal, fish) mostly reported for pre-consumption wastes (Gallego et al., 2019). It is effective for the recovery of both polar and non-polar compounds and for hydrolyzing macromolecules alternatively to acid, base and enzymatic hydrolysis, including pectin (Mao et al., 2019) and protein (Álvarez-Viñas et al., 2021). Subcritical water hydrolysis lacks specificity in cleaving peptide bonds for the preparation of bioactive peptides but overcomes the limitation of enzymatic technologies in relation to the high costs, prolonged times and low yield (Jeong et al., 2021).

3.2. *Ultrasound assistance*

When sound waves with frequencies higher than 16 kHz, propagate in a liquid medium cause compression and rarefaction cycles, which generate microbubbles in a phenomenon known as acoustic cavitation, also inducing micro jets, shockwaves, micro flow and microbubble implosion that can enhance mass transfer. Other physical effects are heating, acoustic streaming and nebulization. Furthermore, sonication can favor the reaction chemistry by enhancing mass transfer, interphase mixing, and the production of highly reactive radicals. This technique can aid in the recovery of bioactives from plant matrixes, since cavitation facilitates leaching of solutes by increasing mass transfer and solvent diffusivity (Wang et al., 2018), and has been successful for pectin (Mao et al., 2019; Gerschenson et al., 2021), protein (Kamal et al., 2021), and bioactives (Kumar et al., 2021). Cavitational equipments are a promising configuration with economic savings due to the improve process performance by 5–25 times compared to conventional technology, and potential for scaling-up (Gogate, 2008). Ultrasounds offer simplicity, time reduction, lower cost and energy consumption in comparison to other techniques (Montenegro-Landívar et al., 2021). Most studies for biomass pre-treatments operate under 50 kHz and caused mainly physical effects by reducing the size diameter of feedstocks, increasing the contact with the solvent and mass transfer. However, at around 300 kHz, a more intense formation of free radicals occurs. Heterogeneous reactions proceeding through ionic intermediates can be improved by agitation conditions, but in heterogeneous reactions with radical and ionic mechanisms, cavitation can improve both mechanisms (Gogate, 2008).

3.3. *Microwave-assistance*

Microwaves are electromagnetic radiation with frequency between 300 MHz and 300 GHz. Compared to conventional heating, microwaves offer a selective internal heating with higher rates. A favored mass transfer can also occur caused by cell wall degradation due to the rapid heating, evaporation and overpressure that break up the vegetal plant cell structures. The microwave assisted hydrothermal treatment and reaction processes have several advantages such as selectivity, reduced installation cost, easy maintenance, as well as lowered time, and energy consumption when compared to conventional methods. Furthermore, microwave installations do not produce dust, noise, gases, vibrations or ambient temperature increase, and the modular design occupies less space and would allow scaling up and down (Călinescu et al., 2021).

3.4. *Alternative solvents*

Ionic liquids are organic salts formed by organic or inorganic cations and anions and found in the liquid state up to high temperatures due to the very low vapor pressures. They are considered green solvents and useful for a number of processes involving recovery and reaction. They are advantageous for their non-flammable and high thermostable character, the possibility of using moderate to mild conditions, lower time, compatibility with microorganisms used for bioconversion and also for the possibility of processing wet biomass. However, the larger scale has economic limitations and other derived from recyclability, the variability of biomass properties (Mudhoo et al., 2018) and especially their prohibitive price, and the need of more studies on their biodegradability and toxicity to the environment (de Jesús and Filho, 2020). Ionic liquids offer potential for the pretreatment of biomass by swelling cell walls, weakening hydrogen bonding and decreasing cellulosic crystallinity. The enhanced accessibility of the substrate for hydrolytic enzymes, favors hydrolysis and a higher yield of biogas/biofuel can be obtained from anaerobic digestion or fermentation processes. Ionic liquids were also used for lipid recovery in biodiesel production (de Jesús and Filho, 2020). The hybrid systems application (US combined with conventional treatments or other intensification tools), i.e., the synergistic effects with microwave, ultrasound and alternative green solvents can be considered (Flores et al., 2021).

3.5. Hybrid processes

The combination of two or more innovative green intensification strategies offers synergistic effects for the recovery, pretreatment and reaction. A combination of microwave and ultrasounds can take advance of the enhanced heat transfer of the first and the enhanced mass transfer from the second (Călinescu et al., 2021), and can be applied either sequentially or simultaneously. The latter approach benefits kinetic effects and mass transfer ensuring the increase of the overall rate of the chemical process (Gerschenson et al., 2021). The joint use of ionic liquids with ultrasounds has been proposed for the production of furan derivatives with the possibility of reusing both the solvent and catalysts (Sarwono et al., 2017). In order to lower the viscosity of ionic liquids, the addition of a cosolvent has been proposed, but they could alter lipid partitioning whereas microwave or ultrasound could be cleaner tools. The combination of ionic liquids with subcritical water was also promising (de Jesús and Filho, 2020).

4. Bioprocessing of kitchen wastes

KW are a suitable feedstock for the production of biofuels, bioproducts, and materials (Carmona-Cabello et al., 2018). This section contains a concise survey, following the classification of Fig. 1 according to the type of products. Emphasis is given to the potential of novel technologies to develop environmentally friendly processes for the transformation of KW into high-value products.

4.1. Animal feed

The direct use of KW as animal feed has been traditionally considered in some regions (Dhinam and Mukherjee, 2021; Georganas et al., 2020), and more recently have been proposed for preparing organic fish food though a microwave heating process (Kan, 2014), as well as in alternative applications, such as insect bioconversion (Ho and Chu, 2019). The feed use is historically associated with disease transmission to animals and humans and even when microbial hazards can be overcome by heat treatments, pathogens, physical and chemical hazards still need more insight (Dame-Korevaar et al., 2021). These practices are not legal in the framework in the European Union, although pet food could be a strategy for using food waste in this context (Ho and Chu, 2019).

4.2. Composting

Composting is a cost-effective and environmentally safe bio-oxidative process for stabilizing organic residues. This simple technology can be performed in small plants, requiring relatively long time and specific conditions (Dhinam and Mukherjee, 2021). Pre-consumption food wastes had more favorable C:N ratios than post-consumption ones (Ho and Chu, 2019), but KW could be used composted by consortia of microbial species (Wang et al., 2016; Hussain et al., 2018). The joint composting of kitchen together with garden waste at the household level generates positive economic and environmental effects but requires support from local authorities regarding environmental awareness and financial aspects (Sulewski et al., 2021). On-site composting, a promising strategy hampered by space constraints and high initial investment costs (Filmonau and Ermolaev, 2021), is gaining importance, especially for hotels with extensive landscaping and gardening needs (Pirani and Arafat, 2014). New Sanitation separation, for the recovery of valuable resources from wastewater and organic waste, can be integrated with Urban Agriculture, to minimize the demand for nutrients and organic matter from urban agriculture (Wielemaker et al., 2018). A recently described application of KW, consisted of the Sporosarcina pasteurii cultivation and the bacterial induced carbonate precipitation showed potential for large-scale applications in wind erosion control of desert soils (Meng et al., 2021).

4.3. Biofuels

Post-consumption food waste can be valorized to different fuels, representing real and viable future sources minimizing the potential conflict between food and fuel (Dhinam and Mukherjee, 2021; Ho and Chu, 2019). Furthermore, this is a bioresource geographically more evenly distributed than fossil fuel (Hafid et al., 2017).

4.3.1. Biogas and biohydrogen

Anaerobic digestion is an economic and environmentally friendly solution for the management of KW, which contain about 96 % biodegradable organics (Yu et al., 2018; Gallipoli et al., 2020), and almost 75 % of the nutrients are water soluble (Carmona-Cabello et al., 2018). The process can be used to convert KW in a methane rich biogas and a digestate that can be applied as a fertilizer or soil additive after additional refining (Kuruti et al., 2017). Biomethane could cut the GHG emission, and the generation of carcinogens compared to fossil fuels (De Clercq et al 2016). Large-scale application for restaurant food waste is hindered by the low biogas production, the weak process monitoring and control, and the excessive troubleshooting due to the sensitivity of methanogenic bacteria to the environmental conditions and substrate inconsistency (De Clercq et al 2016). Alternatively, portable type biodigester (Ajay et al., 2021) and co-digestion with other pre-consumption wastes (Shen et al., 2013) are feasible.

The adequate pretreatment of KW, i.e. thermal pretreatment (120 °C, 15–120 min), could enhance methane production efficiency and rates (Li et al., 2016), and methane yields from both oil and grease and synthetic KW co-digestions, whereas an ultrasonic pre-treatment did not (Li et al., 2013). However, ultrasound pre-treatment of KW increased biogas production during co-digestion with sugar factory wastewater (Nivedha et al., 2019). High temperature and pressure microwave irradiation was tried as a pre-treatment to enhance solubilization of organic material, protein and sugar, which lead to higher anaerobic biodegradability and methane production from a model KW compared to untreated samples (Marin et al., 2010).

Biohydrogen possesses higher calorific value than commercial fuels and KW are a potential feedstock for its production via dark fermentation (Jayalakshmi et al., 2009; Yu et al., 2018). The process performance can be enhanced by pretreatments based on thermal, high pressure, enzymatic, acid, alkaline, ultrasound and microwave assistance, aiding in carbohydrates and proteins solubilization (Gallipoli et al., 2020). The hydrothermal pretreatment (200 °C, 30 min) transformed the raw fat into floatable oil, limiting its inhibitory action on hydrogen-producing bacteria, enhancing the substrate utilization and reactor stability and the hydrolyzed protein could enhance the start-up and the stable operation (Li et al., 2014). In order to overcome the low yield caused by the accumulation of organic acids different strategies have been tried, including photo fermentation (Srivastava et al., 2021) and microbial acetate tolerance (Zhao and Ruan, 2014), but limitations regarding both microorganisms and bioreactor configuration need to be solved (Srivastava et al., 2021). Biohythane, the hydrogen-methane blend with 10–30 % v/v hydrogen, with better combustion performance and lower emissions than other fuels, can be produced by two sequential anaerobic stages (Bolzonella et al., 2018).

4.3.2. Bioethanol

The utilization of KW as substrates for bioethanol production is favored by the high organic matter content, particularly carbohydrates, susceptible of being converted into sugars and useful as carbon source (Hafid et al., 2017) as well as protein and other compounds acting as nutrients in bioconversion processes (Cekmecelioglu and Uncu, 2013). Even KW can serve as nutrients for other nitrogen limited substrates, being comparable to yeast extract and peptone during the production of bioethanol from wastepaper (Nishimura et al., 2017). The major stages for the production of bioethanol from KW are pretreatment, saccharification and fermentation. The pretreatment, determining the organic matter solubilization, accessibility by enzymes and downstream requirements (Hafid et al., 2017), can be physical (milling, grinding), chemical (alkali, dilute acid, organic solvent), and biological (fungal, enzymatic). Pretreatment with inorganic acids (hydrochloric acid, sulphuric acid) is widely used (120–180 °C, 30–90 min), but the harsh conditions cause partial degradation of sugars and generation of inhibitory compounds (Cekmecelioglu and Uncu, 2013). Whereas lignocellulose-based biorefineries require harsh thermomechanical and chemical pretreatments, food waste biorefineries are based on a material rich in starch and protein, which can be easily hydrolyzed by acid and/or enzymes to glucose, peptides and amino acids, further used for bioconversion or as platform chemicals (Esteban and Ladero, 2018). In a typical starchy KW material, a mild acid pretreatment can ease the access to glucoamylase to yield high sugar concentration (Hafid et al., 2017), even the amylase direct use (Wang et al., 2008), and the mixture of cellulolytic and amylolytic enzymes proved also suitable (Ntaikou et al., 2018), particularly when the enzyme is onsite produced, allowing to cut costs (Prasoulas et al., 2020). A hydrothermal treatment operating at 60–170 °C releases high concentration of fermentable sugars from KW (Hafid et al., 2017).

Microwave has been used to assist acid pretreatment and to increase the sugar production by enzymatic hydrolysis. Sondhi et al. (2020)

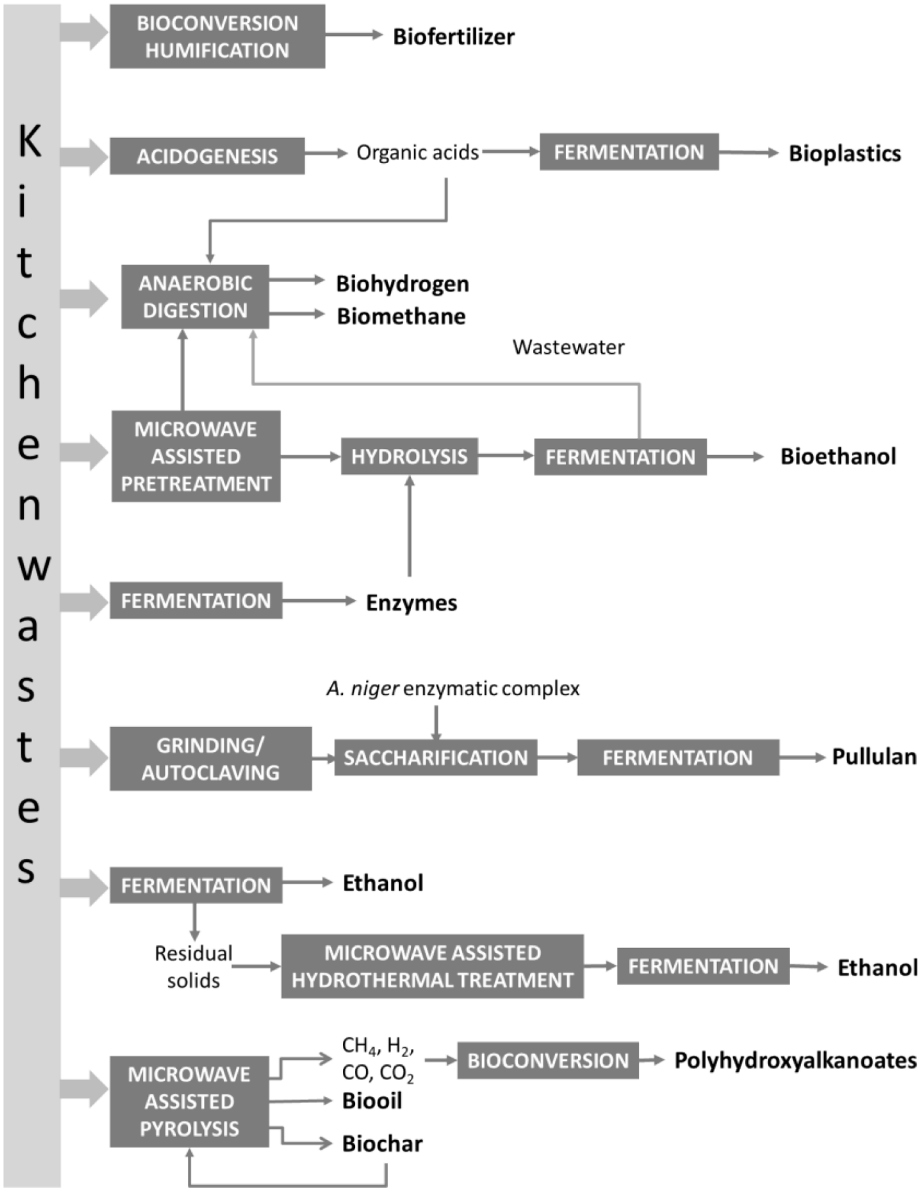

Fig. 2. Alternatives fot the valorization of kitchen wastes and possible incorporation of different intensification strategies (modified from Hafid et al., 2017, with contributions from Matsakas et al., 2014; Hafid et al., 2017; Revelles et al., 2017; Rishi et al., 2020; Marin et al., 2010; Sondhi et al., 2020; Suriapparao and Vinu, 2021).

avoided the use of acid/alkali hydrolysis using microwave-pretreatment (90 W, 30 min) before liquefaction/ saccharification with in-house produced Bacillus licheniformis MTCC 1483 amylase, and the total cost of bioethanol was 8.3 times lower than the market selling price. Matsakas et al. (2014) proposed the bioconversion to ethanol of household food wastes, applying an initial fermentation stage, the remaining solids were hydrothermally pretreated assisted by microwave (200 °C, 10 min). The pretreated solids were separated by filtration and washed to remove inhibitors formed, then were dried before enzymatic saccharification and further utilized for ethanol production (Fig. 2). However, in this case hydrothermolysis (100 °C, 1 h) was not efficient, due probably to the production of inhibitory compounds and sono-electrochemical pretreatments only slightly improved the saccharification yields with high energy demands, whereas solid–liquid fat separation was appropriate to obtain a high sugar yield, by starch and cellulose enzymatic hydrolysis (Taheri et al., 2021). Other authors have preferred bioconversion without previous heat treatment to avoid nutrients spoilage (Wang et al. 2008). Among microorganisms suitable for industrial bioconversion into bioethanol, with good yield, productivity and ethanol tolerance, Saccharomyces cerevisiae is the most used, others are Escherichia coli, Zymomonas mobilis, Candida shehatae, Kluyveromyces marxianus. Co-cultures of S. cerevisiae and Pichia stipitis allow improved utilization of both hexoses and pentoses (Ntaikou et al., 2018). Traditionally, separate hydrolysis and fermentation are performed, but simultaneous saccharification and fermentation h in one reactor, reduces the production time, inhibitory effects and operating costs. Biobutanol, with superior potential than ethanol to replace fossil fuels (Dhiman and Mukherjee, 2020), can be obtenied by saccharification fermentation to acetone, butanol, and ethanol production using Clostridium acetobutylicum (Chen et al., 2017).

4.3.3. Biooil and biochar

The fuel production by thermochemical processes such as pyrolysis, gasification and combustion requires short conversion time and can also provide valuable industrial products. However, these technologies require energy intensive drying stages (Gu et al., 2021). Pyrolysis is based on biomass cracking in the absence of oxygen at 300–1000 °C to produce a bio-oil, gases and a biochar. The final temperature and the heating rate determine the product distribution, at low temperatures dehydration reactions dominate, whereas at 500–600 °C cracking occurs. The presence of catalyst can lower severity, i.e. Agarwal et al. (2013) reported the pyrolysis of kitchen waste yielding maximum biogas and hydrogen at 800 °C, 180 min in non catalyzed reaction, but in the presence of sand as catalyst was reduced to 600 °C, 60 min. Copyrolysis of KW has also been successful, in combination with microalgae enhanced the calorific value of the bio-oil due to increased hydrocarbons production (Chen et al., 2018) and with tyres/plastic waste promoted the selectivity of hydrocarbons and bio-oil energy density (Chen et al., 2019).

Microwave assistance can reduce cost in terms of energy and time and can offer increased syngas production compared to conventional pyrolysis (Revelles et al., 2017). The energy consumption in integrated thermochemical process including drying, pyrolysis and gasification of the organic fraction form municipal solid wastes could be even more cost-effective at a higher scale (Beneroso et al., 2014). It has been applied for torrefaction of model KW into a fuel with increased heating value over the raw materials (Al-attab and Zainal, 2021) and also to process real wastes to obtain a bio-oil containing phenolics, guaiacols, syringols, furans, aromatics, aliphatic hydrocarbons and a biochar for adsorption of heavy metals (Januri et al., 2016). The bio-char obtained increased the heating value and if added as a susceptor to the feedstock (Fig. 2) lowered the energy demands modulating the selectivity (Suriapparao and Vinu, 2021).

4.4. Conversion to value-added products, chemicals and bioproducts

The high organic content, carbohydrates, proteins and lipids makes KW a good substrate for chemical and biotechnological conversion into biobased products and platform chemicals, more profitable than fuel and electricity (Trivedi et al., 2020; López-Gómez et al., 2020). Examples of conversion into both final products and intermediates can be found, such as i) carboxylic acids (lactic, citric, succinic, fumaric and oxalic acid), ii) anaerobic digestion to obtain volatile fatty acids, iii) furans and derivatives, iv) bioplastics, hydroxyalkanoate polyesters or polyhydroxyalkanoates or v) valuable bioproducts such as enzymes, pigments, biofuels, oligosaccharides, proteins, biosurfactants, and bioactive compounds (Vavouraki et al., 2013; Esteban and Ladero, 2018; López-Gómez et al., 2020; Pan et al., 2021; Torres-León et al., 2021) (Fig. 2).

In order to use KW as carbon and nutrients source for bioconversion processes, a pretreatment to facilitate the production of solutions susceptible of being bioconverted is needed as previously mentioned. Pretreatment can be mechanical, thermal, chemical or thermochemical, and biological (Vavouraki et al., 2013; Dhiman and Mukherjee, 2020). Chua et al. (2020) confirmed that hydrothermal pretreatment and enzymatic pretreatment were comparable in terms of the ability to solubilize nutrients from KW, and superior to alkaline pretreatment, cheaper, but performing worse in extracting nutrients (carbohydrate, protein and lipids). A segregation stage may be required because the diversity of these wastes and the possibility of finding them mixed with other solid wastes (eggshells, meat trimmings, bones, packing materials) may affect the performance of the bioconversion process (Dhiman and Mukherjee, 2020). Although not aimed at a valuable product, Gui et al. (2021) used KW microbial hydrolysate for replacing glucose as carbon source in activated sludge sewage treatment.

KW represent a natural environment for lactic acid producing microorganisms and different strategies have been successfully applied to obtain this metabolite, one of the top ten green molecules for chemical synthesis (Ohkouchi and Inoue, 2006; Pleissner et al., 2017; López-Gómez et al., 2020). Furthermore, an initial stage with lactic acid bacteria can prevent the growth of other microorganisms thus avoiding the sterilization stage. Zhao et al. (2009) proposed lactic acid production by ammonia neutralization of the fermentation broth, concentration, catalyzed esterification of the ammonium lactate to butyl lactate and further hydrolysis to pure lactic acid, which can be transformed by lactate oxidase into pyruvate proposing a final ethanol production.

The production of fatty acids has been performed during the dark fermentation processes of KW (Slezak et al., 2021). Also, a two steps process was proposed, an initial anaerobic bioconversion with the mixture of KW and potato peels into short and medium chain volatile fatty acids and a further symbiotic co-culture of Klebsiella mobilis and E. coli under microaerobic conditions to favor chain elongation (den Boer et al., 2016). Simulated KW has been used to overcome the problem of the variation in composition. In the case of anaerobic digestion. Hafid et al. (2010) observed that the organic acids production was the highest in real KW. Hydrothermal pretreatment (150 °C, 60 min) from KW favored the floatable oil content and solubilization of organic components susceptible of being bioconverted to volatile fatty acids (Zhu et al., 2015).

The high starch and cellulose content render a raw material that can be converted to monosaccharide solutions or further dehydrated to hydroxymethylfurfural and levulinic acid (Esteban and Ladero, 2018). More recently, Tian et al. (2020) proposed a heterogeneously catalyzed successive transformation of KW to ethyl levulinate.

Bioplastics, named as polyhydroxyalkanoates (PHA), polyhydroxybutyrate, polyhydroxyvaleric acid and others (Esteban and Ladero, 2018), are promising substituents of synthetic plastics, but scalable, inexpensive production processes are needed to offer a competitive alternative. Different approaches have been developed for their production from KW, such as the conversion of waste into organic acids and their subsequent conversion into PHA, the production of syngas by pyrolysis and further fermentation (Beneroso et al., 2014), or the fermentative production of lactic acid, then used for polylactate production (Brigham and Riedel, 2019). Rao et al. (2019) incorporated different food (kitchen-/agro-) waste for reducing the cost and enhancing the production of PHA by Bacillus subtilis MTCC 144.

The production of advanced functional materials from wastes, particularly through green processes can contribute to a sustainable society (Kobayashi and Nakajima, 2021; Sharma et al., 2021; Esteban-Lustres et al., 2022). Gu et al. (2021) proposed the emulsion polymerization of KW with acrylic monomers to obtain biodegradable films with good sprayability, membrane formation and mechanical properties. These films showed promising application for agriculture since they reduced soil water evaporation and increase soil temperature, enhancing the germination rate and crop yield.

Different examples can be mentioned to illustrate the potential of KW for the production of commercially interesting enzymes, which can also be used for the hydrolysis of these wastes (Liu et al., 2019). Bhatt et al. (2020) reported the amylase production with Bacillus amyloliquefaciens KCP2 under solid state fermentation. The poor performance of solid-state fermentation due to the high-water content and poor porosity of KW was solved by the addition of corn stover or paddy husk to produce glucoamylase by Aspergillus niger UV-60 (Wang et al., 2010). By adequate selection of the operational conditions different final products can be obtained, i.e., Liu et al. (2019) used Bacillus agaradhaerens C9, to secrete various amylase, protease, lipase, cellulase, xylanase and pectinase, and under strong alkaline fermentation condition produced a bioflocculant useful to treat iron mineral processing wastewaters.

Recent examples of microbial conversion into valuable products can be found, Pan et al. (2021) performed a simultaneous enzymatic hydrolysis and fermentation of KW with commercial enzymes and Bacillus amyloliquefaciens HM618 to obtain a lipopeptide biosurfactant. Saleh et al. (2021) proposed the use of starchy KW as a low-cost effective substrate for bacterial cellulose production and loaded with either charcoal or graphite to remove cationic dyes from wastewater. Rishi et al. (2020) autoclaved KW, and the hydrolysate obtained by an in-house produced cocktail of enzymes, was used for fermentation by Aureobasidium pullulans MTCC 2013 to pullulan, with adequate properties to formulate a biodegradable water-soluble film (Fig. 2).

4.5. Solids valorization

The high carbon source and abundance of nutrients make KW an ideal raw material for the production of value-added products, including enzymes, organic acids, bio-fertilizers, biopolymers and biofuels. These could be obtained sequentially from food waste by applying the concept of biorefinery (Álvarez-Viñas et al., 2021; Carmona-Cabello et al., 2018; Carmona-Cabello et al., 2020; Kamal et al., 2021). An important development is expected in future, and some examples are summarized in this section.

The biomass processing can be performed by thermochemical, chemical, enzymatic and microbial processes. Compared to lignocellulose-based biorefineries, requiring harsh thermomechanical and chemical pretreatments before bioconversion, food waste biorefineries utilize a more susceptible biomass, rich in starch and protein. The resulting glucose, peptides and amino acids, can be the carbon and nitrogen source in further bioconversion into energy, platform chemicals and materials. Alternatively, the reduction in water content of FW allows its use as raw material for thermochemical biorefineries and this route can be coupled to bioconversion or with catalytic processes (Esteban and Ladero, 2018). Abundant examples of the biorefinery approach of pre-consumption food wastes containing valuable biomolecules, such as proteins, polysaccharides, lipids, vitamins, and minerals, have been proposed (Freitas et al., 2021), but direct recovery from post-consumption wastes is not reported. Sindhu et al. (2020) used food and KW as carbon source for the bioconversion to valuable products, susceptible of being combined in a biorefinery scheme, including poly-3-hydroxybutyrate with microbial consortiums of Bacillus and Enterococcus sp., bioethanol with Saccharomyces cerevisiae, 2,3-butanediol with Enterobacter cloacae SG1, and pectinase with Bacillus sonorensis MPTD1. Karimi and Karimi (2018) proposed the production of both bioethanol and methane from a kitchen and garden waste mixture (3:1), pretreated with dilute sulfuric acid at 120–180 °C, the liquid was detoxified, and the starch was enzymatically hydrolyzed before ethanol bioconversion with Mucor indicus. Both the dilute acid-pretreated solids and the biomass after fermentation were subjected to anaerobic digestion for biogas production (Fig. 3.a).

Kannengiesser et al. (2016) proposed the production of enhanced biodiesel properties by the recovery of medium chain fatty acids from organic municipal waste. The percolate was treated by anaerobic digestion, followed by two additional bioconversion stages for chain-elongation by adding ethanol to produce a fatty-acid rich liquid fraction. This liquid product was contacted with biodiesel generated from used kitchen oil to extract the non-polar fatty acids, and the biodiesel enriched with the fatty acids was esterified to a biodiesel with a lower viscosity and the fatty acids remaining in the raffinate after the treatment can be used to generate biogas (Fig. 3.b).

Wu et al. (2019) proposed a simple water washing pretreatment on KW in a biorefinery to obtain biogas, biodiesel, bacterial cellulose and a biofertilizer. Glycerol, a by-product in biodiesel stream, was used as carbon source to produce bacterial cellulose and the residual medium was anaerobically digested to produce biogas (Fig. 3.d). Water washing was needed to remove salts and used oil to favor bacterial celulose production and characteristics. The solid residues separated after the enzyme hydrolysis, mainly containing bone, meat, vegetables, etc., were co-composted to a biofertilizer with the solid residues from anaerobic digestion. Alternatively, glycerol could be used as carbon source for fermentation (Fig. 3.e).

5. Thermo-chemical processing of kitchen wastes

The biorefinery represents a sustainable approach for the integral utilization of resources into a wide range of high-value green chemicals, bio-based products, biofuels and power in a zero-residue sustainable process by combining thermal, chemical and biological stages. Targeting on multiple value-added products will improve the overall economics since different sectors can be involved, and the value of a particular feedstock is defined by the commercial value of the different products and market size. The development of efficient environmentally friendly technologies, the reduction in chemicals, time and energy for the integral valorization of the raw materials is also desirable (Carmona-Cabello et al., 2018).

The selective recovery of valuable molecules can be proposed as a first stage to valorizate agroindustrial preconsumption wastes. The choice of green techniques should be considered to lower solvent needs and to shorten time and energy consumption, reducing environmental impact (Carmona-Cabello et al., 2018). The potential of intensification technologies, such as ultrasound-assisted, microwave-assisted, and pressurized liquid treatment is mainly based on their reduction of organic solvents and short operation times (Freitas et al., 2021; Sharma et al., 2021; Gerschenson et al., 2021). Despite some fractions from KW comprise components also found in agroindustrial wastes; the valorization scheme for post-consumption wastes recovers the oil, whereas the carbon and nitrogen are solubilized by hydrolytic processes into oligomers and monomers used as carbon and nitrogen source during bioconversion.

Used cooking oils are produced in large quantities and there is a worldwide network for their collection, trading and transformation by different technologies implemented at the industrial scale, based on recovery, thermochemical and chemical-biotechnological approaches (Cárdenas et al., 2021). The collected oil and grease from restaurant wastewaters, found in different forms: free, mechanically dispersed,

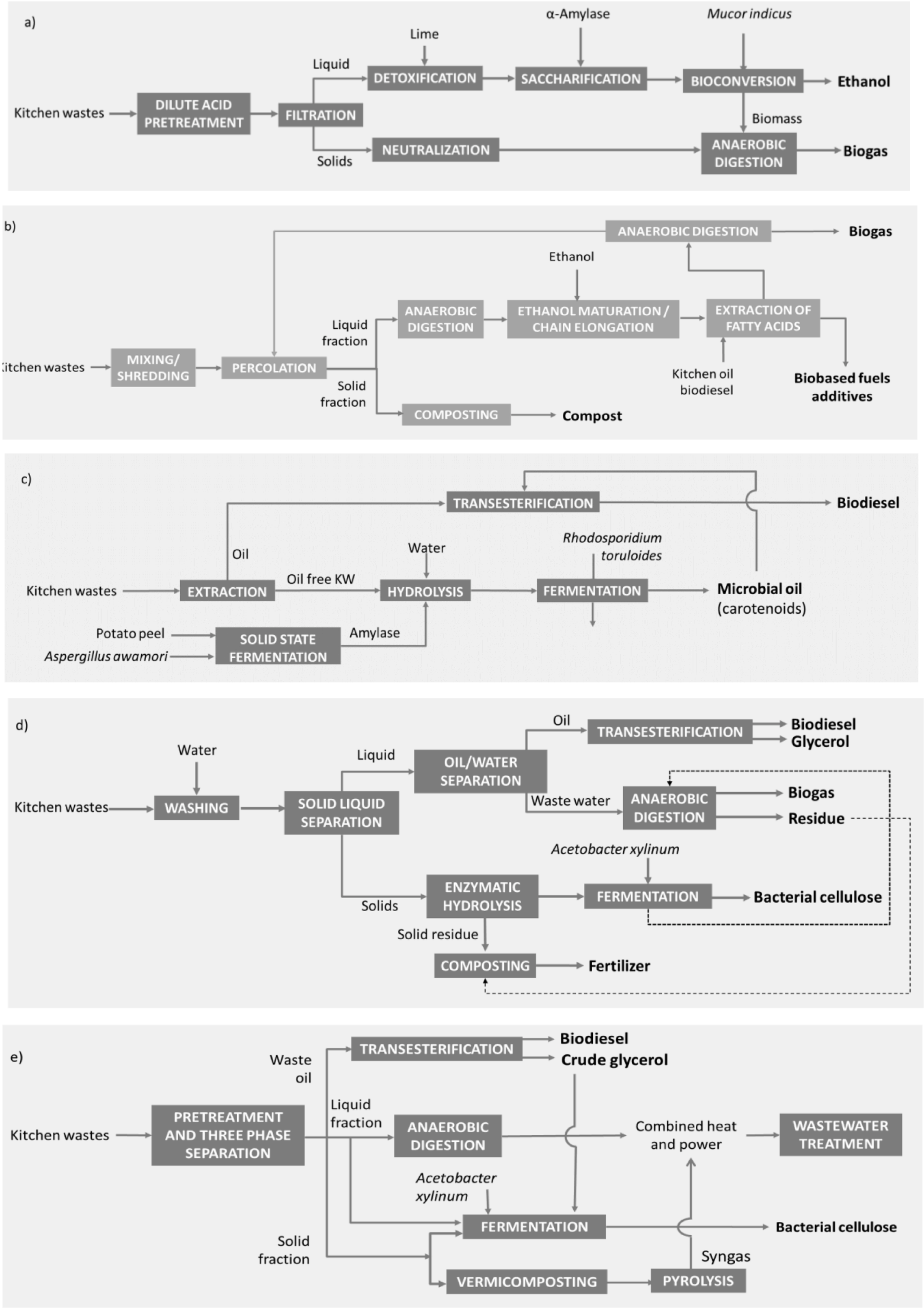

Fig. 3. Examples of biorefineries for the valorization of components from kitchen wastes by, production of ethanol and biogas (Karimi and Karim, 2018), b) production of compost, biogas and biodiesel (Kannengiesser et al., 2016), c) production of biodiesel in combination with enzymes produced from other wastes (Carmona-Cabello et al., 2019), d) production of biogas, biodiesel, bacterial cellulose and fertilizer (Wu et al., 2019) and e) production of biogas, biodiesel, glycerol, bacterial cellulose and fertilizer (Wu et al., 2021).

chemically emulsified, dissolved and in oil-wet solids, can be recycled to valuable products (Yau et al., 2021). Oil can be separated from solids by both mechanical separation and solvent recovery and can be separated from water in integrated equipments. Different patents illustrate the strategies for the separation of oil from solids and the combination with water removal, volume reduction and separation of metalic wastes, and also separated from wastewater (Jing and Shao, 2020). Most processing sequences include automatic equipment for filtering and gravity separation (He, 2016), shredding, drying, air removal, condensation and drainage (Chen et al., 2020), separation, pressure pulping, impurity separation, mixing, three-phase separation and oil storage (Liu et al., 2021). The final use of the waste after crushing or after sorting, crushing, extrusion, dehydration, oil–water separation and pulping can be biogas production by anaerobic digestion (Li and Li, 2020) or, after drying, fermentation, decomposition and odor purification, could be used as fertilizer (Hu et al., 2021). Alternatively, a high-pressure extrusion technology for solid–liquid separation has been claimed before removal of impurities and oil (He et al., 2018). Heating can aid for solid–liquid separation before three-phase centrifugation (Yang, 2020), or before sorting, squeezing and filtering (Song and Wen, 2020) or to aid in the mechanical separation of oil, pressing and packaging of residues, purification of wastewater, and treatment of gas and solid (Cai et al., 2020).

The physicochemical characteristics of used kitchen oils depend on the oil, cooking practices and waste management. The high temperatures during cooking can cause degradation reactions, leading to the formation of free fatty acids, peroxides, polymers, volatile organics, nitrogen- and sulfur-containing compounds. The high heterogeneity and impurities affect further thermal, chemical and biochemical routes of valorization, but in less extent to thermal pyrolysis or gasification (Cárdenas et al., 2021).

5.1. Biodiesel

Biodiesel production is an attractive option to utilize the lipid fraction hindering methane production during anaerobic digestion of solid KW. Waste cooking oils are low-cost feedstocks for the sustainable biodiesel production without competing with human edible oils (Pirani and Arafat, 2014; Ho and Chu, 2019; Supraja et al., 2020), with lower emissions and safer transportation and handling than non-renewable fuels.

Transesterification is widely used, based on the reaction of triglycerides with short chain alcohols in the presence of catalyst to form esters and glycerol. Both fatty acids and water hinder the alkaline transesterification of used cooking oils, by inducing saponification, reducing catalyst activity, and difficulting separation. Different alternatives lower the free fatty acid content, including biological conversion, acid or supercritical esterification, steam stripping, nanocatalytic technology, glycerolysis, adsorption, membrane separation and solvent treatment (Cárdenas et al., 2021).

Microwave, ultrasonic and hydrodynamic cavitation, are cleaner intensification approaches to lower the energy consumption due the need of high temperature and pressure, and to overcome mass transfer resistance in the biphasic system for biodiesel production. Ultrasounds (25–45 kHz) can favor the interaction between alcohol and fatty acids

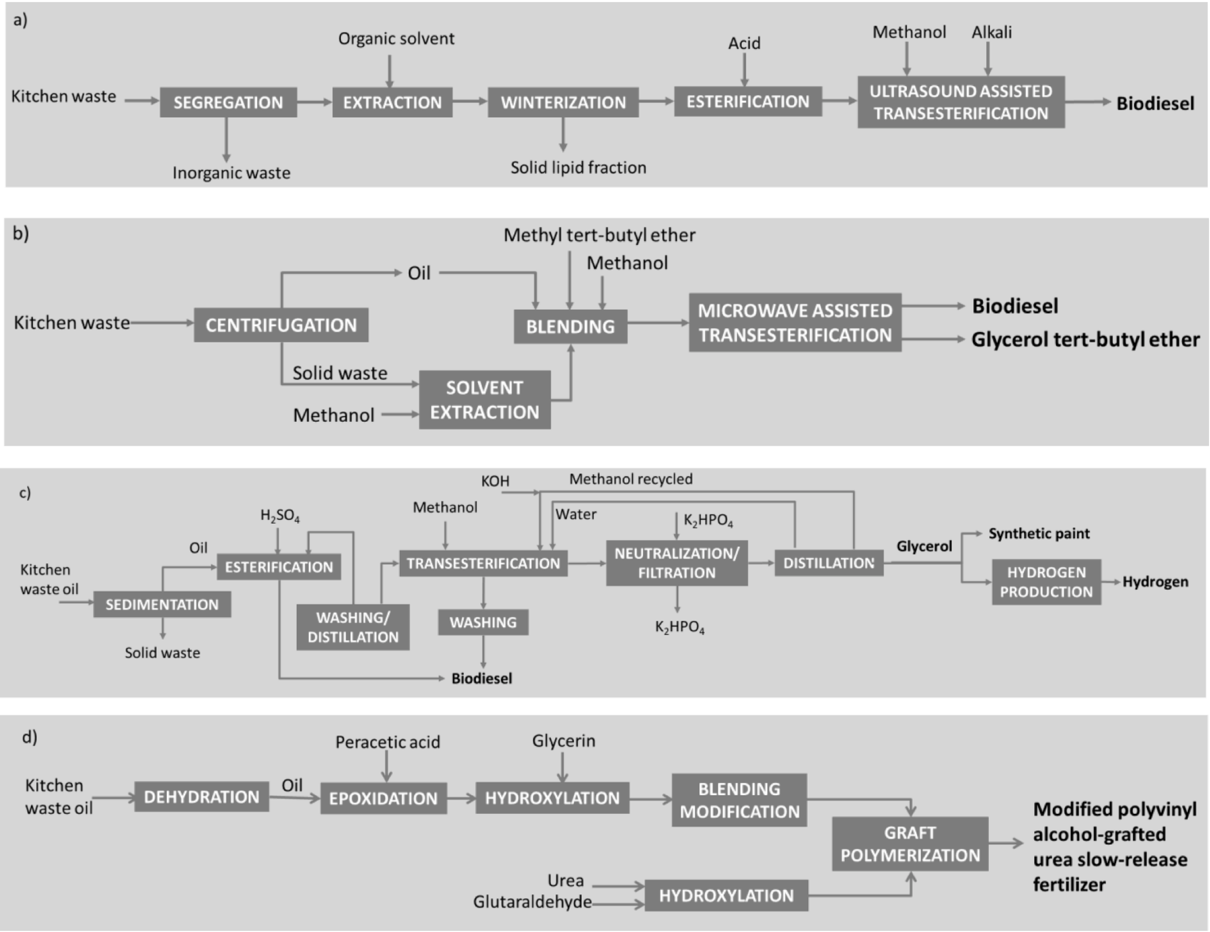

Fig. 4. Examples of utilization of the lipid fractions separated and extracted from KW for the production of a) biodiesel (Carmona-Cabello et al., 2019), b) biodiesel (Priyadarshi and Paul, 2018), and direct utilization of kitchen waste oil to obtain c) different products (Taipabu et al., 2021) and d) modified polyvinyl alcohol-grafted urea slow-release fertilizers (Qi et al., 2022).

during transesterification (Cárdenas et al., 2021). Carmona-Cabello et al. (2019) applied ultrasounds to the transesterification of the oil extracted from a mixture of KWs (Fig. 4.a) and Sáez-Bastante et al. (2020) to the production of biodiesel at room temperature from fat residues from a kebab restaurant. Ultrasounds have also been used for the synthesis of a reusable catalyst with enhanced performance in solar-heated transesterification of waste cooking oil (Tabah et al., 2017). Le et al. (2010) applied low frequency ultrasounds (20 kHz) for the transesterification of used kitchen oil with methanol, with potassium hydroxide as a catalyst. Maceiras et al. (2017) reported a reduction in operation time and catalyst consumption compared to conventional method and Poppe et al. (2018) reduced the costs of transesterification with immobilized lipases. Gupta and Rathod (2018) used microwave assisted intensification of biodiesel production from waste cooking oil to double the efficiency of a heterogeneous catalyzed process compared to conventional heating and the fuel properties of biodiesel met the standards. Supraja et al. (2020) proposed the conversion of waste cooking oil with high fatty acid content into biodiesel with physicochemical properties comparable with the standards via acid-catalyzed esterification. An ultrasound and microwave hybrid installation for the transesterification of vegetal oil with ethanol under heterogenous acidic catalysis has been used (Călinescu et al., 2021). Priyadarshi and Paul (2018) proposed the biodiesel production from lipid phases mechanically separated from restaurant KW, the lipid extracted by conventional solvents from the dried solids and those further separated from the aqueous phase by centrifugation (Fig. 4.b). Microwave assistance lowered the energy demand, the biodiesel showed improved cetane number and the byproduct glycerol *tert*-butyl ether is a useful fuel additive.

5.2. Pyrolysis

Bio-oil with a high caloric value and yields in the range 64–80 % have been obtained from waste cooking oil, but the high acidity and high viscosity limit the direct use in engines (Kraiem et al., 2017). Alternatively, this bio-oil could be used for chemical synthesis, the syngas produced could be an energy source in the pyrolysis reactor and the solid or biochar was suitable as fertilizer. Pyrolysis using microwave heating offers a promising energy-efficient and time saving alternative for the conversion of used frying oil into a biofuel with improved properties. Lam et al. (2017) applied microwave heated pyrolysis of used food oil in a bed of activated carbon and obtained a biofuel with calorific value nearly comparable to diesel fuel, free of carboxylic acid and sulphur, with low amounts of nitrogen and oxygenated compounds. Co-pyrolysis with other materials has been tried, i.e., Wan Mahari et al. (2018) confirmed that microwave co-pyrolysis of a mixture of used frying oil and polyolefinic-based plastic waste yielded a fuel product with improved stability and fuel properties similar to transport-grade diesel, with low oxygen content, free of nitrogen and sulphur and high energy content (42–46 MJ/kg). They observed positive synergistic effects resulting in fast heating rate and a lower reaction time, with up to 81 % bio-oil yield and 18 % gas yield.

5.3. Other applications

Oil-rich fractions from KW are good raw materials for valuable green chemicals, such as polymers, biomaterials, building blocks, resins, surfactants, soaps, plasticizers, and lubricants (Ho and Chu, 2019; Gaur et al., 2022). Some of these alternative valorization schemes have been summarized in Fig. 4.c. Oil-based polymer materials have advantages because they are hydrophobic, inexpensive and environmentally friendly. Qi et al. (2022) proposed KW oil to prepare modified polyvinyl alcohol grafted urea with good hydrophobicity and degradation when used as slow-release fertilizer, reducing environmental pollution and water eutrophication. Das et al. (2018) used waste kitchen chimney oil to prepare fluorescent multifunctional highly stable and biocompatible carbon quantum dots, with optical properties suitable for sensing, bio-labeling, light emitting nano-composite and biomedical applications. They proposed a cost effective and simple method based on ultrasonication during 10 min using concentrated sulfuric acid at 100 °C, further dilution, neutralization, centrifugation and dialysis (1 kDa). Fernandes et al. (2020) used KW oil as a substrate for Wickerhamomyces anomalus to obtain a biosurfactant, efficient against Aedes aegypti larvae, responsible for dengue epidemics, and also showed antibacterial, anti-adhesive, and antifungal activity.

6. Challenges and opportunities for management of kitchen wastes

Kitchen waste is a zero-value worldwidely available resource, continuously produced in household and foodservices (Hafid et al., 2017; Dhinam and Mukherjee, 2021; Mahjoub and Domscheit, 2020). Since not all these wastes can be avoided, this global issue requires innovative management and valorization solutions as well as their integration into the bioeconomy. The presence of valuable organic material offers potential for conversion into a vast range of bioproducts, chemicals, or energy through different processes (Mahjoub and Domscheit, 2020). Table 1 summarizes the major challenges and opportunities in relation to the valorization of the organic fraction of these post-consumption wastes, starting with the need of standard methodological tools for quantifying food waste generation (Withanage et al., 2021). The effective conversion of food to valuable resources is often challenged by the high moisture content, heterogenous nature and variability, depending on the particular service, being inconsistent in production rate and volume, and often geographically distributed (Sindhu et al., 2019; Engelberth, 2020). Proper collection, storage, segregation and the difficulties for separating from municipal solid waste are among major identified needs. The high variability depending on the source does not recommend the same strategy for all of them (Sindhu et al., 2019; Dhinam and Mukherjee, 2021; Mahjoub and Domscheit, 2020). Separation according to their sources and types helps reducing the composition variability and increases the consistence in waste-derived products (Ho and Chu, 2019). Previous conditioning to lower the water content would facilitate storage due to lower risks of microbial contamination, easier management and transport.

The development of innovative biobased industries is valid for the valorization of waste fractions through the integral utilization of resources, minimizing fossil-fuel dependency (Maina et al., 2017). The wastes collection in a common consolidated facility aimed at processing a combination of waste streams from food services, households, and from different sector, such as forestry, agriculture, aquaculture, agrifood, paper, energy or chemistry, aimed at obtaining an assortment of products, would likely be the most efficient and profitable (Engelberth, 2020; Mahjoub and Domscheit, 2020). Additionally, small and medium scale biorefineries can be associated with large restaurants to minimize the expenses of transportation (Dhiman and Mukherjee, 2020).

Further research for novel products and development of efficient technologies, with moderate cost, ecologically correct and scalable is required, needing an integration between academic studies and industrial applications (Mahjoub and Domscheit, 2020; Freitas et al. 2021). Cárdenas et al. (2021) suggested the need of designing resilient technologies implemented by intensified approaches for processing wastes with high variability and heterogeneity to overcome the limitations of traditional processes, performing simultaneous pre-treatment and valorization, aiding in reducing food waste and environmental impacts and consolidating sustainable production models. Process intensification represents a tool to replace large, expensive, energy-intensive equipment or processes by smaller, less costly, more efficient plants (Sharma et al., 2021).

Both the potential recovery of high-value products and environmental impact evaluation such as lifecycle assessments and techno-economic analyses are vital for large-scale implementation. Decisions should also consider environmental and social concerns, requiring a holistic program and strategy for the implementation of sustainable development goals worldwide with governmental support in policies and legislations to mitigate and utilize food wastes (Engelberth, 2020; Mahjoub and Domscheit, 2020). Regulations should incentivize sectorial synergies and diversity of products, but also services, infrastructures and consumer's attitude towards waste-based products must be studied and modified through public awareness enhancement, including behavioral changes to reduce of food waste in households and restaurants (Pelt et al., 2020). Interactions between various intermediary stakeholders are needed to establish links between various sectors and a compromise between the economic, environmental and social aspects. In order to connect and develop such interactions, collaboration among both public and private organizations is needed (Mahjoub and Domscheit, 2020).

7. Conclusions

To conclude, the advance in biorefineries of KW using flexible technologies such as subcritical water, microwave or ultrasound to supply products similar to those produced via the fossil fuel processes, involves consideration not only of productivity but also aspects related of environmental safety. The bioeconomy model has been described as a potential emerging market, where the KW can be collected, processed, and regarded as a primary material for conversion to greener and sustainable products. A rational and integral utilization of KW can be technically feasible by designing suitable management strategies established as a collaboration of different agents.

CRediT authorship contribution statement

Rebeca Esteban-Lustres: Writing – original draft. **María Dolores Torres:** Conceptualization, Writing – original draft, Writing – review & editing. **Beatriz Piñeiro:** Writing – review & editing. **Cristina Enjamio:** Writing – review & editing. **Herminia Domínguez:** Conceptualization, Writing – original draft, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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