Perspective

Biofpr Biofuels Bioproducts & Biorefining

Current and future trends in food waste valorization for the production of chemicals, materials and fuels: a global perspective

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Received March 8, 2014; revised May 22, 2014; accepted June 2, 2014
View online at Wiley Online Library (wileyonlinelibrary.com); DOI: 10.1002/bbb.1506;
Biofuels, Bioprod. Bioref. (2014)

Abstract: Food waste is currently generated in significant quantities worldwide. While most of this has generally few uses different from landfilling or composting, advanced valorization alternatives should be developed to maximize the value derived from such an important waste source. This contribution aims to illustrate a series of examples and current valorization strategies proposed in different countries in order to tackle the food waste issue. Proposed processing schemes involve biorefinery approaches based on both chemical and biological technologies. Important legislation aspects in different countries are also presented. © 2014 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: food waste valorization; biorefinery; bioprocessing; green chemical conversion; waste water; platform chemicals

Introduction

Environmental concerns, the recent economic crisis, and political issues have created the need for industrial innovation that can lead to new job opportunities, enhanced competitiveness, and improved economic growth. Replacement of fossil resources for the production of chemicals, materials, polymers, energy, and fuels can only be achieved through efficient utilization of renewable resources and exploitation of renewable carbon. Sustainable industrial development will rely on the efficient exploitation of agricultural and forestry residues,

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aquatic biomass, and various waste streams by means of integrated biorefining, industrial symbiosis, cascade processing, on-site processing of seasonal waste streams, extraction of specialty products, and conversion through green chemical or biotechnological processes. Food supply chain waste residues constitute a major resource for the development of bio-based processes.[1,2]

The successful transition to the bioeconomy era will be achieved by restructuring significantly current manufacturing practices. For instance, in the food industry, the traditional meaning of 'processing' is associated with transformation of the initial raw material into a food product with optimum structure, properties, quality, safety, and nutritional requirements. However, in the dawn of a bio-based society, food processing should also provide viable alternative schemes that combine food production with minimization of energy consumption and water usage as well as valorization of waste and by-product streams. Packaging should also be included as an essential processing aspect considering both the production of a safe, fresh, and high quality food product, while recyclable or re-usable in a cascade system for different value-added applications. Pyrolysis of PET could for instance lead to the production of sodium terephthalate that can be subsequently utilized as precursor for the fermentative production of medium chain length polyhydroxyalkanoates under fed-batch fermentation of *Pseudomonas putida* GO16.[3] In the future, any sustainable industrial sector should rely on bio-based or (ideally) entirely biodegradable polymers for packaging applications.[4] It should be stressed that bio-based polymers include those polymers that are entirely or partly produced from renewable resources.[5]

Valorization of food waste could be combined with improving shelf-life of food products. The extraction of compounds with antioxidant and antimicrobial activity from waste and by-products could be incorporated in biodegradable packaging articles produced via fermentation using food waste streams. Hafuka *et al.* employed fermented food-waste liquid as carbon source for fed-batch cultivations of *Cupriavidus necator* leading to the production of polyhydroxybutyrate.[6] Campos *et al.* showed that whey protein isolate could be used for the production of edible films with incorporated natural antimicrobials (e.g. oregano or clove essential oils) that enhance the microbial quality of poultry.[7] The benefits of such practices include the development of processes with lower carbon footprint, the production of biodegradable packaging materials and the improvement of shelf-life of food products. Antioxidant compounds could be also used in other industrial sectors.

Industrial symbiosis should be accomplished in order to allow utilization of co-products and processing streams by different industrial sectors. Furthermore, integration of chemical production in a traditional food industry is a new concept that will create significant added-value and investment opportunities. This argument could be supported by the fact that, in 2007, the industrial sectors of food and beverages, and chemicals including pharmaceuticals were among the largest three industrial sectors in EU-27 regarding added-value and investments.[8] Valorization of food waste via integrated biorefinery schemes should target the production of both commodity and specialty products. As an example, producing high-value products for cosmetic, pharmaceutical, and neutraceutical applications could provide the profitability margin that is necessary for the generation of low-value higher-volume products including chemicals and biodegradable polymers. For instance, bioethanol production from olive pulp waste and orange processing waste streams could be cost-competitive only in the case that value-added products are extracted prior to further processing.[9,10] Development of optimum resource utilization could combine the extraction of high value compounds with production of fermentation products. Kachrimanidou *et al.* presented processing schemes for the production of polyhydroxybutyrate and other co-products from various industrial waste and by-product streams including wine lees.[11] The quantities of value-added co-products contained in food waste are significant in certain cases. The main problem for ensuring the profitability of the whole integrated process is to identify diversified market applications to avoid saturation of a single market outlet.

Integration of chemical production in existing food industries using food waste can also provide a low cost source of carbon. The development of large-scale fermentative production of commodity chemicals is mainly hindered by the high cost of raw materials (mainly purified sources of carbon such as glucose or sucrose) used in traditional fermentation processes. Furthermore, integrated production of chemicals in existing food industries could reduce fixed capital investment, which is also significant in traditional fermentation processes and hinders industrial implementation.

Food waste is produced along any stage of the supply-chain extended from the agricultural site to the processing plant and finally the retail market. Although the capacity of food waste production is significant, the variability in composition and the seasonal production of case-specific food waste are important drawbacks that hinder industrial implementation. Current food supply chain waste streams are exclusively processed in basic waste management/

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valorization strategies as animal feed, for the production of compost and fertilizer as well as anaerobically digested to biogas. Importantly, selected food waste residues can be in principle used for the extraction or production of value-added products (e.g. whey protein isolate, essential oils).

In the light of the above premises, this contribution aims to showcase a number of studies focusing on integrated valorization of food supply chain waste for the production of a variety of products ranging from biomaterials to chemicals and fuels. Processing schemes include green chemical conversion routes and biotechnological applications.

Updates in the valorization of food supply chain waste in different areas around the globe

In this section, some examples of recent developments in the area of food waste valorization in different regions are presented.

Cheese whey waste water

Cheese whey waste water (CWW) is a by-product coming from the precipitation and removal of milk casein during cheese manufacturing. There are three types of waste-water streams in a cheese manufacture unit, which, herein, will be referred to as CWW, regardless they are mixed or not. These include cheese whey from cheese cutting and mature phase, cheese whey after soft cheese production, and wash-out water containing cheese, milk residues, detergents, etc. All three streams contain milk constituents and their derivatives at some extent. For example, cheese whey retains most of the milk lactose. Apart from lactose (39–60 kg m^{-3}), cheese effluents also contain proteins (1.4–33.5 kg m^{-3}) and fats (0.99–10.58 kg m^{-3}), mineral salts (0.46–10%), calcium salts, lactic acid, citric acid, urea and others.[12]

The organic content of CWW accounts for 50–102 kg COD m^{-3} and 27–60 kg BOD_5 m^{-3} with a BOD_5/COD>0.5. CWW is produced in large quantities (9 kg CW per kg cheese produced according to Siso or 2.3 L waste water per kg cheese produced after whey recovery according to Economopoulos.[13,14] Because of the large quantities produced and the high biodegradable CWW organic fraction, CWW is currently considered as a residue instead of as valuable source of matter and/or energy. CWW management has been restricted mostly to disposal practices. However, as technology develops, the focus turns to upgrading the potential of CWW major components (lactose and proteins). Moreover, the stringent legislation on waste disposal contributes into exploring feasible alternatives to recover and/or produce high-added value products as well as energy from CWW.

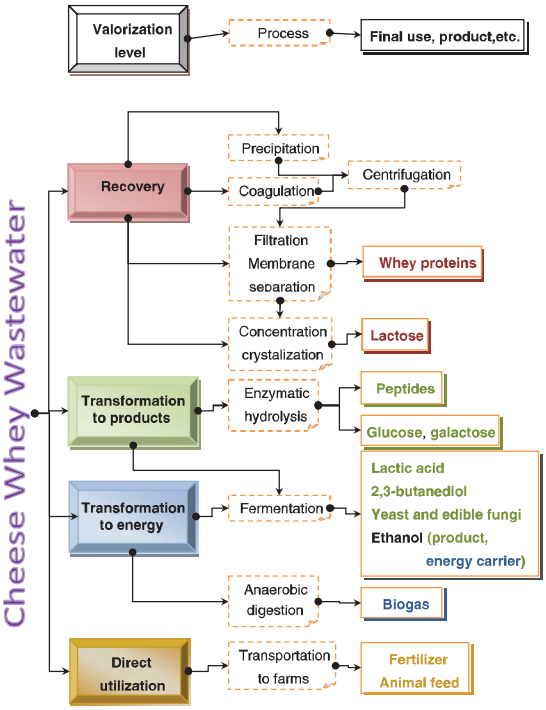


Figure 1. Options for CWW valorization.

There are several levels of valorizing waste; recovering the already existing high-added value compounds, utilizing (chemical, thermal, biochemical) transformation processes to convert the key compounds to high-added value compounds, converting the organic matter into energy carriers (biogas, hydrogen, ethanol, etc.) or using it directly as a fertilizer (e.g. land application through irrigation) or animal feed (Fig. 1). All these options have been studied in the case of CWW and the highest product yields are summarized in Table 1.

Recovery processes

Lactose and its derivatives are used in the food and confectionery industry as an additive that prolongs storage life, increasing the weight of products (filler) without altering the flavor, etc., as well as in pharmaceutical industry as excipient.[24,25] It is also used in non-food applications such as protein based films and biomaterials.[26] Proteins originated from milk, have been used in the production of functional foods or pharmaceutical formulations.[19]

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Table 1. Overview of the main CWW valorization options.

Product or use/process	Conditions	Yield	Reference
Proteins/precipitation	duration: 37.5 min, pH:4.5 & 5.3, T=93°C	79% protein, 20.5% fat	15
Proteins/ thermocalcic precipitation and microfiltration & ultrafiltration–diafiltration	1.53% protein, 1.11% fat in the dry matter pH 7.3-7.5, $CaCl_2$: 1.2 g L^{-1}, 50°C, 8 min	66.85% protein, 0.4% fat at the diafiltration retentate	16
Proteins/ coagulation with chitosan	pH: 4.5, chitosan 0.25 mg ml^{-1}, removal of precipitate & pH: 6.2 chitosan 1.9 mg ml^{-1} duration: 10 min	The 1st treatment removed 95% turbidity and the 2nd yielded 95% recovery of β-lactoglobulin	17
Proteins/coagulation with polyacrylic and trichloroacetic acid	duration: 1 h, pH:3.8-4.2, T=18°C	62–87%	18
Proteins/membrane separation (potential lack uniformity in protein composition)	Ultrafiltration, Microfiltration, Nanofiltration Reverse Osmosis	28–85% 56–81% 87–100% 94–96%	12
Lactose/membrane separation and spray drying for purification	Nanofiltration Reverse Osmosis	>89%	12
Bioactive peptides/mild enzymatic hydrolysis	pH: 6-8, T: 40-60° C addition of protease	<10% hydrolysis to avoid bitterness	19
Hydrolysis products of lactose/ enzymatic hydrolysis	β-galactosidase immobilized	80–95%	20
Lactic acid/fermentation	Immobilized or free cells of mixed or pure cultures of *Lactobacillus* genus species, pH 6-6.5, lactose: 30–100 kg m^{-3}, HRT: 24–78h, T:ambient-32° C	70–100%lactose conversion, lactic acid concentration: 11–52 kg m^{-3}	12
Ethanol/fermentation	Pure cultures, pH 3–7, lactose: 35–150 kg m^{-3}, HRT: 18–70 h, T:ambient-45° C	83–100% lactose conversion, ethanol concentration: 20-81 kg m^{-3}	12
Single cell protein/ fermentation	pH 3.5 and 38°C	50%	13
Biogas/anaerobic digestion	Two-phase systems (acidogenesis-methanogenesis), loading: 11–25 kg COD m^{-3} d^{-1}), HRT 1.8–4.5 d	0.33–0.345 m^3 CH_4 kg^{-1} COD_{fed} at STP	21
Hydrogen/fermentation	Pure or mixed cultures, indigenous microorganisms, pH: 5–7, HRT~1d	0.8–2.5 mol H_2 mol^{-1} equivalent glucose, 20–60% content in biogas	12, 22
Fertilizer/application on field	Dilution 1:20, salt loading 40–60 kg total salt ha^{-1}		23

HRT: hydraulic retention time, COD: chemical oxygen demand

The processes used to recover proteins and lactose from CWW are physicochemical: thermal and isoelectric precipitation, coagulation and flocculation and membrane separation.[12] The CWW should be immediately processed since microbial activity is favoured on a lactose rich feedstock due to the indigenous micro-organisms. Alternatively, CW should be stored at 5°C to temporarily stop the microbial activity. Lactose can be obtained from CWW through crystallization on pre-concentrated whey (60–62% dry matter) without or after protein removal. The crystallized lactose is separated usually via centrifugation and then is dried and grounded to powder.

CWW proteins involve mainly the beta-lactoglobulin and a-lactoalbumin as well as serum albumin, immunoglobulins and protease-peptones.[27] These proteins have high affinity for water and do not precipitate with casein during cheese making procedure. As a result, they remain in the CWW. The precipitation of proteins is based on their denaturation properties. Denaturation of proteins occurs at elevated temperatures (90–120°C) or at the isoelectric pH value of the protein. Upon denaturation, proteins unfold and aggregate. However, for each type of CWW (characterized by different protein concentrations, ionic strength, mineral salts, etc.), the parameters such as temperature, duration and rate of heating and optimum pH should be specified and controlled precisely.[15] After thermal treatment, the thermal stability or functionality of the recovered proteins is a challenge for the food industry.[28–32]

Following precipitation, processes such as centrifugation and filtration are applied to separate and purify the protein fractions. Since lipids may be present in the precipitated aggregate, membrane pore fouling is possible.

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These lipids are phospholipoproteins resulting from the fat globule membrane. Fauquant *et al.* and Pereira *et al.* showed that a pretreatment step (thermocalcic precipitation), involving the formation and removal of insoluble lipid–calcium phosphate aggregates at moderate temperatures and neutral, enhance the performance of membrane filtration.[16,33]

Another option for protein recovery is the coagulation of the CWW with chitosan (manufactured from the outer shell of crustaceans). After protein removal, the CW contains lactose of high purity (99.89%). Since chitosan regeneration with acid increases the cost and decreases the adsorption efficiency, novel molecular imprinting methods have been developed to overcome the drawback of using the natural chitosan.[34,35] Coagulation with chemicals such as polyacrylic and trichloroacetic acid has also been studied and was found to yield a 85.7–86.7% protein recovery.[18]

Compound separation via membrane filtration is an established technology. Its main drawback is the operational cost due to the high energy for applying the required pressure and the frequent cleaning of the membranes due to fouling. There are mainly four levels of membrane separation: microfiltration, ultrafiltration, nanofiltration and reverse osmosis. The particle or molecule size determines the permeation or the rejection from the membranes, while separation of small molecules is influenced mainly by the chemical nature of the compounds. Prazeres *et al.* reviewed the performance of various membrane systems and concluded that microfiltration and ultrafiltration are effective mostly for removing fat and proteins, while ion exchange and reverse osmosis are more suitable for lactose purification and concentration.[12]

Transformation processes to chemical production

Enzymatic transformation

Peptides obtained from milk by-product have attracted the attention of the scientific community due their functional properties and their positive impact on health.[36] Peptides are the products of protein hydrolysis and can be obtained directly from CWW under mild conditions (pH 6–8 and 40–60 °C). Urista *et al.* reviewed the production and functionality of the main peptides obtained from milk and cheese whey protein.[19]

Lactose can be utilized directly by fewer microorganisms than its monomers (glucose and galactose). Therefore, the prior hydrolysis of lactose may be preferable for the addition of cheese whey in food products (especially in the case of consumers who have intolerance to lactose). Lactose hydrolysis can be chemical or enzymatic. Chemical hydrolysis takes place in harsh conditions (pH of 1.2 and 150 °C) with undesired side effects and is generally not preferred.[13] Enzymatic hydrolysis is achieved via lactase. Lactase is produced by a restricted number of yeast and microfungi to be safely consumed by humans (according to the legislation) such as *Kluyveromyces lactis* and *K. fragilis, Aspergillus niger* and *A. oryzae*. The hydrolysis may be homogeneous or heterogeneous but the latter is more effective in terms of productivity. More details upon enzymatic conversion having been applied on CWW can be found in several reviews such as Siso,[13] Kosseva *et al.*,[20] and Illanes.[37]

Fermentation

Common products of fermentation of lactose are lactic acid, ethanol, volatile fatty acids (acetic and propionic acids), 2,3-butanediol, etc.,[13] all of which are high-added-value products serving as chemical platforms for the formation of various products.[26] Separation and purification of the metabolic products remains an important issue.

The majority of studies have been focused on lactic acid and ethanol fermentation. Lactic acid is used as a preservative and acidulant in food and chemical industry. It has also been used as a component of biopolymers.[38] The bacteria responsible for its production belong to the *Lactobacillus* genus, abundant in the cheese whey. The lactic acid can be produced in high concentrations (11–52 kg m^{-3}) and at high rates under surplus of nutrient supplements (manganese, yeast extract, peptone, etc.) in heterogeneous bioreactors.[12] On the other hand, cheese whey lactose fermentation to ethanol is hardly considered economically competitive to feedstocks such as cane sugar or lignocellulosic biomass.[39] The factors that could improve the economics and the yield of the process are the lactose concentration at the level of 200 kg m^{-3} (final ethanol concentration up to 10–12%), the absence of proteins in the CWW and the pre-hydrolysis of lactose.[39–41] Ozmihci and Kargi estimated that the cost entailed in the cheese whey powder production (as a mean of lactose concentration instead of direct lactose concentration through ultrafiltration processing) can be compensated by the reduction in the cost of the evaporation of mixture higher in alcohol content.[42] Ethanol production under anaerobic conditions is even less efficient.[12] Ethanol from CWW can be used in various industries (food, chemical, pharmaceutical, and cosmetics and as a biofuel).

CWW have been used as a substrate for single cell protein (SCP) production. Yeast species such as

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Kluyveromyces lactis, K. fragilis, Torulopsis bovina can be grown under continuous operation at specific conditions (e.g. pH 3.5 and 38°C) to avert contamination by bacteria. Precautions should be made to avoid ethanol formation. The yield in dried yeast may be up to 50% of the weight of the lactose used.[13] Yeast biomass, after recovered and dried, can be used as an animal-feed supplement but also in human foods and as bakery yeast.[43] CWW can also be used as a substrate for edible mushroom production.[44]

Transformation processes to energy

Biogas formation

Biogas production from CWW is feasible through the application of anaerobic digestion, a mature technology through which energy recovery is combined with pollution reduction. Under anaerobic conditions, the organic matter is broken down successively by several groups of microorganisms to a gas mixture (biogas) consisting of methane and carbon dioxide. Anaerobic digestion is usually applied to stabilize waste of high organic load, such as sewage sludge and agroindustrial waste including CWW. Due to the high content of lactose in CWW and its low alkalinity, the biogas plants usually depend on a robust pH control system and/or proper bioreactor configurations (single or two-phase systems separating the acidogenesis and the methanogenesis phases).[12,22,45,46] Yields close to the maximum (0.33–0.345 m^3 CH_4 kg^{-1} COD_{fed} at STP have been recorded in two phase systems operated under a high organic loading rate (11–25 kg COD m^{-3} d^{-1}) and hydraulic retention times close to 1.8-4.5 d at mesophilic conditions.[21] The presence of lipids in the CWW may cause operational problems because of potential sludge floatation.[47]

Hydrogen production

Hydrogen is considered to be an alternative environmentally friendly energy carrier, the combustion of which does not produce greenhouse gases. Biological methods for hydrogen production involve biophotolysis of water or the action of photosynthetic and chemosynthetic- fermentative bacteria. Dark fermentation seems to be more promising since it does not depend on photoenergy and a wide variety of renewable biomass can be utilized as long as it is rich in soluble carbohydrates. Fermentation of hexoses to various metabolic products may be accompanied by hydrogen production. This happens if acetic or butyric acid is produced, while in the case of propionic acid production, hydrogen is consumed. When the metabolism is shifted to lactic acid or ethanol there is no hydrogen production.

There are several studies conducted on CWW using pure cultures of hydrogen forming microorganisms or using the indigenous microflora of the CWW.[48–50] In the case of mixed cultures, the pH (or the alkalinity provided) determines to a great extent the metabolic products of fermentation (and as a consequence if hydrogen can be produced). Other important parameters are the hydraulic retention time (should be low enough to avert methanogenesis), trace metals, partial pressure of hydrogen (should be low enough to avert product inhibition), carbohydrate concentration, operation type (batch operation favours hydrogen production compared to continuous) as reviewed by Tommaso *et al.* and Prazeres *et al.*[12,22] The yields reported so far are low (0.8–2.5 mol H_2 mol^{-1} equivalent glucose) compared to the maximum yield (4 mol H_2 mol^{-1} equivalent glucose) at hydraulic retention times of the order of 1 d and a biogas content in hydrogen of 20–60%. An important and challenging issue in the research of biohydrogen production is to comprehend the action of the hydrogen consuming bacteria which decreases the yield. The low hydrogen yield through bioprocessing combined with the high cost of recovery, purification, and storage of hydrogen have increased skepticism against this option. However, the recent concept of biohythane production (a mixture of hydrogen and methane) could be applied using CWW as feedstock in a two stage process, and, instead of isolating hydrogen mixing it with the biogas produced in the subsequent step to make an efficient biofuel mixture.[51]

Direct utilization

Due to the high-quality proteins and lactose, calcium, phosphorus, sulfur, and water-soluble vitamins, CWW can be supplied into drinking waters for farm animals if lactose and mineral proportions are within certain limits.[13] CWW contains organic matter, nutrients and trace metals so that it could potentially be used as a fertilizer and spread on the land. There are many limitations, however, which restrict its use as a fertilizer. The high salinity could have a negative impact on the physicochemical structure of soils.[52] Dilution with water (at a ratio of 1:20) to lower the salinity and a surfacing loading of 40–60 kg total salt ha^{-1} could be acceptable.[23] Land application should be avoided if the aquifer zone is close to the surface or other water sources are near the application area. The positive effect of CWW application has been demonstrated in the case of basic soils where pH drops at the desired levels.[53] The degradation of CWW organic matter on land also favours the organic extracellular compounds formation stabilizing the aggregates formed, although excessive degradation could deplete the oxygen from the

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soil affecting the microflora.[12] Moreover, the cost of transferring large quantities of CWW in farms for animal feeding or land application may be prohibitive.

Winery waste and by-products

Worldwide wine production is about 280 million hectoliters.[54] The main waste and by-product streams produced are grape stalk, grape pomace or grape marc, waste water, and wine lees (Fig. 2). The disposal of such waste streams without treatment cause significant environmental pollution. Among the proposed routes to tackle this problem, the development of novel biorefinery concepts could provide a viable and sustainable solution.

Grape stalks are of lignocellulosic nature with a significant mineral content. Grape stalks are traditionally burnt in the field causing significant environmental problems through the release of toxic compounds (polycyclic aromatic hydrocarbons) and greenhouse gases. Grape stalks could be utilized for the production of C5 and C6 sugars that could be employed in fermentation processes for the production of platform chemicals or other metabolic products. Hemicellulose hydrolyzates obtained from stalks were fermented by *L. pentosus* to produce lactic acid and biosurfactants.[55–58] Moldes *et al.* obtained 0.71 g of biosurfactant per g of biomass and 25.6 g/L lactic acid using trimming vine shoots hydrolyzates as fermentation medium.[58] Portilla-Rivera *et al.* used *L. acidophilus* and *D. hansenii* for the production of 32.7 g/L lactic acid and 31.3 g/L xylitol, respectively, from pre-treated grape stalks.[59]

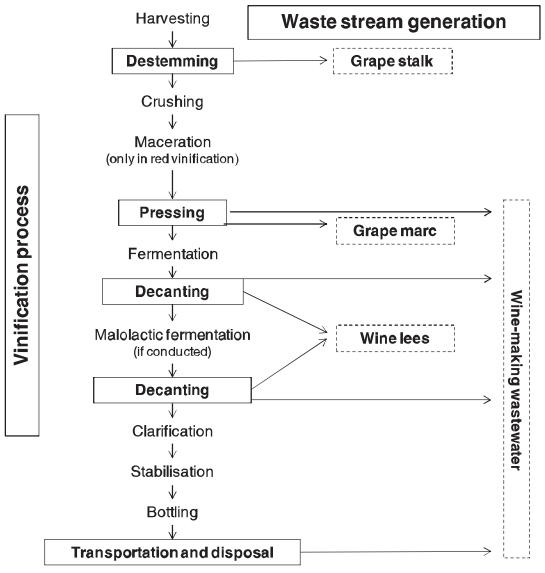


Figure 2. Vinification process diagram.

Grape stalk contain antioxidant compounds such as hydroxycinnamic (mostly ferulic and p-coumaric) and hydroxybenzoic (mostly gallic) acids. In this biorefinery concept, extraction of antioxidants should be carried out prior to pre-treatment of grape stalk for the production of sugar-rich hydrolysates. Max *et al.* proposed a sequential treatment process involving pre-hydrolysis and alkaline hydrolysis in order to obtain antioxidant-rich extracts that could be used in food, pharmaceutical and cosmetic applications.[60] Sanchez *et al.* applied solid state fermentation of grape stalks using *Pleurotus* spp. for food and feed applications.[61] Grape stalks have been also evaluated as raw material for the production of compost that could be reintroduced into the vineyard as a mean to close the residual material cycle.[62]

Grape marc is a waste stream generated after pressing of grapes. It is also described as 'exhausted' grape marc, if it has undergone a distillation process in order to obtain ethanol. As in the case of stalks, grape marc contains a significant quantity of hemicellulosic sugars, which have been employed as carbon sources for fermentative production of lactic acid with a sugar conversion yield of 0.71 g/g, and intracellular biosurfactants (measured as biosurfactin) at a concentration of 4.8 mg/L or extracellular bioemulsifiers.[63,64] Grape marc has been also used for the extraction of phenolic compounds with antioxidant activity using organic solvents, supercritical carbon dioxide and isothermal autohydrolysis.[65,66] The extraction of tannins from grape marc in order to be used as wood adhesives was also studied.[67] Grape marc has also been employed as substrate in solid state fermentations for enzyme or bioethanol production.[68,69] Production of fertilizer from grape marc via composting or vermicomposting has been studied in many literature-cited publications.[70,71]

Cleaning of equipment after wine production generates significant quantities of waste water with high organic load, low pH and variable nutrient levels. Although there is significant variation in the quantity of waste water generated by different wineries, approximately 3–5 m^3 of waste water is produced per t of grapes crushed.[72] It is obvious that the disposal of such high quantities of waste water, in streams, creeks, rivers and on soils involves unacceptable environmental risk. Besides physicochemical and biological treatment, such waste waters could be employed as process water in fermentation processes.

According to EEC No. 337/79 regulation, wine lees is 'the residue that forms at the bottom of recipients containing wine, after fermentation, during storage or after

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authorized treatments, as well as the residue obtained following the filtration or centrifugation of this product'.[73] Wine lees can be divided into 'heavy' or 'light' lees depending on the decanting step. It represents 2–6% of the total volume of wine produced and it contains significant quantities of ethanol, tartaric acid and yeast cells. [74,75] Wine lees are currently used for the production of tartaric acid and/or ethanol.[76,77] Wine lees is not suitable as animal feed supplement mainly due to their high polyphenolic content.[78] Perez-Serradilla and Luque de Castro reported an optimized process for obtaining phenolic compounds from wine lees by microwave-assisted extraction,[73] while Naziri *et al.* recovered squalene from wine lees using ultrasound assisted extraction.[75] Wu *et al.* employed supercritical fluids for the extraction of antioxidant compounds from wine lees.[79]

Bustos *et al.* used various lees (from red or white wines, distilled or not, from the first or second decanting step) as nutrients for lactic acid production by *Lactobacillus rhamnosus*.[80] Wine lees were also applied as substrate in solid state fermentation with *Trichoderma viride* in order to produce a biocontrol agent.[74] Rivas *et al.* employed distilled wine lees for the recovery of tartaric acid, while residual solids were used for lactic acid production by *Lactobacillus pentosus*.[81] Salgado *et al.* proposed a process in which wine lees were employed for the recovery of tartaric acid followed by xylitol production (33.4 g/L) using the remaining stream as fermentation nutrient supplement.[82]

Synergistic valorization of whey and wine lees

In several countries, cheese and wine production is accomplished in the same regions enabling transportation of resources or construction of new biorefinery plants for valorisation of waste and by-product streams. Such synergistic processing will be one of the features of the bioeconomy era where fractionation of renewable resources will result in various products with diversified market outlets. The seasonal operation of many food industries, such as wineries, is a major problem that should be tackled in order to develop highly efficient and sustainable biorefineries. This problem could be addressed through the development of regional industrial plants that valorize waste and by-product streams generated by various local industries operating either on a seasonal basis or throughout the year. In this way, a continuous supply of renewable resources could be ensured leading to the production of various products with diversified market outlets. This section presents an integrated biorefinery approach based on separate or combined valorization of whey and wine lees for the production of both commodity and speciality products (Fig. 3) currently under development at the Agricultural University of Athens in Greece.

Wine lees and cheese whey could be valorized separately for the production of various value-added products as mentioned above. In the proposed concept, wine lees could be valorized separately in a way that leads to the production of at least four end-products (ethanol, tartaric acid, antioxidants, and nutrient-rich supplements equivalent to commercial yeast extract). Wine lees could be initially fractionated into a solid and liquid fraction using a conventional rotary vacuum filtration unit operation. Potable ethanol is extracted from the liquid phase via distillation, whereas the remaining ethanol-free liquid is used as process water in the production of nutrient supplements for fermentation processes. The solids are treated via solvent extraction to remove a phenolic-rich extract of high antioxidant activity. Subsequently, remaining solids are treated with hydrochloric acid to separate tartrate salts. Finally, yeast cells are lyzed using crude enzymes produced via solid state fermentation for the production of generic fermentation nutrient supplements that could be characterized as a crude yeast extract. This nutrient supplement could be combined with various crude carbon sources for the production of fermentation products. Recent research has shown that more than 1 g/L of free amino nitrogen could be produced from spent yeast contained in wine lees (results not yet published). Yeast hydrolyzates from wine lees have been evaluated for the production of PHB using crude glycerol from biodiesel producers as carbon source (data not yet published). The same yeast hydrolyzates could be also combined with lignocellulosic hydrolyzates from grape stalks and marc for the production of microbial oil. This is a feasible scenario depending on the capacity of wine lees that is available in a specific region.

Whey could be also valorized separately via ultrafiltration membranes to produce a whey protein concentrate (WPC) stream and a lactose-rich permeate stream that is subsequently used for the production of microbial oil with yeast or fungal strains. The lactose-rich permeate stream could be supplemented with a crude yeast hydrolyzate derived from wine lees that is rich in nitrogen sources and other nutrients necessary for microbial growth and microbial oil production. The spent yeast cells could be used as animal feed, while the microbial oil could be used as a value-added food additive if it contains a significant content of γ-linolenic acid.

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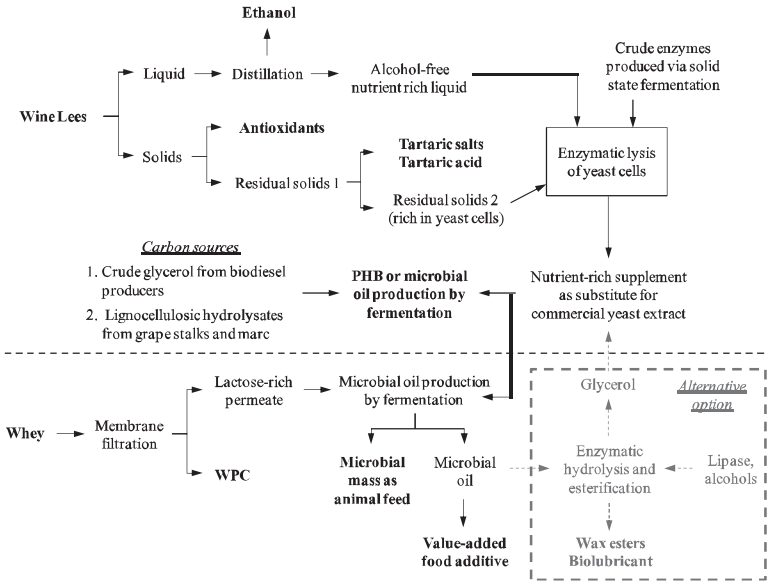


Figure 3. Schematic diagram of synergistic valorization of whey and wine lees.

In an alternative scenario, microbial oil could be used for the production of wax esters or biolubricants using lipase for triglyceride hydrolysis and esterification of fatty acids with alcohols. The glycerol that is generated via enzymatic hydrolysis of microbial oil could be used as carbon source combined with crude hydrolyzates from wine lees for the production of various fermentation products, such as microbial oil and PHB. Microbial oil production from crude or pure glycerol is feasible. This alternative processing scenario is illustrated as *alternative option* in Fig. 3. The proposed process presented in Fig. 3 shows that valorization of whey and wine lees could take place in a synergistic mode leading to the production of antioxidants, WPC, animal feed, potable ethanol, tartaric acid, oleochemicals, and PHB.

Cheese whey valorization for the production of microbial oil using oleaginous yeast, such as *Cryptococcus curvatus*, has been previously reported.[83–85] Research at the Agricultural University of Athens in Greece has focused on the utilization of lactose or cheese whey for the production of microbial lipid by oleaginous strains belonging to Zygomycetes.[86,87] Cultivation of the oleaginous strain *Mortierella isabellina* ATHUM 2935 on lactose-enriched cheese whey resulted in the production of a total dry weight of 42 g/L, while the maximum microbial oil concentration and content achieved were 8 g/L and 25% (*w/w*), respectively.[87] When this strain was cultivated on cheese whey with an initial lactose concentration of 60 g/L, the total dry weight produced after 440 h fermentation was 30.2 g/L (Fig. 4). Complete lactose consumption was achieved at approximately 280 h. Storage lipid accumulation was initiated at approximately 80–90 h with a maximum microbial oil concentration of 5.1 g/L at around 170 h corresponding to a microbial oil content

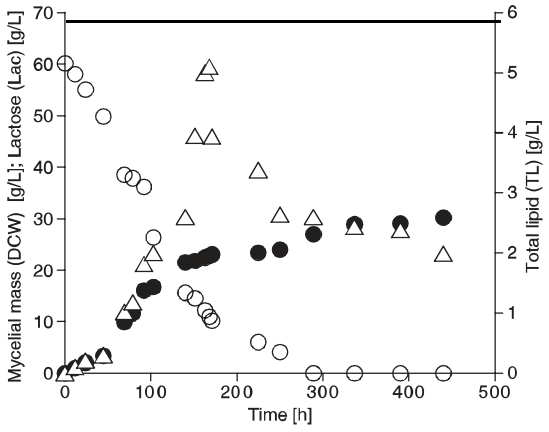


Figure 4. Microbial oil (Δ) and total dry cell weight (•) production and lactose consumption (○) during cultivation of *Mortierella isabelina* on cheese whey.

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Table 2. Fatty acid composition produced by *Mortierella isabellina* during fermentation of cheese whey.

Time (h)	Lipid (%, w/w)	C16:0	$^{\Delta 9}$C16:1	C18:0	$^{\Delta 9}$C18:1	$^{\Delta 9,12}$C18:2	$^{\Delta 6,9,12}$C18:3
102	12.0	23.5	n.d.	6.0	49.6	14.7	3.1
168	22.3	24.3	2.11	4.2	50.3	13.6	3.5
250	11.0	21.8	4.2	3.7	48.3	14.4	4.3
337	8.4	21.7	3.4	2.6	45.7	20.1	4.2
440	6.6	19.0	2.9	2.2	49.1	19.2	5.7

of 23% (*w/w*). The maximum lipid content occurred when the lowest dissolved oxygen concentration (around 50% *v/v*) was observed. Accumulated lipids were subsequently subjected to degradation (turnover). As shown in Fig. 4, the lipid biodegradation period occurred simultaneously with lactose consumption. This could be attributed to the biochemical and physiological event of the non-saturation of the microbial metabolic requirements only by lactose assimilation that was accompanied by the intra-cellular carbon supplementation by biodegradation of cellular lipid reserves.

The main fatty acids produced by *M. isabellina* were palmitic (C16:0), oleic ($^{\Delta 9}$C18:1), linoleic ($^{\Delta 9,12}$C18:2), γ-linolenic (GLA, $^{\Delta 6,9,12}$C18:3), palmitoleic ($^{\Delta 9}$C16:1) and stearic (C18:0) (Table 2). The concentrations of the fatty acids $^{\Delta 9}$C16:1, $^{\Delta 9,12}$C18:2 and GLA increased, while the ones of C16:0 and C18:0 decreased during fermentation. By taking into consideration that in the case of *M. isabellina* non-negligible quantities of lipid were re-consumed, the increase of the cellular concentrations of $^{\Delta 9}$C16:1, $^{\Delta 9,12}$C18:2 and GLA suggests that principally the cellular saturated fatty acids were preferentially consumed by the micro-organism, in accordance with the results reported for other oleaginous Zygomycetes like *Cunninghamella echinulata*.[88]

The highest quantity of GLA produced was approximately 180 mg/L. This quantity is lower than the highest GLA production reported in the literature (800–1300 mg/L).[88–92] However, by taking into consideration that the cultivation of Zygomycetes on media composed of lactose (such as cheese whey), with only some notable exemptions, results in very poor microbial growth, the presented original findings are of importance.[86,87] Plant lipids that contain γ-linolenic acid and are currently commercialized may have a market price up to approximately 50 $/kg. For instance, the oil derived from the plant *Oenothera biennis*, called also Evening primrose oil, contains a GLA content in the range of 8–10 % (*w/w*), which is slightly higher than the GLA concentration presented in this study. Therefore, the GLA-based economy is of significant commercial importance especially in the case that the microbial lipids are produced from a waste stream such as cheese whey. It should be stressed that the results presented in this study were obtained via shake-flask cultivations. The significantly low (or even negligible) cost of raw cheese whey, the potential of high biomass production by *M. isabellina* and the high price of the microbial lipid produced can render, after optimization of microbial lipid production in a bioreactor, this fermentation economically viable.

Concerning the utilization of microbial oils as precursors for the synthesis of biodiesel, a representative production cost for yeast lipid reported in 2008 was approximately 3.0 $/kg (excluding cost of feedstock used for lipid production).[93] The market prices of rapeseed oil, soybean oil and sunflower oil in the same period were 1.4–1.5, 1.2–1.3, and 1.8–1.9 $/kg, respectively.[93] An extensive and detailed techno-economical analysis on biodiesel production from microbial oil produced by oleaginous yeast has indicated that the cost of microbial lipid production is approximately 3.6 $/kg, when the volumetric productivity of lipid is 0.5 g/L/h.[94] The significant increase of biodiesel demand has resulted in a 2-fold increase of the price of conventional plant commodity oils in 2007 and 2008.[93,95] Therefore, the necessity of discovery of novel sources of oils for biodiesel production is of crucial importance, with the oleaginous microorganisms being considered as perfect candidates specifically by taking into consideration the potential conversion of waste or residues as carbon sources.[96]

Cashew, cashew nut shell oil and derivatives

In Tanzania, cashew is the fourth most valuable export crop after coffee, cotton and tea with the area under production ranging between 80 000 and 90 000 hectares. The total production of raw cashew nut in the last two years has been above 100 000 t per annum.[97] About two-thirds of the raw cashew nut is a shell and it can therefore be estimated that in Tanzania, about 60 000 t of cashew nut shell (CNS) agro-waste is being generated per year. This creates a lot of waste disposal problem because until now, the

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cashew shells are to a small extent used as fuel for wood-burning and very little is used for production of the valuable cashew nut shell liquid.

The cashew nut fruit has many uses derived from its major parts where the kernel, is consumed as a nut, eaten alone or as an ingredient in sauces, cakes and candies. Cashew apple is locally used to make Juices, wine/liquor, jellies, jams, candies, cakes. The cashew nut shell liquid (CNSL) is mainly used in adhesives, paint, and other industrial materials. Cashew peel (testa) is used in brake pad linings and can also be used for animal feed. Cashew nut shells are used as fuel for wood-burning stoves and ovens.[98]

In both small-scale and industrial-scale cashew nut processing, the cashew shell has been and is being regarded as a waste material obtained as by-product of the cashew industry in the recovery of edible cashew kernel. Recently however, cashew nut shells has become among one of the most important renewable and natural materials that is widely available, at relatively low-cost. The cashew shell contains various compounds which can be functionalized to form various new compounds and hybrid compounds, and thus it has attracted the attention of several scientists as reported elsewhere.[1] This attention is due to the major components of the CNSL that possess special and unique characteristic as they contain in the meta position of the phenolic ring, a long alkyl chain which bestows their interesting properties. Each of these major components of CNSL is a mixture of saturated, monoene, diene, and triene in the 15-carbon chain.

Unlike many other nuts, cashew nuts are only sold to consumers in the kernel form. Cashew kernel is a food product so the taste should remain as natural as possible, and therefore, the processing of cashew nuts is done in a safe manner. The objective in processing cashew nuts is to remove the highest possible weight of kernels from the nut in-shell, unbroken and with the distinctive light ivory cashew color. Hence the profitability of cashew processing depends largely on the proportion of kernels extracted without being broken or damaged. There are a number of different methods of shell removal and testa removal. An overview of the processing of cashew nuts is shown in Fig. 5.[99]

The cutting and shelling operation performed in the mill during cashew nut processing generates huge quantity of the cashew nut shell as waste, that is, about 67% of total weight of raw cashew nut seeds.[99] The cashew nut shell contains a viscous and dark liquid, known CNSL, which is extremely caustic. It is contained in the thin honeycomb structure between the soft outer skin of the nut and the

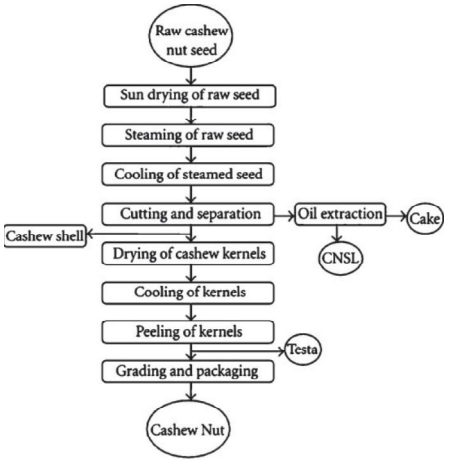


Figure 5. Generalized process flow chart of small-scale cashew processing industries.[99]

harder inner shell. The CSNL content of the raw nut varies between 20 and 30%. The liquid has four major phenolic constituents namely anacardic acid, cardanol, cardol and traces of methyl cardol (Fig. 6). The composition of these phenolic constituents varies depending on the mode of extraction of the liquid from the shells.[100] A solvent extracted cashew nut shell liquid contains anacardic acid (60–65%), cardanol (10%), cardol (15–20%) and traces of methylcardol. Technical extracted cashew nut shell liquid is obtained by roasting the nuts contains mainly cardanol (60–65%), cardol (10–15%), polymeric material (10%), and traces of methylcardol.[100]

Having hydroxyl and carboxylic functional groups in the benzene ring together with double bonds along the side chain, these components of CNSL offer the possibility of transforming them into various other useful chemicals, and therefore, becoming an important step toward adding value to waste produced during cashew processing. There is enormous information from different research groups on how this waste produced during cashew processing can be converted into useful materials. For example, previous studies have shown that the double bond of cardanol can be isomerized to be conjugated with the ring where upon butene metathesis, the isocardanol gives (E)-3-(Prop-1-enyl)phenol and (E)-hexadec-2.ene (Fig. 7). The catalytic hydrogenation of (E)-3-(Prop-1-enyl)phenol in methanol affords 3-propylphenol; a kairomone component for tse-tse fly control.[101]

Through metathesis reactions from cardanol by using Hoveyda-Grubbs Catalyst second-generation cross

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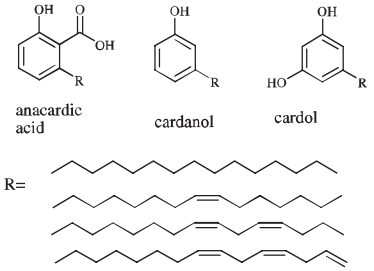


Figure 6. Components of cashew nut shell liquid.

metathesis reaction involving the olefinic double bond of cardanol, many new and interesting olefinic cardanol derivatives and hybrids compounds have been produced.[102] The unsaturation in the chain of 3-(-pentadeca-8-enyl)phenol of cardanol through cross metathesis reaction can give rise to new cardanol compounds with new double bonds.

The use of cardanol to synthesize cardanol polysulfide (CPS) have been reported,[103] wherein a sulfur donor type vulcanizing agent is produced (Fig. 8). The synthesis involved a reaction between an element sulfur and cardanol to form cardanol polysulfide. The study established a remarkable effect of the polysulfide as a vulcanizing agent on the properties of rubber compounds. For instance, apart from CPS rubber having lower reversions, the optimum cure time of rubber containing CPS was reduced while its mechanical properties improved.[103]

CNSL is also useful without doing any kind of chemical transformation. For example, cashew nut shell liquid when combined with sulfited wattle tannin and copper (ii) chloride has resulted into an environmentally friendly termite preservative.[104] The formulated preservatives were tested for their ability to preserve wood blocks from a soft wood, ponderosa pine (*Pinus ponderosa*) and a hard wood, trembling aspen (*Populus tremuloide*). After 108 days exposure, evaluation of termite attack by measuring the weight losses and damage showed that the test wood treated with

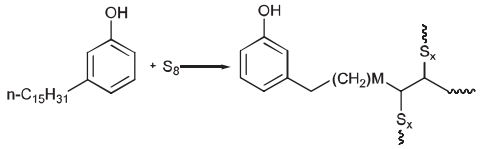


Figure 8. Scheme of the chemical structure of cardanol polysulfide (CPS). [103]

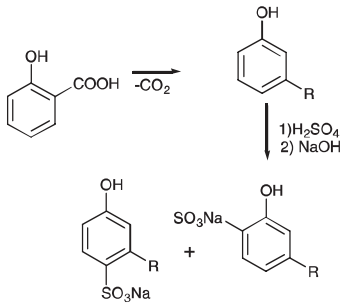


Figure 9. Preparation of cardanol sulfonate from anacardic acid.[106]

the combinations of 40% CNSL + 1% $CuCl_2$ and 40% CNSL + 2% $CuCl_2$ were among the least damaged.[104] It is also reported elsewhere that when copper is incorporated into Cashew nut shell liquid (CNSL) and Neemseed oil, it protects wood rotters and termites.[105] When it evaluated to find out the effectiveness as wood preservatives against decay fungi and termites, these combinations of copper and CNSL, and copper and Neemseed oil in pressure treatment have proved to have very high protection against both wood rotters and termites.[105]

The synthesis of surfactants such as sodium cardanol sulfonate surfactant from cardanol has also been reported by some research groups (Fig. 9).[106] Surfactant properties of cardanol sulfonate were determined and compared with dodecylbenzene sulfonate. Surface tension values were determined to be 32.25 mN/m for cardanol sulfonate at

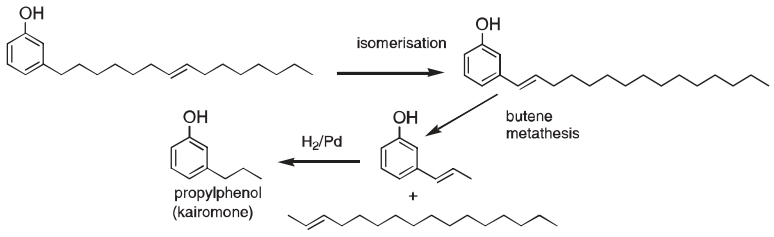


Figure 7. Synthesis of kairomone from cardanol.[101]

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20% *w/v* and 28.00 mN/m for dodecylbenzene sulfonate at 15% *w/v*. Critical micelle concentrations of dodecylbenzene sulfonate and cardanol sulfonate were found to be 0.435 and 0.372 mol/L, respectively. In comparison with dodecylbenzene sulfonate, the relative detergency of cardanol sulfonate was calculated to be 93.7%; which is better than dodecylbenzene sulfonate and hence cardanol sulfonate can be used as alternative anionic surfactant.[106]

In the field of polymer science, CNSL (especially the cardanol component) has been widely used to synthesize polymers with different properties. The polymers from CNSL components have displayed a wide range of properties from soft and flexible rubbers to hard and rigid plastics, giving an assurance that CNSL components are alternative renewable monomers to petroleum-based monomers. Several workers have reported on polymer synthesis using cardanol as a starting material. The spherical polymeric particles (SPP) have been prepared from CNSL by suspension polymerization technique involving either step-growth or chain growth polymerization mechanisms.[107] The sizes of the SPP, which ranged from 0.1 to 2.0 mm, were strongly influenced by the amounts of stabilizers in polymerization recipes used. The particles showed variable surface areas, indicative of the presence of pores in some of the preparations and the highest surface area recorded was about 260 m^2g^{-1}. The particles were found to exhibit Langmuir-type adsorption isotherms with saturation capacity of about 9.0 and 44.2 mg/g for Na^+ and Ca^{2+}, respectively. Step-growth polymerization produced SPP with relatively smaller surface areas and lower adsorption capacities of sodium and calcium ions compared to the particles produced through the chain-growth mechanism. Other particle characteristics depended strongly on the recipe employed and the surface OH functional groups apparently determine the potential applications of the SPP.[107] Moreover, the development of a new class of polyurethanes from cardanol has been reported,[108] whereby cardanol-based novolac type phenolic resin was synthesized by condensing cardanol with formaldehyde in the mole ratio of 1:1 using sebacic acid catalyst. The resulting novolac resin was then subjected to epoxidation followed by hydrolysis to give the hydroxyalkylated derivative (synthesized polyol). The novolac resin/synthesized polyol was condensed with hexamethylene diisocyanate to produce rigid polyurethanes. Tough polyurethanes were produced by condensing novolac resin / synthesized polyol with the commercially available polyol, polypropylene glycol-1200(PPG-1200) and hexamethylene diisocyanate. The physico-chemical, mechanical and thermal properties of polyurethanes were studied. These studies revealed high performance character of rigid polyurethanes with respect to their mechanical and thermal properties.[108] Similar polyurethanes were also prepared by a different research group using glutaric acid instead of sebacic acid catalyst.[109] In this study, cardanol was allowed to react with formaldehyde in a particular molar ratio in the presence of glutaric acid catalyst to give high-ortho novolac resin. The resulting polyol was then condensed with diphenylmethane diisocyanate to produce rigid polyurethane. A commercially available polyol, polypropylene glycol-2000 (PPG-2000), was also condensed with diphenylmethane diisocyanate and polyol to produce tough polyurethane. These polyurethanes were characterized with respect to their resistance to chemical reagents and mechanical properties such as tensile strength, percentage elongation, tear strength and hardness. The rigid polyurethane was found to possess higher hardness when compared to the tough polyurethane. Also rigid polyurethane was more stable in chemical reagents when compared to tough polyurethanes and possess good thermal stability.[109]

CNSL-based polymer latexes of narrow size distribution and average particle sizes ranging from 0.1 to 0.4 nm by base catalyzed emulsion polycondensation of cashew nut shell liquid with formaldehyde have been reported.[110] The influence of emulsifier concentration, sodium hydroxide concentration and stirring rate on average particle size and size distribution was studied for the given geometry of the reactor and the stirrer. It was found that these variables had a significant effect on the particle size and distribution, which can be predicted by the controlling experimental variables. Interrelationships between these variables appeared to be complex, even though the apparent monotonic variation of average particle size with emulsifier concentration makes the emulsifier concentration the most convenient parameter of controlling the particle sizes.[110] In another front, composite materials from cashew nut shell and rice husk have also been prepared.[111] The study aimed for the search of natural fibres in order to minimize environmental pollution. In this study, cashew nut resin reinforced rice husk composite was fabricated at different particle sizes and different filler loading. The study revealed that both filler loading and particle sizes affected the tensile strength, young modulus; strain at failure, flexural strength, and impact strength of the composite. The study concluded that RH/CNSR composite could be considered as a potential source of low cost, natural fibre for composites.[111] In general, CNSL from the cashew shells has numerous applications in various polymer based industries such as friction linings, clutch disks, paints, varnishes, laminating resins, cashew cements,

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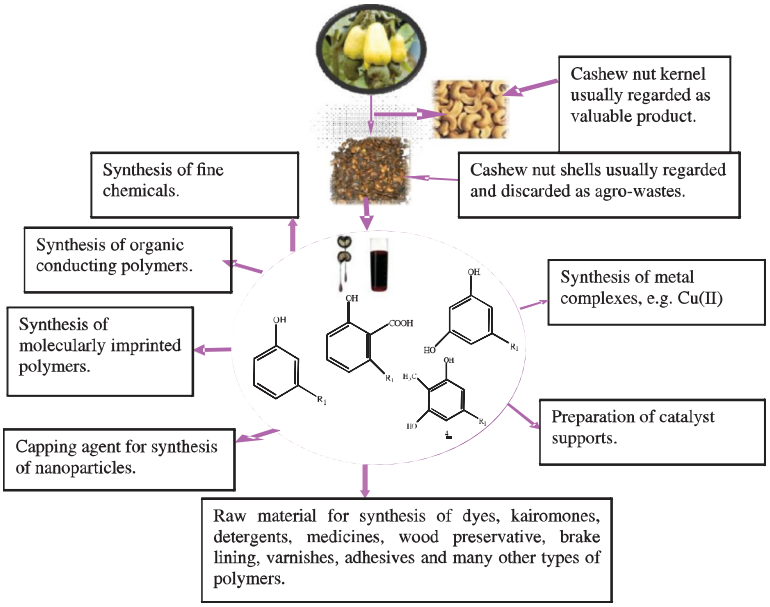


Figure 10. Opportunities from cashew nut shell agro-waste in the production of chemicals and other products.

polyurethane based polymers, surfactants, epoxy resins, and intermediates for the chemical industry.[112–114]

In the preparation of catalyst supports using micelle templating methods, CNSL has successfully been used in place of n-dodecane as a surfactant. The prepared micelle templated silica (MTS) have been used as supports for both metal catalysts and biocatalysts.[115,116] Moreover, anacardic acid, a component of CNSL, has proved to be an excellent capping agent in the synthesis of semiconductor quantum dots (QDs).[117] The generated nanoparticles had improved properties behaving in a quantum manner and were of comparable structural quality to that of pure nanocrystals.

Recently, the synthesis, spectroscopy and X-ray single crystal structure of catena-has been reported.[118] In this study, the complex was prepared by hydrogenation of anacardic acid (a component of CNSL) to obtain a transparent crystalline product upon recrystallization. The transparent crystalline product was then reacted with copper nitrate in the presence of pyridine to produce green crystals of a pyridine adduct of a dimeric copper (II) anacardate with the copper acetate structure. The overall potential to develop novel methodologies to convert naturally occurring oils from cashew nut shells waste into building blocks for various applications is extremely high and offers many different possibilities for a diverse range of chemical products as summarized in Fig. 10.

Mixed food waste and bakery waste

Indeed, food waste is an imminent problem in the globe. Around 1.3 billion t of food is wasted in the world, implying one third of the food produced globally for human consumption is wasted every year.[119] Various food waste valorization technologies were developed while the first generation including composting, anaerobic digestion, incineration and animal feed production has already been scaled–up and commercialized to relieve the food waste in many regions for a decade. With the accelerating pace of research in this area, some novel technologies have been invented highlighting of the limitations of the existing first generation technologies. For instance, the conversion of biomass waste to bulk chemicals was found to be nearly 7.5 and 3.5 times more profitable than the conversion to animal feed and transportation fuel, respectively.[120] What is more, Pfaltzgraff *et al.* showed the feasibility of making use of all of the valuable components present in the food waste by isolating the high-value chemicals like limonene from waste orange peel.[121]

The utilization of food waste as a renewable biorefinery feedstock in cultivation of microorganisms has become a

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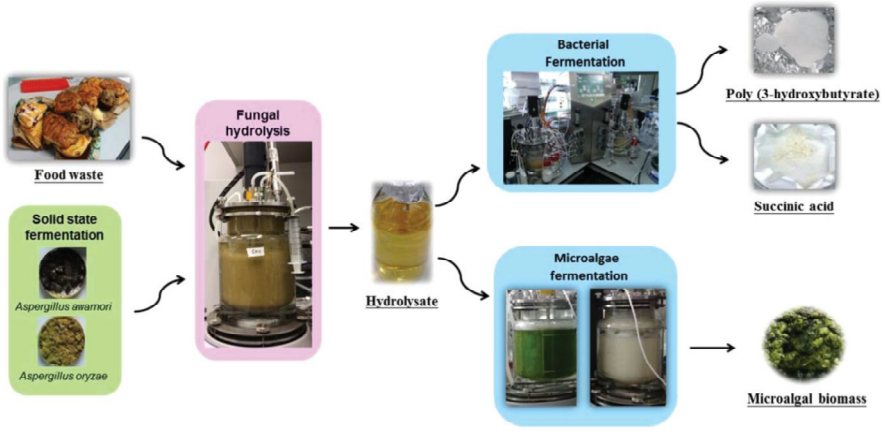


Figure 11. Process flow diagram of the utilization of food waste for bacterial fermentation and microalgae cultivation.[124, 126]

new research avenue. Sugar monomers, amino acids, short and long fatty acids, glycerol and phosphate derived from food waste are common nutrients for the cultivation of bacteria, fungi, and algae to produce biomass and various primary and secondary metabolites, which finally lead to production of chemicals, materials and energy.[122] By this approach, the recycling of carbon, nitrogen and phosphorous compounds in the food waste can be facilitated by the assimilation in biomass and the metabolites of the micro-organisms.

Food waste is proven as a good source for the recovery of nutrients in view of the composition of 30–60% starch, 5–10% proteins and 10–40% (*w/w*) lipids.[122,123] Pleissner *et al.* also reported similar result of 332.6 mg carbohydrate, 150.3 mg lipid and 103.7 mg protein per gram of food waste collected from canteen in Hong Kong.[124] However, these large molecules cannot be utilized for the growth of microorganisms prior to degradation. Therefore, hydrolysis of food waste is necessary before the cultivation process. In view of the high complexity of food waste, Kim *et al.* used commercial enzyme mixture consisting of carbohydrase, glucoamylase, cellulase and protease to hydrolyze food waste.[125] It was found that 0.63 g of glucose was obtained from one gram of the total solids applied. In view of the high cost of commercial enzymes, one of our projects funded by Industrial Technology Funding (ITF) from the Innovation and Technology Commission (ITS/323/11) in Hong Kong successfully developed a multi-enzyme solution produced by fungi for the utilization of industrial food co-products and organic food waste from coffee shops. Leung *et al.* (2012) and Pleissner *et al.* reported fungal hydrolysis using *Aspergillus awamori* and *Aspergillus oryzae*, which are known producers of glucoamylases, proteases and phosphatases, to recover the nutrients in form of glucose, free amino nitrogen (FAN) and phosphate. The result was promising that 0.32–0.47 g glucose and 2.8 mg of FAN were recovered from 1 g of food waste.[124,126] Also, *Pleissner et al.* reported 31.9 g glucose, 0.28 g FAN, and 0.38 g phosphate recovery from 100 g food waste (dry weight), which indicated the recovery rates of 85%, 40%, and 100% (*w/w*) for carbohydrate, total nitrogen, and phosphate, respectively.[124] Given that the fungal enzymes are cost-free and there is no need to recycle these enzymes, fungal hydrolysis definitely helps achieve a sustainable biorefinery process of food waste. Furthermore, the nutrient-rich hydrolyzate was utilized as feedstock in subsequent bacterial fermentation for chemicals production like succinic acid and polyhydroxyalkanoates as illustrated in Fig. 11.[126–128] As reported by Leung *et al.*, the yield of 0.55 g succinic acid per gram of waste bread was the highest yield among other food-waste-derived media.[126]

Currently, another project funded by ITF (ITS/353/12) entitled 'Sustainable Biorefinery Concept Based on Microalgal Biomass Produced from Mixed Food Waste Hydrolysate' is still ongoing in the School of Energy and Environment at the City University of Hong Kong. Nevertheless, Pleissner *et al.* has already reported the use of nutrient rich food waste hydrolyzate as culture medium for microalgae cultivation as illustrated in Fig. 11.[124] Two heterotrophic microalgae *Schizochytrium mangrovei* and *Chlorella pyrenoidosa* were found to grow well on the food

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waste hydrolyzate without supplements of trace metals and vitamins. After seven days of cultivation, 10–20 g of algal biomass rich in carbohydrate, protein, lipid and fatty acid was produced. The biomass composition of the cells grown on food waste hydrolyzate and conventional medium was similar except the protein content, which was 2 to 3 times greater compared with cells that have been grown on conventional medium. In view of the good growth performance and the biomass composition rich in carbohydrate, protein, lipid and fatty acid, it was concluded that food waste hydrolyzate is a suitable culture medium for *S. mangrovei* and *C. pyrenoidosa* cultivations.

Interestingly, it was also found that the composition of biomass is controllable by the limitation of glucose and phosphate in the culture medium. Both algal strains yielded the highest concentration of carbohydrate (300–400 mg/g), lipid (300 mg/g) and fatty acid (150 mg/g) under certain nutrient limitations. For instance, the carbohydrate and lipid content in *S. mangrovei* rose to the highest in a glucose and phosphate depleted environment while they kept constant when only glucose was depleted. In contrast, *C. pyrenoidosa* produced double amount of biomass, carbohydrate, lipid and fatty acid in a glucose-depleted culture when compared to that in glucose and phosphate-depleted culture. The controllable composition can definitely lead to higher yields of the desired compound, which help the applications of microalgal biomass.

In fact, the microalgal biomass is of interest for various applications. First, it can be applied in the food industry due to numerous health benefits.[129] The long-chain polyunsaturated fatty acids like the docosahexaenoic acids and eicosapentaenoic acids found in the algal biomass are commonly used for prophylactic and therapeutic treatment of chronic inflammations. Polysaccharide complexes from *C. pyrenoidosa* have been found with immunomodulating properties that can stimulate immune response. Extract of *Chlorella* sp. can also increase hemoglobin concentrations and lower blood sugar levels as well.[130] Secondly, the high content of carbohydrate and protein make microalgal biomass a good option for aquaculture and animal feed, and thus microalgae have already been used for culturing many aquatic animals and zooplankton for many years.[129] Thirdly, the high lipid content is definitely a good resource for biodiesel production. Miao & Wu (2005) extracted the microalgal oil using *n*-hexane from the biomass of *Chlorella protothecoides* which contained a high lipid content of 55% *(w/w)*.[131] Biodiesel (Free fatty acid ester) with comparable quality of conventional diesel was produced from the extracted microalgal oil by an acidic transesterification. The highest yield was 63% (*w/w*) with 56:1 molar ratio of methanol to oil at 30°C. Last but not least, pigments extracted from microalgae can be used by food coloring. For example, the xanthophylls (lutein, zeaxanthin, violaxanthin and neoxanthin) produced by *C. pyrenoidosa* used by food industry to color skins of meat and egg yolk.

The food waste biorefinery provides many advantages for the society. The utilization of food waste into microalgae cultivation or bacterial fermentation relieves the food waste problem by assimilating the nutrients in food waste into the microalgal biomass and bacterial metabolites. Meanwhile, the substitution of the petroleum-based product by food waste-derived bioproducts like biodiesel, bioplastic, and biocolorant definitely lead to a greener society with bio-economy. Moreover, turning cost-free food waste into feedstock for bioproducts production, which reduces the cost for purchasing raw materials, creates a favorable business environment. In view of that, further scale-up study on food waste biorefinery should be worked out to facilitate the commercialization. However, several difficulties have been identified. First, the condition of fermentation needs to be sterilized with the control of pH, temperature and dissolved oxygen level. Furthermore, Hong Kong is limited with land supply that the cost for space can contribute to a significant portion of the total cost. High initial investment is required due to the land cost and purchase of equipment like fermentors and incubators. Also, the high population density makes the siting of the food waste valorization facilities difficult since food waste usually releases unpleasant smell and attracts pest. Therefore, there is still a long way to put the food waste biorefinery process into commercialization but it should be worked out so as to move toward the sustainable society. Techno-economic study of sustainable biorefinery concept based on microalgal biomass produced from mixed food waste is currently undergoing in our research group. The aim is to determine the viability to build a pilot plant for the production of biodiesel and other value-added products using food waste as substrate for microalgal fermentation. Similar to Lam *et al.*, the economic success of such pilot scale facility is anticipated with the support of local government such as land subsidy.[132]

Waste oil and grease for the production of biodiesel: The ASB biodiesel production plant

ASB Biodiesel (Hong Kong) Limited has developed the largest biodiesel plant in Hong Kong with a production capacity of 100 000 tons of low-carbon transport fuel per

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Figure 12. The ASB Biodiesel plant in Hong Kong.

Table 3. Information of ASB biodiesel plant.[134]

Location	Hong Kong
Capital Cost	US $ 165 million
Operating mode	Semi-continuous
Operating days per year	330 days (guaranteed), 358 days (anticipated)
Operating hours per day	24 hours
Fuel Quality	European standard CEN EN 14214
Technology used	BioDiesel International technology (multi-feedstocks)
Feedstocks	Waste cooking oil Grease trap waste Waste animal fat Palm fatty acid distillate

year (Fig. 12). It came into operation in November 2013. Table 3 summarizes the information of ASB biodiesel plant. The plant utilizes different kinds of waste including waste cooking oil (WCO), grease trap waste (GTW), waste animal fat, and palm fatty acid distillate (PFCD) to produce biodiesel which will be sold to local and international markets. It is estimated that around 795 t of waste per day will be processed to produce 330 t of biodiesel, 23 t of bioheating oil, 7 t of fertilizer and 7 t of glycerol per day. CO_2 emission (257 000 t) will be avoided due to the prevention of waste disposal, substitution of fossil fuel and onsite power generation.[133]

As the largest biodiesel plant in Hong Kong, it currently collects around 20 t of WCO from 4000 outlets every day. It is expected that 6000 t of WCO will be treated after one year of operation, accounting for 30% of the total WCO produced in Hong Kong.[133] Apart from WCO, GTW is also an abundant source of oil and grease for biodiesel production. In Hong Kong, the content of grease and oil in waste water is restricted by the Water Pollution Control Ordinance for the prevention of the greasy waste water from blocking the city's drains. Therefore, restaurants and food processing facilities are required to install and maintain grease traps, which can remove oil and grease from waste waters, to ensure the grease and oil levels in the waste water below the limits. According to the data released by Hong Kong Environmental Protection Department (EPD), 475 t of grease trap waste was generated and disposed every day in 2011, which is indeed an abundant and also cost-free source of oil and grease.[135]

The ASB biodiesel plant adopts the BioDiesel International technology, which is specialized to process multi-feedstock in biodiesel production. The oil and grease in the feedstock are transformed into the biodiesel by base-catalyzed transesterification and three by-products namely glycerol, fertilizer and bioheating oil. Potassium hydroxide is the alkaline catalysts for the transesterification reaction in which triglyceride in the feedstock reacts with methanol to produce three moles of fatty acid methyl ester (FAME) and one mole of glycerol. The biodiesel produced can meet the specification of European standard CEN EN 14214, which is listed in Table 4, and is certified by independent auditors according to the EU's International Sustainability and Carbon Certification scheme.[133] On the other hand, the glycerol produced is sold to the oleochemical industry in the globe after purification. While the fertilizer, which is a good potassium and sulphur source, is sold to the local market. The bioheating oil, which is a heavy fraction of the biodiesel with very low carbon footprint, is used as a fuel for the onsite boiler to prevent the use of diesel. Also, there is no solid waste generated from the biodiesel production process.[133]

The ASB biodiesel plant is composed of several major facilities,[134] which are described below.

- *Feedstock reception and handling facilities*
  The WCO and GTW collected by sealed road tankers are weighed at the weighbridge office. The GTW is randomly sampled in the reception area for contamination with chemical waste. Then, it is unloaded through flexible hoses to the storage tanks directly in a closed system. For the PFAD, it is delivered by barge and pumped from the barge to the storage tank.
- *GTW pre-treatment and waste-water treatment works*
  The pre-treatment of GTW comprises of screening process and recovery of oil and grease. The solid impurities like food residues are removed in the screening process and disposed of at landfill. Then, the oil and grease in GTW are recovered and purified by a

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Table 4. The specification of European standard CEN EN 14214.

Property	Units	Limits		Test method
		Lower limit	Upper limit	
Fatty acid methyl ester content	% *(m/m)*	96.5	—	EN 14103
Density at 15°C	kg/m^3	860	900	EN ISO 3675 EN ISO 12185
Viscosity at 40°C	mm^2/s	3.5	5.0	EN ISO 3104
Flashpoint	°C	101	—	EN ISO 2719 EN ISO 3679
Sulphur content	mg/kg	—	10	EN ISO 20846 EN ISO 20884
Carbon residue (on 10% distillation residue)	% *(m/m)*	—	0.3	EN ISO 10370
Sulphated ash content	% *(m/m)*	—	0.02	ISO 3987
Water content	mg/kg	—	500	EN ISO 12937
Total contamination	mg/kg	—	24	EN 12662
Copper band corrosion (3 hours at 50°C)	Rating	Class 1		EN ISO 2160
Oxidation stability at 110°C	Hours	6	—	PrEN 15751 EN 14112
Cetane number	—	51	—	EN ISO 5165
Acid value	mg KOH/g	—	0.5	EN 14104
Methanol content	% *(m/m)*	—	0.20	EN 14110
Monoglyceride content	% *(m/m)*	—	0.8	EN 14105
Diglyceride content	% *(m/m)*	—	0.2	EN 14105
Triglyceride content	% *(m/m)*	—	0.2	EN 14105
Free glycerol	% *(m/m)*	—	0.02	EN 14105 EN 14106
Total glycerol	% *(m/m)*		0.25	EN 14105
Iodine value	g iodine/100g		120	EN 14111
Linolenic acid methyl ester	% *(m/m)*		12	EN 14103
Polyunsaturated (≥ 4 Double bonds) methyl ester	% *(m/m)*		1	—
Phosphorus content	mg/kg	—	4	EN 14107
Group I metals (Na+K)	mg/kg	—	5	EN 14108 EN 14109 EN 14538
Group II metals (Ca+Mg)	mg/kg	—	5	EN 14538

multi-step purification system, which reduces the water content in oil to 5 to 10%, in the oil and fat preparation tank. The purified oils are stored in the buffer tanks before transesterification. The waste water generated in the pre-treatment process is treated at the on-site waste water treatment facility before discharge into foul sewer. It includes an oil-water separator, a dissolved air flotation system, an internal circulation (IC) reactor, an aerobic treatment system and a secondary clarifier. Anaerobic digestion of organic matter takes place in the IC reactor in which biogas generated is then used by the steam boiler. After the aerobic treatment in the aeration tanks, the effluent is treated in the secondary clarifier for sedimentation. The resulting sludge is dewatered, temporarily stored in enclosed containers and finally delivered to landfill. The filtrates from the dewatering process are flowed back to the aeration tank for further treatment.

- *Biodiesel production and glycerol purification system*

  Purified feedstock undergoes transesterification process with the presence of Methanol-KOH catalyst at room temperature and under normal pressure.

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The fatty acid methyl ester is then purified in biodiesel distillation tank to produce biodiesel and bioheating oil. On the other hand, the glycerol separated in the transesterification process is purified by addition of sulfuric acid to neutralize unused potassium hydroxide resulting in the formation of fertilizer. Also, evaporation is then applied to remove unused methanol and water, which will flow back for transesterification and onsite waste-water treatment, respectively. Finally, the crude glycerol is produced with around 80% purity.

- *Product storage and ancillary facilities*

  There are in a total of 24 storage tanks in the plant for different materials. All the storage tanks are gas tight with a gas displacement system for quality assurance and safety. The steam boiler system, which is the main part of ancillary facilities, uses the produced biogas, bioheating oil and biodiesel for heating. It is estimated that fuel consumption equivalent to 8.4 tons per day of biodiesel can be saved.

In the foreseeable future, ASB Biodiesel (Hong Kong) Limited is facing two major challenges. First, the Hong Kong government has not mandated the use of biodiesel blend. It is still not compulsory to use biodiesel in Hong Kong. While both biodiesel and fossil diesel are duty free but the price of biodiesel is slightly higher than that of fossil diesel. The local market of biodiesel is not likely to expand much, which lead to a tough business environment. In view of that, ASB Biodiesel is planning to export the biodiesel as well as other by-products to Europe in which mandatory biodiesel blending ranged from 2.5% to 7% is implemented.[136] Secondly, the market of WCO become competitive since the demand of WCO from China is increasing, which definitely raises the price of WCO. According to the data from ASB Biodiesel (Hong Kong) Limited (Fig. 13), other regions like Jakarta and Bangkok also produce significant amount of WCO every year, which is indeed a good opportunity for regional expansion. Therefore, ASB Biodiesel (Hong Kong) Limited has been planning for collecting WCO from the surrounding region in the coming 2–3 years.

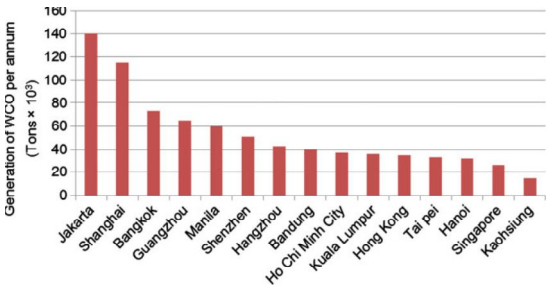


Figure 13. Annual generation of waste cooking oil in different regions.[133]

Updates in food waste legislation

Hong Kong

Significant amount of solid waste (13 458 tonnes) are currently generated in Hong Kong every day, of which nearly 67% (8996 tonnes) is municipal solid waste (MSW) from domestic as well as commercial and industrial (C&I) sectors (Fig. 14).[135] The domestic solid waste mainly comes from households and public areas, while C&I solid waste comes from restaurants, hotels, offices and all industries except construction and chemical waste. Among the MSW, food waste has been the major component in the past ten years, contributing around 40% of the total MSW in 2011 (3584 t per day). Although the amount of daily MSW generation recorded a slight decline from 2002 to 2011 (Fig. 14), the per capita MSW generation contrarily increased from 2.42 kg in 2005 to 2.69 kg in 2010.[137] With the waste-to-landfill approach, nearly all of the MSW is sent to the three existing strategic landfills, which will be exhausted by 2020. In view of imminence of the waste management problem, the Hong Kong government proposed MSW charging scheme to create financial incentive for the public with the objective to change their waste-generating behavior so as to facilitate waste reduction and enhance waste recycling rate. On the basis of the feedback from the first phase public consultation, in which 57% of the written submission supported the quantity-based approach, the Hong Kong government introduced the quantity-based MSW

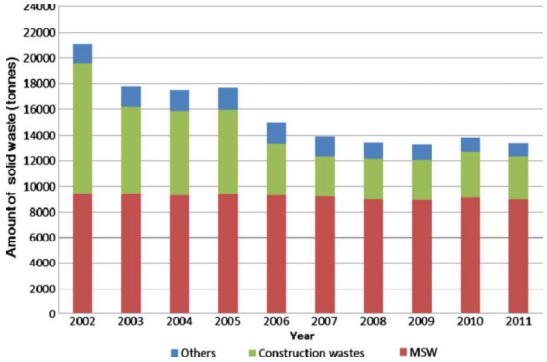


Figure 14. The amount of solid waste generated daily in Hong Kong from 2002 to 2010.[135]

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charging scheme together with the charging mechanism in the second phase public consultation in 2013.[138]

When composing the charging mechanisms, a basket of key features and challenges has been considered by the government. First, both government and private waste collectors provide MSW collection services. About 85% of domestic waste is collected by the Food and Environmental Hygiene Department (FEHD) of the government, while the private waste collectors collect nearly the entire C&I waste and a small portion of domestic waste. Therefore, the government has to coordinate the private waste collectors into the MSW charging scheme. Then, over 90% of households live in properties with building management agents, who can help coordinate waste collection and charging activity. However, most of the village houses and low-rise single-block buildings do not have property management bodies. It implied that the MSW charging scheme should be able to cater for both properties with or without property management service. Besides, around 88% of households live in multi-tenant buildings of more than 10 stories. MSW is usually left in the refuse collection point. Also, about 11 000 composite buildings have the setting of multi-tenant from both domestic and C&I occupants, which adds difficulty during implementation for tracing waste to the source.[138]

Different charging mechanisms were proposed for domestic solid waste and C&I solid waste to make the MSW charging scheme practicable and enforceable. For the C&I solid waste, the majority of C&I sector currently purchases the services of waste collection and disposal from private waste collectors, who then dispose of the waste at landfill without any charges or refuse transfer stations (RTS) with the payment of gate fee of HK$30–110 per tonne. In view of that, the Hong Kong government proposed to charge the waste at landfills or RTS by weight. By this mean, the private waste collector will play a significant role to share the charge with the waste producers. For domestic sector, the collection of domestic solid waste is similar to C&I solid waste except it is collected by the FEHD or its contractors without extra payment, thus two mechanisms were proposed for charging domestic solid waste,[138] which are shown below.

- *By household by volume*
  Each household is required to purchase a designated garbage bag to contain the waste and dispose it within a prescribed period of time at specific collection point, where is under monitoring.
- *By building by weight/volume*
  An agent like building management collecting the wastes from the whole building or estate will be charged by the total weight/volume of the waste. The fee will be shared with each household by the agent. For the building without building management, the waste should be disposed at specific RSP for charging.

The second phase public consultation was ended on January 24, 2014. Public opinions in the charging mechanism, charging level as well as the coverage of the charging scheme are the major issue in the consultation.[138] The Environment Bureau of the Government expected to finish the law drafting for MSW charging scheme by 2015.[139]

With the implementation of MSW charging scheme, it is expected that people will be encouraged to separate the recyclables at source. Therefore, the Hong Kong government also proposed and carried out different measures to promote recycling activities. First, the types of waste collected by the tri-color recycling bins have been broadened to papers, plastics, metals, old clothes and electronic appliances. Also, the glass beverage bottles will be covered by the tri-recycling bins scheme in 2015. Then, the Environment and Conservation Fund will financially support 50 private housing estates for on-site food waste recycling and reduction. Last but not least, the legislation of Producer Responsibility Scheme for Waste Electrical and Electronic Equipment will been proposed to Legislative Council in 2013–2014 legislative session.[138]

United Kingdom

Although the UK contribution to the staggering 1.3 billion metric tonnes of food waste generated globally every year, which is approximately 1% (15 million metric tonnes). It represents a significant proportion (approximately 30%) of UK food production, which costs the national economy £18.9 billion per year (£12 billion household and £6.9 billion supply chain). The biggest losses appear to occur at opposite ends of the value chain with both agriculture and supply, and consumers each responsible for 16% whilst retailers contribute to less than 1%.[119,140–142]

For example, supermarket giant Tesco announced it generated a colossal 30 000 metric tonnes of food waste across its UK operations in the first six months of 2012, of which, 21% was from fruit and vegetables, and 41% from bakery items. Tesco have established the waste profiles for 25 of the most frequently purchased products, five (grapes, apples, bananas, bakery and bagged salads) are highlighted in Table 5.[143]

However, the data displayed in Table 5 should be read with caution as it does not account for the fact that up to 40% of some farmers' crops never make it to store because of how the supermarkets order their food, insisting on

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Table 5. Farm to consumer waste hot spots for 5 selected grocery items.[143]

		Loss profile across supply chain (%)			
Food waste type	Total Wasted (%)	Farming	Processing	Retail	Consumer
Grapes	24	6	<1	<1	16
Apples	41	11	2	<1	27
Bananas	20	2	7	1	10
Bagged salad	68	17	15	1	35
Bakery	48	5	14	4	25

overproduction in case of a bad harvest or a surge in consumer demand, as well as demanding certain 'cosmetic' standards driven by consumer needs for blemish-free, perfectly sized fruit and vegetables.

In 2011, the UK government identified food waste as a priority concern in its Review of Waste Policy in England 2011 from which two actions arose:[144]

i. The Courtauld Commitment – a responsibility deal in the grocery retail sector which includes finding ways to reduce household waste from groceries.
ii. The hospitality and food service voluntary agreement, which aims to cut food and associated packaging waste by 5% and increase the overall rate of food and packaging waste that is being recycled, sent either to anaerobic digestion or composted to 70% by 2015.

The Courtauld Commitment (CC)[145]

The Courtauld Commitment (CC), administered by the Waste and Resource Action Program (WRAP),[145] supports the UK government's policy goal of a 'zero waste economy' and the objectives of the Climate Change Act to reduce greenhouse gas emissions by 34% by 2020 and 80% by 2050. In 2013, the CC entered Phase 3 of its life cycle which first began in 2005 with CC 1 and subsequently followed CC 2 (2010–2012).

Courtauld Commitment 1 (CC1)[145]

CC1 (2005–2009) was adopted by over 40 major retailers, brand owners, manufacturers and suppliers; retailers represented 92% of the UK's grocery supermarkets, who set out to:

1. Design out packaging waste growth – *zero growth achieved in 2008.*
2. Reduce food waste by 155,000 tonnes by 2010, against a 2008 baseline – *exceeded with 270 000 tonnes less food waste arising in 2009/2010 than in 2007/2008.*
3. Reduce the amount of packaging waste – not achieved as total packaging *consistently remained at approximately 2.9 million tonnes between 2006 and 2009 due to a 6.4% increase in grocery sales volumes since the agreement began in 2005 and participating retailers taking a greater proportion of the overall market for beer and wine. Bottles and cans for beer, wine and cider represented a third of all grocery packaging by weight.*

During Phase 1, 1.2 million metric tonnes of food and packaging waste was prevented; 670 000 tonnes of food waste and 520 000 tonnes of packaging, were avoided across the UK.

Courtauld Commitment 2 (CC2)[145]

CC2 (2010–2012) was adopted by 53 signatories with more focus on reducing secondary and tertiary packaging, supply chain waste, and encouraging the sustainable use of resources throughout the whole supply chain. Specific targets set out by CC2 were:

1. Packaging – to reduce the weight, increase recycling rates and increase the recycled content of all grocery packaging, as appropriate. Through these measures the aim was to reduce the carbon impact of this grocery packaging by 10%.
2. Household food and drink waste – to reduce UK household food and drink waste by 4%.
3. Supply chain product and packaging waste – to reduce traditional grocery product and packaging waste in the grocery supply chain by 5% – including both solid and liquid waste.

Although CC2 final reports have not been published the target for supply chain waste was met in 2011 with the other two targets well on their way to being achieved by 2012. Based on 2010/2011 data CC2 has enabled (based on tonnage and carbon impact metrics against a 2009 baseline):

1. Packaging: 8.2% reduction in associated greenhouse gas emissions against a 10% target.

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2. Supply chain: 8.8% cut in waste against a 5% target.
3. Household food waste: a 3% reduction was achieved in 2010 against a 4% target.

Courtauld Commitment 3 (CC3)[145]

The CC3 (2013–2015) aims to further reduce the weight and carbon impact of household food waste, grocery product and packaging waste, both in the home and the UK grocery sector. A 20% reduction in household food waste is envisaged by improving design to optimize recycled content, improve recyclability and thus helping to reduce food waste. If it is successful, then CC3 is anticipated to offer £1.6 billion of savings to consumers, food and drink sector and local authorities, associated with a cumulative reduction of 1.1 million tonnes of waste and 2.9 million tonnes of CO_2 emission. CC1 and CC2 improved and optimized packaging to such an extent that packaging is now 'fit for purpose', i.e., allowing food to stay fresher for longer, thus there are limited opportunities to reduce it further in CC3 without risking increased product wastage.

Targets set by CC3 measured against a 2012 baseline include:

1. Reduce household food and drink waste by 5% by 2015 but actually represents a reduction of 9% relative to anticipated changes in food and drink sales.
2. Reduce traditional grocery ingredient, product and packaging waste in the grocery supply chain by 3% by 2015 (actual reduction of 8% relative to anticipated production and sales volumes).
3. Improve packaging design through the supply chain to maximize recycled content as appropriate, improve recyclability and deliver product protection to reduce food waste, while ensuring there is no increase in the carbon impact of packaging by 2015 (actual target represents a carbon reduction of 3% relative to anticipated sales volumes).

Although the CC is a step in the right direction, alone as an action, it is insufficient to achieve the European Commission's target of a 50% reduction in food waste by 2020. Major collaborative initiatives between academia, industry and relevant stakeholders are needed. As summarized by Boyce and Arcand in their review on current trends in green technologies in food production and processing to ensure success, regional, national, and international collaborative efforts along the food chain continuum will be increasingly required.[146] Additionally, sustainable food engineering approaches which harness the power of open innovation and which take into consideration social, environmental, economic concerns will be needed. In 2013, the UK government funded two major food waste reduction programmes:

1. *Engineering and Physical Sciences Research Council (EPSRC): Centre for innovative manufacturing in food.*[147]
   This Centre aims to provide a step change in process engineering, with the key transformations required in intelligent product design providing targets for novel resource efficient engineered processes. Delivering step changes requires a fundamental change in manufacturing practice linking long term consumer/product requirements, in a co-creation with industry, to provide pull through of technical unlocks in territories in which innovations are required. The Centre aims to meet the current and future needs of the Food Manufacturing Industry, tackling issues in the four main areas of global need: (1) Global food security – providing manufacturing capability for conversion of (under-utilized) crops; (2) Health enabling food structures manufactured with nutritional value and optimized nutrient delivery; (3) Sustainable production – reduced energy and water requirements including, reduce/re-use waste (for valorization into new materials), and (4) maximize the efficiency of food production and supply using advanced manufacturing strategies for example, flexible and distributed manufacture

2. *Technology Strategy Board (TSB): Transforming wet perishable food waste streams for high value human consumption*[148]
   The project focuses on the innovative recovery and transformation of wet perishable process streams, such as peel, pith, stalk, grain, and other fruit and vegetable waste, into higher value functional and textural ingredients for incorporation into food products. Outcomes will impact the drive toward exploitation rather than simple management of food waste, of strategic importance for security of food supply, also delivering direct commercial benefit. Technological solutions will be developed for stabilization and manipulation of bioproduct materials, focusing on key selected feedstocks, supported by a consortium with synergistic skills, representing the full supply chain. Exciting new developments will be possible by the innovative coupling of process steps and novel combination of transformed materials from different sources.

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Tanzania

On environmental policy and management, Tanzania has the National Environmental Policy (NEP) and the Environment Management Act (EMA) No. 20 of 2004.[149,150] The policy gives direction on elements necessary for mainstreaming environmental matters into sectorial policies while the Act provides the legal and institutional framework for sustainable management of the environment. The Act further offers principles for environmental management, impact and risk assessments, prevention and control of pollution, waste management, environmental quality standards, compliance and enforcement; and the basis for implementation of international instruments on environment. The National Environmental Council (NEMC) which was formed under this act is the Tanzanian Environmental Regulatory Authority that oversees, coordinates and evaluates the implementation of the Environmental Management Act. Despite the existence of this act, Tanzania lacks a food waste management specific legislation because food waste is generally treated in the group of solid waste under this act and under the solid waste regulations of 2009.[151] In a nutshell, the Tanzanian government has a number of institutions dealing with the environment where the office of the Vice President is responsible for all environmental issues, while the local government authorities under the prime minister's office are charged with the responsibilities of environmental management. The present policies, regulation and institutional framework in Tanzania show some inadequacies on food waste management, and hence calls for a more effective and efficient framework that will adequately deal with food waste management issues and problems in Tanzania.

Spain

MSW are regulated in Spain by means of three jurisdictional measurements, namely *Ley 10/1998* (April 21, Law of residues), recently derogated by *Ley 22/2011* (July 28, Law of residues and contaminated soil) as well as by the National Plan of MSW (2000–2006) and the Integrated National Plan of Residues (2008–2015). In these, MSW were defined as residues generated in activities conducted in urban or influence areas (e.g. households, shops, offices) as well as those unidentified residues potentially toxic and hazardous derived from such activities. Although there is no precise food waste policy or legislation in Spain, the most recent Integrated National Plan (2008–2015) contains some interesting points related to food waste, particularly related to the so-called 3R concept (reduce, re-use, and recycle).[152] These relate to seek valorization protocols of the un-recyclable fraction of the residues (e.g. food waste). For these, several measurements are proposed including mainly composting and anaerobic digestion, with a future revised plan for 2015 in which new infrastructures and improvements in already existing facilities will be proposed. The program also envisages an increasing involvement of public administrations, consumers and users in shaping the future of the country in terms of residues, something that from the point of view of the leading author of this contribution has not yet been achieved.

Concluding remarks and future prospects

The future trend regarding waste management is the utilization of waste as raw material in cascade processes leading to the generation of various products with diversified market applications. This approach coupled with minimization of waste generation will lead to the development of no-waste production processes. This can only be achieved through appropriate legislation enforcement in different countries, consumer awareness of the benefits that could be provided by such an approach and the creation of market outlets for the new products. The current industry lacks expertise in waste valorization and experienced workforce. Furthermore, the heterogeneity and seasonal production of food waste create additional problems both in terms of logistics and processing. These problems can only be solved through concerted actions that may lead to significant restructure of conventional industrial processes. For instance, flexible and intensified low-scale processes should be developed for on-site processing of seasonal waste produced by different industrial sectors of medium to low scale in the same region.

It is imperative to associate food processing with waste minimization and valorization including water and energy conservation, and utilization of biodegradable packaging materials. The traditional food processors and consumers could benefit not only through the development of sustainable processes, but also through the production of food products with better quality, safety, properties and shelf-life. Active packaging and radio frequency identification (RFID) technologies could be adopted in order to increase shelf-life of food products and minimize waste along the whole food supply chain due to improper handling and storage conditions.

This study presented representative case studies regarding the valorization of waste streams generated from various food supply chains in different regions worldwide. These studies demonstrated that multidisciplinary

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approaches should be implemented in order to develop integrated biorefineries based on food waste valorization. Extraction technologies should be combined with green chemical conversion and bioprocessing in order to take advantage of all components present in food supply chain waste. Process systems engineering combined with techno-economic evaluation should be subsequently implemented in order to compare processing schemes to identify highly profitable processes. Life cycle analysis (LCA) studies and societal aspects should be also taken into consideration to select optimum technologies.

The COST Action TD1203 entitled *Food Waste Valorisation for Sustainable Chemicals, Materials and Fuels (EUBis)* (http://costeubis.org/) led by Prof. James Clark (University of York, UK) and co-chaired by Prof. Rafael Luque (University of Cordoba, Spain), currently focuses on bringing together all stakeholders interested in developing integrated biorefineries and creating a zero waste economy through valorization of food supply chain waste. It is the largest world network in food waste valorization with over participants from 100 laboratories from 31 countries worldwide. Such concerted actions could create the critical mass for the development of sustainable technologies based on waste re-utilization.

Acknowledgments

Carol Sze Ki Lin acknowledges the Innovation and Technology Funding from the Innovation and Technology Commission (ITS/323/11 and ITS/353/12) in Hong Kong, the donation from the Coffee Concept (Hong Kong) Ltd for the 'Care for Our Planet' campaign, as well as a grant from the City University of Hong Kong (Project No. 7200248). R. Luque gratefully acknowledges the Spanish MICINN for financial support via the concession of a RyC contract (Ref: RYC-2009-04199) and funding under project CTQ2011-28954-C02-02. R. Luque is also indebted to Prof. Guohua Chen, the Department of Chemical and Biomolecular Engineering (CBME) and HKUST for the provision of a visiting professorship as Distinguished Engineering Fellow in 2013. The work presented by A. Koutinas is part of the research project 19SMEs2009 implemented within the National Strategic Reference Framework (NSRF) 2007–2013 and co-financed by National (Greek Ministry – General Secretariat of Research and Technology) and Community Funds (EU European Social Fund).

References

1. Lin CSK, Pfaltzgraff LA, Herrero-Davila L, Mubofu EB, Abderrahim S, Clark JH *et al.*, Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. *Energ Environ Sci* **6**(2):426–464 (2013).
2. Koutinas AA, Vlysidis A, Pleissner D, Kopsahelis N, Lopez Garcia I, Kookos IK *et al.*, Valorization of industrial waste and by-product streams via fermentation for the production of chemicals and biopolymers. *Chem Soc Rev* **43**(8):2587–2627 (2014).
3. Kenny ST, Runic JN, Kaminsky W, Woods T, Babu RP and Connor KE, Development of a bioprocess to convert PET derived terephthalic acid and biodiesel derived glycerol to medium chain length polyhydroxyalkanoate. *Appl Microbiol Biotechnol* **95**(3):623–33 (2012).
4. Li S, Haufe J and Patel M, *Product overview and market projection of emerging bio-based plastics*. 2009. Available at: http://www.plastice.org/fileadmin/files/PROBIP2009_Final_June_2009.pdf [June 21, 2014].
5. Crank M, Marscheider-Weidemann F, Joachim S, Bärbel H and Gerhard A, *Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe*. Institute for Prospective Technological Studies. [Online] (2005). Available at: http://books.google.com.hk/books?id=04qCYgEACAAJ [June 21, 2014].
6. Hafuka A, Sakaida K, Satoh H, Takahashi M, Watanabe Y and Okabe S, Effect of feeding regimens on polyhydroxybutyrate production from food wastes by *Cupriavidus necator*. *Bioresource Technol* **102**(3):3551–3553 (2011).
7. Campos CA, Gerschenson LN and Flores SK, Development of edible films and coatings with antimicrobial activity. *Food Bioprocess Technol* **4**(6):849–875 (2011).
8. Anonymous, *The European chemical industry in a worldwide perspective*. European Chemical Industry Council, Brussels, Belgium. [Online]. (2011). Available at: http://www.esig.org/uploads/FF_Sept2011.pdf [June 21, 2014].
9. Georgieva TI and Ahring BK, Potential of agroindustrial waste from olive oil industry for fuel ethanol production. *Biotechnol J* **2**(12):1547–1555 (2007).
10. Widmer W and Grohmann K, *Ethanol from orange processing waste*. National Meeting of Institute of Food Technologists/ Food Expo. Presentation No. 140-09, Agricultural Research Service. [Online]. Available at: http://www.ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=207114 [June 21, 2014].
11. Kachrimanidou V, Kopsahelis N, Webb C and Koutinas AA, Bioenergy technology and food industry waste valorization for integrated production of polyhydroxyalkanoates, in Bioenergy Research: Advances and Applications, ed by Gupta VG, Tuohy M, Kubicek CP, Saddler J, Xu F. Elsevier, Amsterdam, the Netherlands, pp. 419–433 (2014).
12. Prazeres AR, Carvalho F and Rivas J, Cheese whey management: A review. *J Environ Manage* **110**(0):48–68 (2012).
13. Siso MIG, The biotechnological utilization of cheese whey: A review. *Bioresource Technol* **57**(1):1–11 (1996).
14. Economopoulos AP, Assessment of Sources of air, water and soil pollution: a guide to rapid source inventory techniques and their use in formulating environmental control strategies. World Health Organisation, Geneva (1993).
15. Castro-Rosas J, Guerrero-RodrÍGuez WJ, RodrÍGuez-Miranda J, PÁEz-Lerma JB and GÓMez-Aldapa CA, Optimization of thermal protein precipitation from acid whey. *J Food Process Preserv* **37**(5):924–929 (2013).

© 2014 Society of Chemical Industry and John Wiley & Sons, Ltd

bbb_1506.indd 24 27/06/14 9:36 PM

16. Pereira CD, Diaz O and Cobos A, Valorization of by-products from ovine cheese manufacture: Clarification by thermocalcic precipitation/microfiltration before ultrafiltration. *Int Dairy J* **12**(9):773–783 (2002).
17. Casal E, Montilla A, Moreno FJ, Olano A and Corzo N, Use of chitosan for selective removal of β-lactoglobulin from whey. *J Dairy Sci* **89**(5):1384–1349 (2006).
18. Sternberg M, Chiang JP and Eberts NJ, Cheese whey proteins isolated with polyacrylic acid. *J Dairy Sci* **59**(6):1042–1050 (1976).
19. Muro Urista C, Álvarez Fernández R, Riera Rodriguez F, Arana Cuenca A and Téllez Jurado A, Review: Production and functionality of active peptides from milk. *Food Sci Technol Int* **17**(4):293–317 (2011).
20. Kosseva MR, Panesar PS, Kaur G and Kennedy JF, Use of immobilised biocatalysts in the processing of cheese whey. *Int J Biol Macromol* **45**(5):437–447 (2009).
21. Stamatelatou K, Giantsiou N, Diamantis V, Alexandridis C, Alexandridis A and Aivasidis A, Biogas production from cheese whey wastewater: Laboratory- and full-scale studies. *Water Sci Technol* **69**(6):1320–1325 (2014).
22. Tommaso G, Ribeiro R, De Oliviera CAF, Stamatelatou K, Antonopoulou G, Lyberatos G et al., Clean Strategies for the Management of Residues in Dairy Industries- Anaerobic digestion of cheese whey, in Novel Technologies in Food Science: Their Impact on Products, Consumer Trends and the Environment, ed by McElhatton A, do Amaral Sobral PJ. Springer, Netherlands (2011).
23. Robbins CW and Lehrsch GA, Cheese whey as a soil conditioner, in *Handbook of Soil Conditioners: Substances that Enhance the Physical Properties of Soil* ed by Wallace A, Terry RE. Marcel Dekker Inc, New York, USA, pp. 167–186 (1998).
24. Preedy VR, *Dietary Sugars: Chemistry, Analysis, Function and Effects*. Royal Society of Chemistry, Cambridge UK (2012).
25. Gutiérrez LF, Hamoudi S and Belkacemi K, Lactobionic acid: A high value-added lactose derivative for food and pharmaceutical applications. *Int Dairy J* **26**(2):103–111 (2012).
26. Audic JL, Chaufer B and Daufin G, Non-food applications of milk components and dairy co-products: A review. *Lait* **83**(6):417–438 (2003).
27. De Wit JN, Nutritional and functional characteristics of whey proteins in food products. *J Dairy Sci* **81**(3):597–608 (1998).
28. Xiong YL, Influence of pH and ionic environment on thermal aggregation of whey proteins. *J Agric Food Chem* **40**(3):380–384 (1992).
29. Prabakaran S and Damodaran S, Thermal unfolding of β-lactoglobulin: Characterization of initial unfolding events responsible for heat-induced aggregation. *J Agric Food Chem* **45**(11):4303–4308 (1997).
30. Vardhanabhuti B and Allen Foegeding E, Effects of dextran sulfate, NaCl, and initial protein concentration on thermal stability of β-lactoglobulin and α-lactalbumin at neutral pH. *Food Hydrocolloid* **22**(5):752–762 (2008).
31. Cuellas A, Jagus R and Wagner JR, Optimization of proteins recovery process from cheese whey. *11th International Congress on Engineering and Food*, Athens, May 22–26, 2011 (2011).
32. Ryan KN, Vardhanabhuti B, Jaramillo DP, van Zanten JH, Coupland JN and Foegeding EA, Stability and mechanism of whey protein soluble aggregates thermally treated with salts. *Food Hydrocolloid* **27**(2):411–420 (2012).
33. Fauquant J, Vieco E, Brule G and Maubois JL, Clarification des lactosérums doux par agrégation thermocalcique de la matière grasse résiduelle. *Le Lait* **65**(647/648):1–20 (1985).
34. Su H, Wang Z and Tan T, Adsorption of Ni^{2+} on the surface of molecularly imprinted adsorbent from *Penicillium chysogenum* mycelium. *Biotechnol Lett* **25**(12):949–953 (2003).
35. Shi L, Zhao Y, Zhang X, Su H and Tan T, Antibacterial and anti-mildew behavior of chitosan/nano-TiO_2 composite emulsion. *Korean J Chem Eng* **25**(6):1434–1438 (2008).
36. Gauthier SF, Paquin P, Pouliot Y and Turgeon S, Surface activity and related functional properties of peptides obtained from whey proteins. *J Dairy Sci* **76**(1):321–328 (1993).
37. Illanes A, Whey upgrading by enzyme biocatalysis. *Electron J Biotechnol* **14**:9 (2011).
38. Tango MSA and Ghaly AE, Effect of temperature on lactic acid production from cheese whey using *Lactobacillus helveticus* under batch conditions. *Biomass Bioenerg* **16**(1):61–78 (1999).
39. Guimarães PMR, Teixeira JA and Domingues L, Fermentation of lactose to bio-ethanol by yeasts as part of integrated solutions for the valorisation of cheese whey. *Biotechnol Adv* **28**(3):375–384 (2010).
40. Guimarães PMR, François J, Parrou JL, Teixeira JA and Domingues L, Adaptive evolution of a lactose-consuming *Saccharomyces cerevisiae* recombinant. *Appl Environ Microbiol* **74**(6):1748–1756 (2008).
41. Dragone G, Mussatto SI, Almeida e Silva JB and Teixeira JA, Optimal fermentation conditions for maximizing the ethanol production by *Kluyveromyces fragilis* from cheese whey powder. *Biomass Bioenerg* **35**(5):1977–1982 (2011).
42. Ozmihci S and Kargi F, Ethanol fermentation of cheese whey powder solution by repeated fed-batch operation. *Enzyme Microb Technol* **41**(1/2):169–174 (2007).
43. Mawson AJ, Bioconversions for whey utilization and waste abatement. *Bioresource Technol* **47**(3):195–203 (1994).
44. Inglet BS, Song M, Hansen CL and Hwang S, *Short Communication*: Cultivation of *Lentinus edodes* mycelia using whey permeate as an alternative growth substrate. *J Dairy Sci* **89**(3):1113–1115 (2006).
45. Yan JQ, Lo KV and Pinder KL, Instability caused by high strength of cheese whey in a UASB reactor. *Biotechnol Bioeng* **41**(7):700–706 (1993).
46. Gannoun H, Khelifi E, Bouallagui H, Touhami Y and Hamdi M, Ecological clarification of cheese whey prior to anaerobic digestion in upflow anaerobic filter. *Bioresource Technol* **99**(14):6105–6111 (2008).
47. Perle M, Kimchie S and Shelef G, Some biochemical aspects of the anaerobic degradation of dairy wastewater. *Water Res* **29**(6):1549–1554 (1995).
48. Ferchichi M, Crabbe E, Gil G-H, Hintz W and Almadidy A, Influence of initial pH on hydrogen production from cheese whey. *J Biotechnol* **120**(4):402–409 (2005).
49. Rosales-Colunga LM, Razo-Flores E, Ordoñez LG, Alatriste-Mondragón F and De León-Rodríguez A, Hydrogen production by *Escherichia coli hycA lacI* using cheese whey as substrate. *Int J Hydrogen Energy* **35**(2):491–499 (2010).
50. Antonopoulou G, Stamatelatou K, Venetsaneas N, Kornaros M and Lyberatos G, Biohydrogen and methane production from cheese whey in a two-stage anaerobic process. *Ind Eng Chem Res* **47**(15):5227–5233 (2008).

© 2014 Society of Chemical Industry and John Wiley & Sons, Ltd

bbb_1506.indd 25 27/06/14 9:36 PM

51. Liu Z, Zhang C, Lu Y, Wu X, Wang L, Wang L *et al.*, States and challenges for high-value biohythane production from waste biomass by dark fermentation technology. *Bioresource Technol* **135**(0):292–303 (2013).
52. Dragone G, Mussatto SI, Oliveira JM and Teixeira JA, Characterisation of volatile compounds in an alcoholic beverage produced by whey fermentation. *Food Chem* **112**(4):929–935 (2009).
53. Robbins CW and Lehrsch GA, Effects of acidic cottage cheese whey on chemical and physical properties of a sodic soil. *Arid Soil Research and Rehabilitation* **6**(2):127–134 (1992).
54. OIV (Organisation Internationale de la Vigne et du Vin). *2013 Global economic vitiviniculture data*. [Online] (2013). Available at: http://www.oiv.int/oiv/info/enpoint2013 [December 15, 2013].
55. Bustos G, Moldes AB, Cruz JM and Domínguez JM, Influence of the metabolism pathway on lactic acid production from hemicellulosic trimming vine shoots hydrolyzates using *Lactobacillus pentosus*. *Biotechnol Prog* **21**(3):793–798 (2005).
56. Bustos G, Moldes AB, Cruz JM and Domínguez JM, Production of lactic acid from vine-trimming wastes and viticulture lees using a simultaneous saccharification fermentation method. *J Sci Food Agric* **85**(3):466–472 (2005).
57. Bustos G, de la Torre N, Moldes AB, Cruz JM and Domínguez JM, Revalorization of hemicellulosic trimming vine shoots hydrolyzates trough continuous production of lactic acid and biosurfactants by *L. pentosus*. *J Food Eng* **78**(2):405–412 (2007).
58. Moldes AB, Torrado AM, Barral MT and Domínguez JM, Evaluation of biosurfactant production from various agricultural residues by *Lactobacillus pentosus*. *J Agric Food Chem* **55**(11):4481–4486 (2007).
59. Portilla OM, Rivas B, Torrado A, Moldes AB and Domínguez JM, Revalorisation of vine trimming wastes using *Lactobacillus acidophilus* and *Debaryomyces hansenii*. *J Sci Food Agric* **88**(13):2298–2308 (2008).
60. Max B, Torrado AM, Moldes AB, Converti A and Domínguez JM, Ferulic acid and p-coumaric acid solubilization by alkaline hydrolysis of the solid residue obtained after acid prehydrolysis of vine shoot prunings: Effect of the hydroxide and pH. *Biochem Eng J* **43**(2):129–134 (2009).
61. Sánchez A, Ysunza F, Beltrán-García MJ and Esqueda M, Biodegradation of viticulture wastes by pleurotus: A source of microbial and human food and its potential use in animal feeding. *J Agric Food Chem* **50**(9):2537–2542 (2002).
62. Bertran E, Sort X, Soliva M and Trillas I, Composting winery waste: Sludges and grape stalks. *Bioresource Technol* **95**(2):203–208 (2004).
63. Portilla-Rivera OM, Moldes AB, Torrado AM and Domínguez JM, Lactic acid and biosurfactants production from hydrolyzed distilled grape marc. *Process Biochem* **42**(6):1010–1020 (2007).
64. Portilla-Rivera OM, Torrado AMa, Domínguez JM and Moldes ABn, Stabilization of kerosene/water emulsions using bioemulsifiers obtained by fermentation of hemicellulosic sugars with *Lactobacillus pentosus*. *J Agric Food Chem* **58**(18):10162–10168 (2010).
65. Vatai T, Škerget M and Knez Ž, Extraction of phenolic compounds from elder berry and different grape marc varieties using organic solvents and/or supercritical carbon dioxide. *J Food Eng* **90**(2):246–254 (2009).
66. Conde E, Moure A, Domínguez H and Parajó JC, Production of antioxidants by non-isothermal autohydrolysis of lignocellulosic wastes. *LWT - Food Sci Technol* **44**(2):436–442 (2011).
67. Ping L, Brosse N, Chrusciel L, Navarrete P and Pizzi A, Extraction of condensed tannins from grape pomace for use as wood adhesives. *Ind Crop Prod* **33**(1):253–257 (2011).
68. Diaz AB, de Ong I, Caro I and Blandino A, Production of hydrolytic enzymes from grape pomace and orange peels mixed substrate fermentation by *Aspergillus awamori*. *Chem Eng Transact* **17**:1143–1148 (2009).
69. Rodríguez LA, Toro ME, Vazquez F, Correa-Daneri ML, Gouiric SC and Vallejo MD, Bioethanol production from grape and sugar beet pomaces by solid-state fermentation. *Int J Hydrogen Energy* **35**(11):5914–5917 (2010).
70. García Martínez S, Grau A, Agulló E, Bustamante MÁ, Paredes C, Moral R *et al.*, Use of composts derived from winery wastes in tomato crop. *Commun Soil Sci Plant Anal* **40**(1/6):445–452 (2009).
71. Paradelo R, Moldes AB and Barral MT, Amelioration of the physical properties of slate processing fines using grape marc compost and vermicompost. *Soil Sci Soc Am J* **73**(4):1251–1260 (2009).
72. Mosse KPM, Patti AF, Christen EW and Cavagnaro TR, Review: Winery wastewater quality and treatment options in Australia. *Aust J Grape Wine Res* **17**(2):111–122 (2011).
73. Pérez-Serradilla JA and Luque de Castro MD, Microwave-assisted extraction of phenolic compounds from wine lees and spray-drying of the extract. *Food Chem* **124**(4):1652–1659 (2011).
74. Bai Z, Jin B, Li Y, Chen J and Li Z, Utilization of winery wastes for *Trichoderma viride* biocontrol agent production by solid state fermentation. *J Environ Sci* **20**(3):353–358 (2008).
75. Naziri E, Mantzouridou F and Tsimidou MZ, Recovery of squalene from wine lees using ultrasound assisted extraction - a feasibility study. *J Agric Food Chem* **60**(36):9195–9201 (2012).
76. Versari A, Castellari M, Spinabelli U and Galassi S, Recovery of tartaric acid from industrial enological wastes. *J Chem Technol Biotechnol* **76**(5):485–488 (2001).
77. Braga FG, Lencart e Silva FA and Alves A, Recovery of winery by-products in the Douro demarcated region: Production of calcium tartrate and grape pigments. *Am J Enol Viticult* **53**(1):41–45 (2002).
78. Devesa-Rey R, Vecino X, Varela-Alende JL, Barral MT, Cruz JM and Moldes AB, Valorization of winery waste vs. the costs of not recycling. *Waste Manage* **31**(11):2327–2335 (2011).
79. Wu JJ, Lin JC, Wang CH, Jong TT, Yang HL, Hsu SL *et al.*, Extraction of antioxidative compounds from wine lees using supercritical fluids and associated anti-tyrosinase activity. *J Supercrit Fluid* **50**(1):33–41 (2009).
80. Bustos G, Moldes AB, Cruz JM and Domínguez JM, Formulation of low-cost fermentative media for lactic acid production with *Lactobacillus rhamnosus* using vinification lees as nutrients. *J Agric Food Chem* **52**(4):801–808 (2004).
81. Rivas B, Torrado A, Moldes AB and Domínguez JM, Tartaric acid recovery from distilled lees and use of the residual solid as an economic nutrient for *Lactobacillus*. *J Agric Food Chem* **54**(20):7904–7911 (2006).
82. Salgado JM, Rodríguez N, Cortés S and Domínguez JM, Improving downstream processes to recover tartaric acid,

bbb_1506.indd 26 27/06/14 9:36 PM

tartrate and nutrients from vinasses and formulation of inexpensive fermentative broths for xylitol production. *J Sci Food Agric* **90**(13):2168–2177 (2010).

83. Davies RJ. *Yeast oil from cheese whey – process development*, in Single cell oil, ed by Moreton RS. Longman Scientific & Technical, Harlow, UK, pp. 99–146 (1988).
84. Davies RJ, Holdsworth J and Reader S. The effect of low oxygen uptake rate on the fatty acid profile of the oleaginous yeast *Apiotrichum curvatum*. *Appl Microbiol Biot* **33**(5):569–573 (1990).
85. Davies RJ and Holdsworth JE, Synthesis of lipids in yeasts: Biochemistry, physiology and production. *Adv Appl Lipid Res* **1**:119–159 (1992).
86. Papanikolaou S, Galiotou-Panayotou M, Fakas S, Komaitis M and Aggelis G, Lipid production by oleaginous Mucorales cultivated on renewable carbon sources. *Eur J Lipid Sci Technol* **109**(11):1060–1070 (2007).
87. Vamvakaki AN, Kandarakis I, Kaminarides S, Komaitis M and Papanikolaou S, Cheese whey as a renewable substrate for microbial lipid and biomass production by Zygomycetes. *Eng Life Sci* **10**(4):348–360 (2010).
88. Fakas S, Galiotou-Panayotou M, Papanikolaou S, Komaitis M and Aggelis G, Compositional shifts in lipid fractions during lipid turnover in *Cunninghamella echinulata*. *Enzyme Microb Technol* **40**(5):1321–1327 (2007).
89. Chen HC and Chang CC, Production of γ-linolenic ccid by the fungus *Cunninghamella echinulata* CCRC 31840. *Biotechnol Prog* **12**(3):338–341 (1996).
90. Chen HC and Liu TM, Inoculum effects on the production of γ-linolenic acid by the shake culture of *Cunninghamella echinulata* CCRC 31840. *Enzyme Microb Technol* **21**(2):137–142 (1997).
91. Fakas S, Papanikolaou S, Batsos A, Galiotou-Panayotou M, Mallouchos A and Aggelis G, Evaluating renewable carbon sources as substrates for single cell oil production by *Cunninghamella echinulata* and *Mortierella isabellina*. *Biomass Bioenerg* **33**(4):573–580 (2009).
92. Zikou E, Chatzifragkou A, Koutinas AA and Papanikolaou S, Evaluating glucose and xylose as cosubstrates for lipid accumulation and γ-linolenic acid biosynthesis of *Thamnidium elegans*. *J Appl Microbiol* **114**(4):1020–1032 (2013).
93. Ratledge C and Cohen Z, Microbial and algal oils: Do they have a future for biodiesel or as commodity oils? *Lipid Technol* **20**(7):155–160 (2008).
94. Koutinas AA, Chatzifragkou A, Kopsahelis N, Papanikolaou S and Kookos IK, Design and techno-economic evaluation of microbial oil production as a renewable resource for biodiesel and oleochemical production. *Fuel* **116**(0):566–577 (2014).
95. Papanikolaou S and Aggelis G, Lipids of oleaginous yeasts. Part II: Technology and potential applications. *Eur J Lipid Sci Technol* **113**(8):1052–1073 (2011).
96. Leiva-Candia DE, Pinzi S, Redel-Macías MD, Koutinas A, Webb C and Dorado MP, The potential for agro-industrial waste utilization using oleaginous yeast for the production of biodiesel. *Fuel* **123**(0):33–42 (2014).
97. Nkonya N and Barrein-Hurle J, *Analysis of incentives and disincentives for cashew nuts in the United Republic of Tanzania*. Technical notes series, MAFAP (Monitoring African Food and Agricultural Policies Project), FAO, 1–33 (2013).
98. FAO (Food and Agriculture Organization of the United Nations). *Small scale Regional Cashew Survey Report*. [Online] Sustainable and Agriculture Organisation of the United Nation, Tree Crop Programme (STCP) and Biohybrids, pp.86 (2001). Available at: http://www.anacardium.info/IMG/pdf/Small-scale_Cashew_Nut_Processing_-_FAO_2001.pdf [December 12, 2013]
99. Mohod A, Jain S and Powar AG, Cashew nut processing: Sources of environmental pollution and standards. *BIOINFO Environ Pollut* **1**(1):5–11 (2011).
100. Phani Kumar P, Paramashivappa R, Vithayathil PJ, Subba Rao PV and Srinivasa Rao A, Process for Isolation of cardanol from technical cashew (*Anacardium occidentale* L.) nut shell liquid. *J Agric Food Chem* **50**(16):4705–4708 (2002).
101. Mmongoyo JA, Mgani QA, Mdachi SJM, Pogorzelec PJ and Cole-Hamilton DJ, Synthesis of a kairomone and other chemicals from cardanol, a renewable resource. *Eur J Lipid Sci Technol* **114**(10):1183–1192 (2012).
102. Mele G and Vasapollo G, Fine chemicals and new hybrid materials from cardanol. *Mini-Rev Org Chem* **5**(3):243–253 (2008).
103. Khaokhum L, Sawasdipuksa N, Kumthong N, Tummatorn J and Roengsumran S, Cardanol polysulfide as a vulcanizing agent for natural rubber. *J Sci Res Chula Uni* **30**(1):23–40 (2005).
104. Mwalongo GCL, Lupituko LM, Eqid BM and Bonaventura AM, Preventing termite attack . Environmentally friendly chemical combinations of cashew nut shell liquid, sulfited wattle tannin and copper(II) chloride. *Green Chem* **1**(1):13–16 (1999).
105. Venmalar D and Nagaveni HC, *Evaluation of copperised cashew nut shell liquid and neem oil as wood preservatives*. [Online] Institute of wood Science and Technology, Malleswaram, Bangalore, India. Paper prepared for the 36th Annual Meeting Bangalore, India, IRG Secretariat SE-100 44, Stockholm Sweden. (2005). Available at: http://www.vertinnov.fr/fic_bdd/produits_pdf_fr_fichier/12242579720_Neem+Cashew_wood_preservative.pdf [December 12, 2013]
106. Peungjitton P, Sangvanich P, Pornpakakul S, Petsom A and Roengsumran S, Sodium cardanol sulfonate surfactant from cashew nut shell liquid. *J Surfactants Deterg* **12**(2):85–89 (2009).
107. Mkayula LL, Makame YMM and Matechi TH, Preparation of spherical polymeric particles from Tanzanian cashew nut shell liquid by suspension polymerization. *Tanz J Sci* **30**(2):1–10 (2004).
108. Gopalakrishnan S and Fernando TL, Processability and characteristics of novel polyurethanes from cardanol. *Res J Pharmaceut Biol* **1**(4):252–261 (2010).
109. Mythili CV, Retna AM and Gopalakrishnan S, Synthesis, mechanical, thermal and chemical properties of polyurethanes based on cardanol. *Bull Mater Sci* **27**(3):235–241 (2004).
110. Makame YMM, Johnson W and Mkayula LL, Micron-sized polymeric particles from cashew nut shell liquid: influence of reaction parameters on particle size. *Tanz J Sci* **31**(1):36–43 (2005).
111. Ofem MI, Umar M and Ovat FA, Mechanical properties of rice husk fiiled cashew nut shell liquid resin composites. *J Mater Sci Res* **1**(4):89–97 (2012).
112. Bhunia HP, Nando GB, Chaki TK, Basak A, Lenka S and Nayak PL, Synthesis and characterization of polymers from

bbb_1506.indd 27 27/06/14 9:36 PM

cashewnut shell liquid (CNSL), a renewable resource II. Synthesis of polyurethanes. *Eur Polym J* **35**(8):1381–1391 (1999).

113. Nayak PL, Natural oil-based polymers: Opportunities and challenges. *J Macromol Sci C* **40**(1):1–21 (2000).
114. Attanasi OA, Berretta S, Fiani C, Filippone P, Mele G and Saladino R, Synthesis and reactions of nitro derivatives of hydrogenated cardanol. *Tetrahedron* **62**(25):6113–6120 (2006).
115. Hamad FB, Mubofu EB and Makame YMM, Wet oxidation of maleic acid by copper(ii) Schiff base catalysts prepared using cashew nut shell liquid templates. *Catal Sci Technol* **1**(3):444–452 (2011).
116. Mubofu EB, Mdoe JEG and Kinunda G, The activity of invertase immobilized on cashew nut shell liquid-templated large pore silica hybrids. *Catal Sci Technol* **1**(8):1423–1431 (2011).
117. Mlowe S, Nejo AA, Pullabhotla VSRR, Mubofu EB, Ngassapa FN, O'Brien P *et al.*, Lead chalcogenides stabilized by anacardic acid. *Mater Sci Semicond Process* **16**(2):263–268 (2013).
118. Malik MA, O'Brien P, Tuna F, Pritchard R, Buchweishaija J, Kimambo E *et al.*, The synthesis, spectroscopy and X-ray single crystal structure of catena-[(μ-anacardato)-copper(II) bipyridine][Cu_2{(μ-$O_2CC_6H_3$(*o*-OH)(o-$C_{15}H_{31}$)}$_4$(NC_5H_5)$_2$]. *Dalton Trans* **42**(40):14438–14444 (2013).
119. FAO (Food and Agriculture Organization of the United Nations). *Global food losses and food waste - Extent, causes and prevention*. [Online] (2011). Available at: http://www.fao.org/docrep/014/mb060e/mb060e00.pdf [December 9, 2013].
120. Tuck CO, Pérez E, Horváth IT, Sheldon RA and Poliakoff M, Valorization of biomass: Deriving more value from waste. *Science* **337**(6095):695–699 (2012).
121. Pfaltzgraff LA, De bruyn M, Cooper EC, Budarin V and Clark JH, Food waste biomass: A resource for high-value chemicals. *Green Chem* **15**(2):307–314 (2013).
122. Pleissner D and Lin CSK, Valorisation of food waste in biotechnological processes. *Sust Chem Process* **1**(1):1–6 (2013).
123. Sayeki M, Kitagawa T, Matsumoto M, Nishiyama A, Miyoshi K, Mochizuki M *et al.*, Chemical composition and energy value of dried meal from food waste as feedstuff in swine and cattle. *Anim Sci J (Japan)* **72**:34–40 (2001).
124. Pleissner D, Lam WC, Sun Z and Lin CSK, Food waste as nutrient source in heterotrophic microalgae cultivation. *Bioresource Technol* **137**(0):139–146 (2013).
125. Kim JH, Lee JC and Pak D, Feasibility of producing ethanol from food waste. *Waste Manage* **31**(9–10):2121–2125 (2011).
126. Leung CCJ, Cheung ASY, Zhang AYZ, Lam KF and Lin CSK, Utilisation of waste bread for fermentative succinic acid production. *Biochem Eng J* **65**(0):10–15 (2012).
127. Du C, Sabirova J, Soetaert W and Lin CSK, Polyhydroxyalkanoates production from low-cost sustainable raw materials. *Curr Chem Biol* **6**(1):14–25 (2012).
128. Arancon RAD, Lin CSK, Chan KM, Kwan TH and Luque R, Advances on waste valorization: new horizons for a more sustainable society. *Energ Sci Eng* **1**(2):53–71 (2013).
129. Mata TM, Martins AA and Caetano NS, Microalgae for biodiesel production and other applications: A review. *Renew Sust Energ Rev* **14**(1):217–232 (2010).
130. Barrow C and Shahidi F. *Marine Nutraceuticals and Functional Foods*. CRC Press, Taylor & Francis Group, pp. 34 (2008).
131. Miao X and Wu Q, Biodiesel production from heterotrophic microalgal oil. *Bioresource Technol* **97**(6):841–846 (2006).
132. Lam KF, Leung CCJ, Lei HM and Lin CSK, Economic feasibility of a pilot-scale fermentative succinic acid production from bakery wastes. *Food Bioprod Proc* DOI:10.1016/j.fbp.2013.09.001
133. ASB Biodiesel (Hong Kong) Limited, [Online] (2013). Available at: http://www.asb-biodiesel.com/about.php [December 11, 2013].
134. ERM (Environmental Resources Management), *Development of a Biodiesel Plant at Tseung Kwan O Industrial Estate, Environmental Impact Assessment Report – Executive Summary*. [Online] (2007). Available at: http://www.epd.gov.hk/eia/register/profile/latest/dir158/dir158.pdf [December 10, 2013].
135. EPD (Environmental Protection Department of HKSAR), *Monitoring of Solid Waste in Hong Kong 2011*. [Online] (2011). Available at: https://www.wastereduction.gov.hk/chi/materials/info/msw2011tc.pdf [December 10, 2013]
136. SCMP (South China Morning Post), *Biofuel maker pushes product use in market*. [Online] (2013). Available at: http://www.scmp.com/business/companies/article/1341490/biofuel-maker-pushes-product-use-market [December 10, 2013]
137. EPD (Environmental Protection Department of HKSAR), *An Urgent Need to Suppress Waste Generation*. [Online] (2013). Available at: http://www.epd.gov.hk/epd/msw_consult/file/MSW_ENG_ch3.pdf [December 10, 2013]
138. Council for Sustainable Development, *Waste Reduction by Waste Charging How to Implement?* [Online] (2013). Available at: http://www.susdev.org.hk/share/pdf/MSW_IR_ENG.pdf [December 9, 2013]
139. Environment Bureau. *Hong Kong: Blueprint for Sustainable Use of Resources 2013-2022*. [Online] (2013). Available at: http://www.enb.gov.hk/en/files/WastePlan-E.pdf [December II, 2013]
140. IMECHE (Institution of Mechanical Engineers), *Global Food, Waste not, Want not*. [Online] (2013). Available at: http://www.imeche.org/docs/default-source/reports/Global_Food_Report.pdf?sfvrsn=0 [December 12, 2013].
141. Bond M, Meacham T, Bhunnoo R and Benton TG, *Food waste within global food systems*. [Online] (2013). Available at: http://www.foodsecurity.ac.uk/assets/pdfs/food-waste-report.pdf [December 12, 2013].
142. WRAP (Waste and Resource Action Program), *Estimates of waste in the food and drink supply chain*. [Online] (2013). Available at: http://www.wrap.org.uk/sites/files/wrap/Estimates%20of%20waste%20in%20the%20food%20and%20drink%20supply%20chain_0.pdf [December 12, 2013].
143. Tesco. *Tesco and society: Using our scale for good. 2013/14 half year update.*: [Online] (2013). Available at: http://www.tescoplc.com/files/pdf/reports/tesco_and_society_2013-14_halfyear_summary.pdf [December 12, 2013].
144. Defra (Department for Environment, Food and Rural Affairs. *Government Review of Waste Policy in England 2011*. [Online] (2011). Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69401/

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pb13540-waste-policy-review110614.pdf [December 12, 2013].

145. WRAP (Waste and Resource Action Program), *The Courtauld Commitment.* [Online] (2013). Available at: http://www.wrap.org.uk/content/what-is-courtauld [December 12, 2013].
146. Boye J and Arcand Y, Current trends in green technologies in food production and processing. *Food Eng Rev* **5**(1):1–17 (2013).
147. EPSRC, Foster T, EPSRC Centre Director (2013).
148. Anonymous. Marson A, Lead Participant (2013).
149. URT, *National Environmental Policy*, Government of Tanzania (1997).
150. URT, *National Environmental Management Act No. 20.* Government of Tanzania (2004).
151. URT. The Environmental (Solid Waste Management) Regulations. Government of Tanzania (2009)
152. Ministerio de Agricultura, Alimentación y Medio Ambiente, Actividad legislativa [Online]. Available at: http://www.magrama.gob.es/es/ministerio/actividad-legislativa/ [June 21, 2014].



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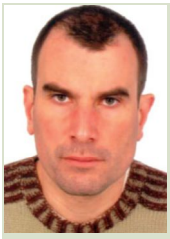
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