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# Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective

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Increasing demand for fuels and chemicals, driven by factors including over-population, the threat of global warming and the scarcity of fossil resources, strains our resource system and necessitates the development of sustainable and innovative strategies for the chemical industry. Our society is currently experiencing constraints imposed by our resource system, which drives industry to increase its overall efficiency by improving existing processes or finding new uses for waste. Food supply chain waste emerged as a resource with a significant potential to be employed as a raw material for the production of fuels and chemicals given the abundant volumes globally generated, its contained diversity of functionalised chemical components and the opportunity to be utilised for higher value applications. The present manuscript is aimed to provide a general overview of the current and most innovative uses of food supply chain waste, providing a range of worldwide case-studies from around the globe. These studies will focus on examples illustrating the use of citrus peel, waste cooking oil and cashew shell nut liquid in countries such as China, the UK, Tanzania, Spain, Greece or Morocco. This work emphasises 2nd generation food waste valorisation and re-use strategies for the production of higher value and marketable products rather than conventional food waste processing (incineration for energy recovery, feed or composting) while highlighting issues linked to the use of food waste as a sustainable raw material. The influence of food regulations on food supply chain waste valorisation will also be addressed as well as our society's behavior towards food supply chain waste. "*There was no ways of*

## Broader context

The valorisation of food waste is an increasingly "hot" topic, as demonstrated by the publication of several reports on the quantities of food wasted along our supply chains and the increasingly recognised need to both avoid waste and find new renewable resources. The low efficiency of these supply chains has economical and environmental impacts, wasting resources such as water, energy, labour, land and agrochemicals. While 1st generation waste valorisation techniques such as AD and composting have some value, the inherent chemical complexity of food waste makes it a very attractive source of higher value products. This perspective article highlights initiatives around the globe on 2nd generation use of food supply chain waste as a resource, providing a renewable feedstock for diverse sectors of the chemical industry. The review highlights the limitations linked with the use of food waste as a resource, connecting it with social and policy issues, giving for the first time a complete picture of the state-of-the-art in this multidisciplinary research area and in the light of recent technological advances and the drive towards using waste as a raw material to both reduce the environmental burden of disposal and the concerns about future resources.

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dealing with it that have not been known for thousands of years. These ways are essentially four: dumping it, burning it, converting it into something that can be used again, and minimizing the volume of material goods – future garbage – that is produced in the first place." *William Rathje on waste (1945–2012) – Director of the Tucson Garbage project.*

## 1 Introduction, current context and drivers

Environmental issues and the growing global population combined with the increasing global demand for energy, chemicals and materials in our current society have fostered research efforts to develop low environmental impact technologies based on renewable raw materials to meet such global targets. Alternative feedstocks to conventional fossil raw materials have attracted an increasing interest over recent years, contributing to the creation of a new paradigm: the biorefinery concept.

A biorefinery is in essence an analogous concept to that of a conventional refinery in that it aims to maximise outputs (*i.e.* energy/fuel, chemicals and materials) from the processing of raw materials. In this case, biomass and waste (as opposed to crude oil) are selected as renewable feedstocks and converted into valuable marketable products by using a series of sustainable and low environmental impact technologies,[1] http://www.legiste.co.uk.

The biorefinery concept stimulated a great deal of interaction between scientists from different fields including (bio) chemistry, biology, environmental sciences, economics and (bio)chemical engineering in an attempt to switch to a bio-based industry that can make use of renewable resources for an increased competitiveness. In this regard, recent studies on the use of various food crops for biofuels, chemicals and materials production pointed to several deficiencies and concerns for

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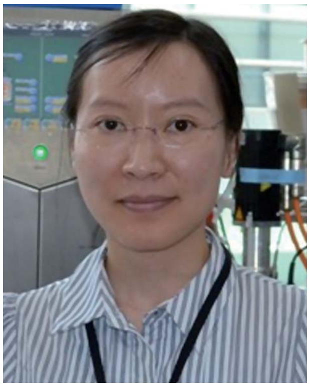

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their implementation in a bio-based economy.[2,3] The development of a more integrated approach to resource management based sustainable strategies along the whole supply chain (to valorise residues, by-products and waste in order to maximise the ratio products/feedstock) is essential.

Waste is currently a major issue worldwide, becoming more and more important in developing countries (China, India, *etc.*) as well as in Europe. Different types of waste can be categorised into industrial, agricultural, sanitary and solid urban residues based on their origin. Solid urban residues can at the same time be subdivided into glass, paper, plastics, metals, organic matter and others. The distribution of these may significantly change from country to country so that figures have to be studied on a case to case basis. Waste produced by food processing companies is a good example of a pre-consumer type of waste generated on a large scale globally. This type of waste is becoming increasingly problematic as in some cases it may account for over 50% of the total waste produced in countries, with 60% of it belonging to organic matter. The McKinsey Global Institute announced that FW is ranked third of fifteen identified resource productivity opportunities as part of its 2011 report entitled "Resource Revolution: Meeting the world's energy, material, food and water needs".[4] In spite of these encouraging reports, many of these food waste residues find no current uses different from landfilling or first generation recycling practices (*e.g.* composting, animal feed) and/or reuse of organic matter. However, our current society needs in terms of economic competitiveness, efficiency and maximisation of profit minimising waste and energy consumption are fostering the design and development of advanced strategies and approaches to process food waste residues aiming to produce high added value end products which can be implemented into existing markets. In addition to this, society also needs a major change of mentality and perception on waste as a resource instead of an issue, which should be steered by Governments and Environmental Agencies worldwide.

The scale and rate at which our food supply chain produces waste and its putrescible nature represents a problem for the industry concerned.[5] In this context, food supply chain waste (FSCW) emerges as a truly sustainable feedstock to be employed in the production of bio-derived chemicals, materials and fuels, in our current scenario that experienced a "147% increase in commodity prices since the turn of the century" and increasingly higher price volatility.[5]

Waste is also becoming increasingly expensive to dispose off. The EU landfill directive has caused landfill gate fees to increase from £40–74 to £68–111 between 2009 and 2011.[6,7] Improved resource utilisation will positively influence industry's profits, produce new growth and expand innovation opportunities through the achievement of a zero waste economy.

In the light of these comments, this contribution is aimed to provide a comprehensive and multidisciplinary approach on the basics of advanced and innovative food valorisation practices providing a variety of case-studies that illustrate the potential of food waste valorisation and its contribution to a future bio-based economy.

### 1.1 Basics and figures of food waste

Food waste (FW) can be defined as the "end products of various food processing industries that have not been recycled or used for other purposes. They are the non-product flows of raw materials whose economic value is less than the cost of collection and recovery for reuse; therefore discarded as waste".[8]

Around 89 million tonnes of FW are generated every year in the E.U.-27.[9] 80% of this total figures account for the contributions of the manufacturing sector (38%) and household sector (42%), highlighting how FW arises at every stage of food supply chain. Particularly, domestic waste produced by individuals at home represents a problem from the logistics viewpoint, making difficult a multiple collection and concentration in one place.

Comparatively, waste produced by the agricultural and processing sectors is generated in a more concentrated manner and

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*Prof. Rafael Luque has significant expertise on biomass/waste valorisation practices to materials, fuels and chemicals over the past 10 years. He has published over 140 research articles, filed 3 patent applications and edited 5 books as well as other numerous contributions and invited lectures worldwide. Prof. Luque is also an Editorial Advisory Board member of Chem. Soc. Rev., Catal. Commun., COS and CGC and was recently awarded the Marie Curie Prize in Spain (2011), the Green Talents award in Germany (2011) and the TR35 Spain award from MIT (2012) as a young entrepreneur of the company Green Applied Solutions S.L. (GAS).*

would therefore be easier to collect and valorise. Problems associated with such waste include:

- Severe pollution problems due to high associated chemical and biological oxygen demand (COD and BOD),[10]
- Varying pH and chemical composition due to seasonal variations and changes in food processing,[10]
- Materials prone to bacterial contamination (*e.g.* fruit and vegetable by-products),[5]
- High accumulation rate leading to disposal management problems.[11,12]

### 1.2 Food supply chain waste (FSCW)

FSCW is the organic material produced for human consumption that is discarded, lost or degraded primarily at the manufacturing and retail stages, including waste arising from pest degradation or food spoilage. FW is produced at every stage of the food supply chain, being more obvious at the retail and consumer stage. Recent FAO reports estimated that as much as 50% of the food produced is lost or wasted before and after reaching the consumer,[13] accounting for over 1.3 billion tons per year of food globally produced for human consumption. These obviously represent a major environmental, economic and social problem.[14]

The agro-food supply chain encompasses a broad variety of manufacturing processes that generate accumulative quantities of different waste, especially organic residues.[15,16] The increasing demand for chemicals and fuels, together with other drivers, are encouraging the re-use and efficient valorisation of organic waste from the food supply chain for the production of novel added-value materials, chemicals and fuels, as a complementary approach to the aforementioned conventional practices (*i.e.* animal feed, composting, incineration and landfill).

Industry's shift towards higher sustainability to improve cost-effectiveness, process efficiency and green credentials makes economically sound the development of sustainable and innovative strategies for the reuse of food waste. Industry is nevertheless not the only driver promoting advanced waste valorisation practices. The increasingly strict European regulations and standards as well as costs associated with their compliance (in relation to the Landfill Directive in Europe for example ref. 17) are also major drivers of the use of FSCW as feedstock to valuable products (Fig. 1).

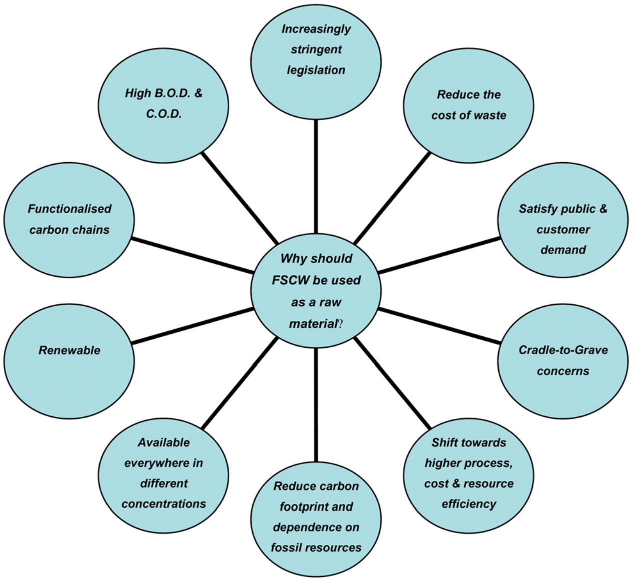


**Fig. 1** Drivers for a change: FSCW as a renewable feedstock.

Several reasons can be taken into account to develop advanced valorisation practices on residues and by-products of FW. These comprise significant quantities of functionalised molecules (*i.e.* carbohydrates, proteins, triglycerides, fatty acids, phenolics as shown in Fig. 2), being at the same time abundant, readily available, under-utilised and renewable. Various waste streams even contain valuable compounds including antioxidants which could be recovered, concentrated and re-used in functional foods and lubricants additives. Fig. 2 illustrates how daily used compounds in common consumer applications are present in FSCW. Examples of types of FSCW and associated "corresponding target ingredient for recovery" have been listed by Galanakis in an effort to highlight the potential of FSCW as a source of sought-after chemical components.[18] Shieber *et al.* emphasized the favourable technological or nutritional properties of fruit and sugar processing by-products a decade earlier.[5] The next step would be to identify associated volumes available of different types of FSCW.

The development of such valorisation routes may address the main weakness of the food processing industry, aiming to develop more sustainable supply chain and waste management systems. They can solve both a resource and waste management problem, as the issues associated with agro-food waste are important, including:

- Decreasing landfill options,
- Uncontrolled greenhouse gas (GHG) emissions,
- Contamination of water supplies through leaching of inorganic matter and
- Low efficiency of conventional waste management methods (*i.e.* incineration and composting).

Good examples of schemes likely to be successful are the development of closed-loop supply chain models.[19] In such models, all types of waste residues are fed back into the value chain (such as packaging waste being re-used), food graded as

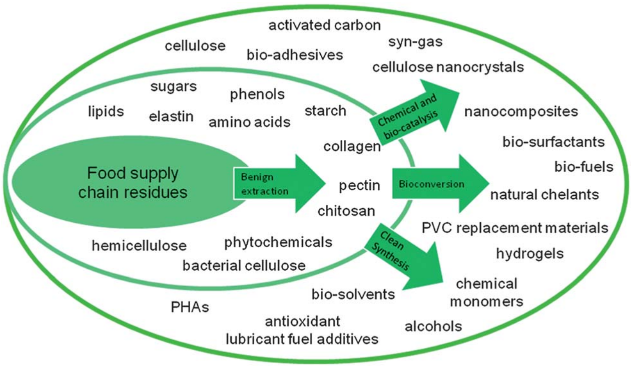


**Fig. 2** Components present in FSCW and their uses in common consumer applications.

lower quality for cosmetic reasons and food that is surplus to retailers or manufacturers to be made available through alternative routes (*e.g.* Fareshare or as cheaper alternatives), while unavoidable FW would be utilised as a by-product, *e.g.* in providing energy from waste using the appropriate technology. Several additional initiatives are currently ongoing which will be detailed in the next sections.

### 1.3 Current food waste valorisation practices

Current waste management practices for FSCW (Fig. 3) in decreasing order of added value waste include:

- Animal feed
- Composting
- Incineration and
- Landfill.

Animal feed is generally the most cost effective route for FSCW, however it is sometimes limited by regulatory issues as well as the nature of the co-product generated in the process.[20] Composting, generally as land spread/land injection, is the most popular and extended practice. It is environmentally acceptable as it diverts waste from landfill and reduces farmers' needs for fertilisers and fresh water from the use of effluent and solid waste from factories. However, this type of practice is still carried out at a relatively elevated cost, with the exception of some digestates from anaerobic digestion (AD).[21]

Studies by the UK Department of Environmental, Food and Rural Affairs (DEFRA) in a number of facilities of members of the Federation of Food and Drink (FDF) showed that over 90% (2010) of food waste from the sites was utilised in some form [animal feed (10%), land spread agents (around 75%), by anaerobic digestion (around 1%) or incineration (4%)] from the total quantities of food waste, with *ca.* 9% going to landfill. These figures showed an overall waste reduction from previous years and demonstrate that the food sector in the UK is making good progress towards zero organic and packaging waste going to landfill by 2015.[25]

Waste management strategies for FW raise significant environmental concerns. Disposal of FW in landfill is both costly and has a large environmental impact, with direct and indirect emission of GHG ($CH_4$ and $CO_2$). As an example, 4.2 tonnes of $CO_2$ are emitted along the supply chain for every tonne of FW generated in addition to further emissions to soil, air and water.[19] Energy recovery through incineration is not always feasible,[26] typically due to the energy loss to evaporate the large water content in FW. The use of FW as a compost/soil enhancer is likely to be reviewed in years to come.[27] Tuck *et al.* recently demonstrated the economical advantage linked to the valorisation of waste biomass to bulk chemicals. The average value of bulk chemicals and transportation fuels produced from waste biomass was estimated to be around 1000 and 200–400 $ per tonne of biomass, respectively. Comparatively, cattle feed or electricity were evaluated to be in the range of 70–200 and 60–150 $ per tonne of biomass respectively, which in any case highlights the significant differences in value between final produced outputs.[28]

### 1.4 Food supply chain waste (FSCW) as a raw material

Current management practices for FW could be complemented with lower environmental impact strategies that will have the potential to generate valuable products with current and novel applications, thus offering added value for companies and/or research institutions.[29] This is in essence the proposed concept of a waste-based biorefinery. Here research has a considerable emphasis on the recovery, recycling and upgrading of wastes.[16] Despite clear benefits, utilisation of FW currently represents a challenge due to several drawbacks and limitations. These include its inherent heterogeneously variable composition (lipids, carbohydrates, proteins),[29,30] fluctuating volumes in seasons,[29–31] high water content and low calorific value,[15] which constitutes a challenge for the development of robust large scale, consistent industrial processes.[30] Technological limitations and knowledge-based processing and efficient and cost-competitive ways to convert it into valuable products as well as insufficient legislative and infrastructure support for the use of perishable feedstocks in industry will also make their implementation at large scale facilities challenging. Industry and public perception as well as acceptance will be also important barriers to overcome in the future.

Fig. 4 and 5 illustrate the occurrence of FSCW in several locations across the globe. Up-to-date and accurate data on the production of FW at every stage of the food supply chain are still missing, making comparisons very difficult. Nonetheless, there are strong drivers for stakeholders and public organisations in the food processing and other sectors to reduce costs, and to develop suitable strategies for the conversion and valorisation of side streams. The development of knowledge-based strategies to unlock the enormous potential of FW should also satisfy an increasing demand for renewably sourced products, leading to sustainable, bio-derived chemicals, fuels and materials, and effecting waste management regulations over the years to come. The valorisation of FSCW is rendered absolutely necessary in order to improve the food chain's sustainability and

**Fig. 3** Animal feed, land injection and incineration, current alternatives to landfill for food waste.[22–24]

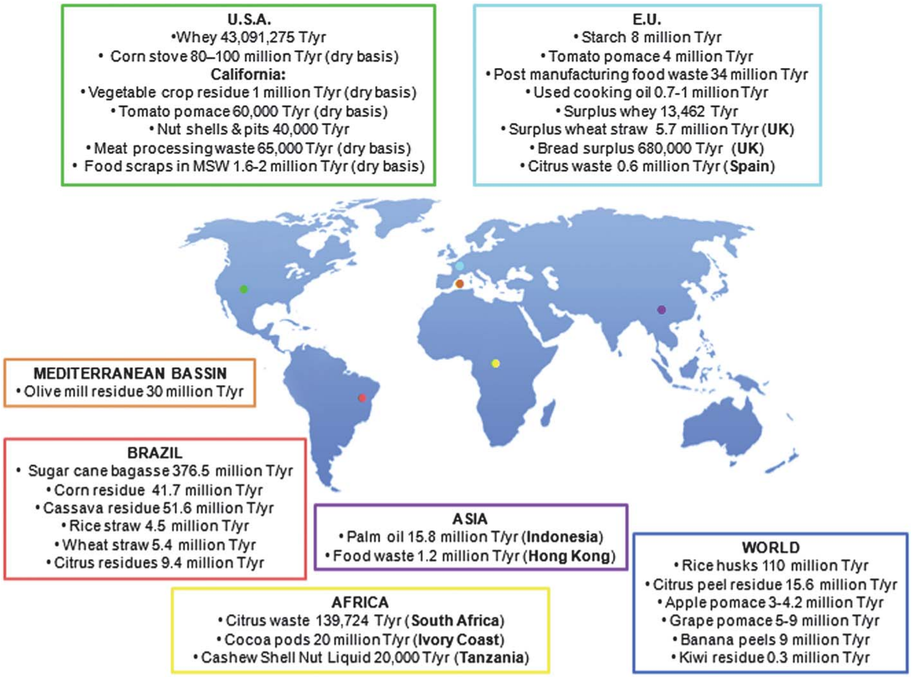


**Fig. 4** Examples of FSCW volumes available across the world.

**Fig. 5** Examples of waste streams generated by the food manufacturing sector (spent coffee grounds, pea pods and waste citrus peel, from left to right) in front of a 30 kg per hour pilot scale microwave at the Biorenewable Development Center of the University of York.

cost-effectiveness together with its ethical and environmental issues, especially in the light of recent technological advances and the drive towards re-using waste as a raw material to improve process efficiency in general.

## 2 Overview of waste generated in the food supply chain

FW generates at various points in the food supply chain, starting at the farm even before a commodity moves into the marketing system (Fig. 6).[31–33] Periodic pre-harvest losses take place due to extreme weather conditions (*i.e.* droughts) or pest infestations. FSCW generated at the harvesting stage is generally subjected to technical variables including increased mechanization, equipment malfunction and new management practices.[32] Economic factors, which affect producers' willingness to bring their product to market, are also a common cause of FSCW production.

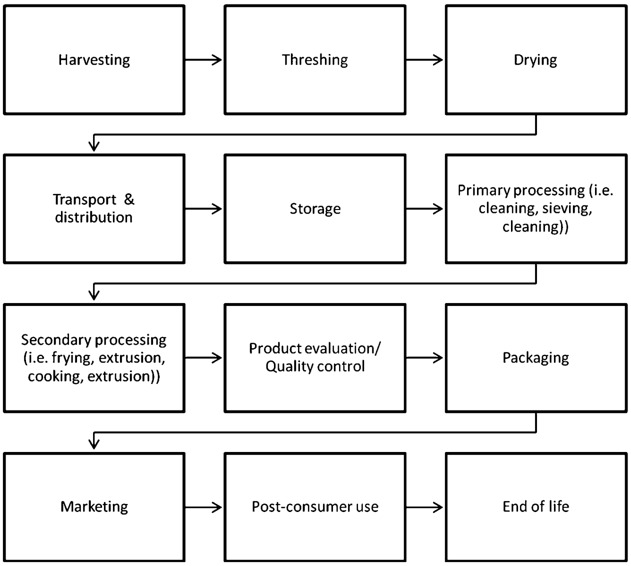


**Fig. 6** Illustration of processing steps of the food supply chain.

Food is also subjected to additional losses as it leaves the farm and enters the food marketing system. Examples of such losses include meat, bread and related foodstuffs prepared by restaurants or caterers that are never served as well as the disposal of blemished, badly labelled/packaged, inappropriately storage/transported or over-riped products which cannot

**Table 1** Types of FW available in the food supply chain

| | Stages | Characteristics of food waste |
|---|---|---|
| Pre-consumer | Production | Crop residues, crop waste through poor harvest techniques, pest and diseases, poor transport infrastructure and severe weather conditions |
| | Processing and manufacturing | Waste through packaging damages, contamination, storage and cold storage, poor transport |
| | Retail | Stock management and compliance to regulation, storage, and packaging |
| Post-consumer | Consumer | Stock management at home, poor food preparation, confusion over 'use by' dates |

be marketed but are otherwise nutritious and safe. An important component of food loss at the retail end of the supply chain is stock removed from retail shelves when it reaches its "sell-by" date.[31,32] Freshly produced dairy products and other perishable items make up the largest share of retail food losses. Kader estimated that about one-third of all fresh fruit and vegetables produced worldwide are lost before it reaches consumers.[34] This figure has been estimated to account for 9% in the UK.[35] Table 1 summarises the different forms that food waste may have in a food supply chain.

Table 2 provides a summary of total waste arising at different stages of the food supply chain, and separated into the types of waste generated. The total amount of FW generated in the UK every year and arising from the supply chain and households amounts to 11.3 million tonnes, and total packaging amounts to 5.1 million tonnes.[36] In addition, there are 2.2 million tonnes of by-product sent to animal feed from the manufacturing stage of the supply chain.

Retail and distribution packaged surplus production contributes to a significant proportion of FW at this stage; however, the food and drinks sector efficiently manages to reuse a large proportion of FW generated.[37,38] Increased consumer choices as well as an improved proportion of disposable income spent on food had the tendency to increase the wasteful behaviour at the consumer end of the supply chain.

FW is also an important component of the household waste stream, making up a significant proportion (around 20%) of domestic waste.[39,40] FW also has a high carbon impact relative to other types of waste, which is expected to be one of the fastest growing household streams in future.[41] Given that 61% of all FW is avoidable, better management could lead to significant reductions in FW.[31] Domestic FW prevention also appears to be an area of waste prevention where there is little public resistance, at least in principle, with 9 out of 10 people agreeing to reduce their FW footprint.[31] However, there is a dilemma with regard to the perception of domestic FW. Consumers in general do not perceive FW as an environmental problem, although two thirds of the population claim to be concerned about FW, highlighting a lack of personal responsibility in relation to FW.[42] Exploring this issue further highlights that there are no social and ethical pressures to avoid FW in today's society, which seems to be related to the fact that the majority of the population in the developed world have not experienced food shortages in their lifetime.[42]

**Table 2** Contribution of food industry to industrial and commercial waste[37]

| Contribution of food industry to industrial and commercial waste | | | |
|---|---|---|---|
| Type | Percentage amount of total | Percentage of type | Amount (Mtonnes p.a.) |
| **Industrial waste** | **69%** | | **48–69** |
| Food, drink and tobacco | | 16% | 7.7–11.0 |
| Other industrial | | 84% | 40.6–58.0 |
| **Commercial waste** | **31%** | | **22–31** |
| Hotels and catering | | 16% | 3.5–5.0 |
| Wholesale (inc. food and drink) | | 39% | 8.5–12.0 |
| Other commercial | | 45% | 9.8–14.0 |
| **Total industrial and commercial waste** | | | **70–100** |

## 3 Influence of food regulations on food waste reduction and valorisation

### 3.1 Legislation current overview: definitions and background

From a legal perspective, any analysis of FW should begin with the laws applicable to its country of origin, treatment or disposal, although supranational considerations may arise (*e.g.* if international transportation is contemplated for the treatment or disposal of waste).[43]

Legislation applicable within the European Union (EU) provides an interesting case study with regard to the treatment or disposal of FW for the following reasons. Firstly, the EU has considerable experience in developing policy measures and regulations to address the environmental problems of waste[44] and is currently developing policies aimed at ensuring the efficient use of resources[45] and sustainable patterns of consumption and production.[46] Secondly, EU waste legislation and regulations apply throughout all twenty seven Member States, thus providing a reasonable degree of geographical coverage for the purpose of a comparison in a global context. Last, but not least, environmental policies and regulations developed in the EU play an increasingly important role in shaping policies and regulations in other countries.[47]

The European Economic Community (EEC), the precursor to the EU, first engaged with the issue of waste in the early 1970s,[44] developing a uniform definition of "waste" as the basis of a range of policies and laws aimed at regulating the production, handling, storage, transfer, treatment and disposal of waste with the overriding objective of avoiding and/or minimising the negative effects of waste generation on human health and the environment. The essence of that definition ("substances or objects that the holder discards or intends or is required to discard")[48] has remained largely unchanged in subsequent years, although there have been many attempts to clarify it as well as to ensure its uniform application throughout the EU. Differentiating waste from by-products and residues as well as waste from substances that have been fully recovered (the 'end-of-waste' issue) are recurring themes that the European Court of Justice (ECJ, now the Court of Justice of the European Union) has been asked to consider. These are critical issues to address in order to develop and implement advanced valorisation routes different from common current valorisation practices for FW (animal feed, composting and AD).

Assuming a particular FW stream is indeed waste in its legal sense and it does not exhibit any of the properties that would render it "hazardous", then within the EU at least FW is broadly subjected to the same management principles and controls as other types of "non-hazardous waste" within the EU, with the notable exception of animal by-product wastes. These are subject to uniform and stringent controls with respect to their storage, transport, treatment and disposal, principally through Regulation (EC) no. 1069/2009 (which replaces Regulation (EC) no. 1774/2002 and others),[49] in order to prevent associated risks to animal and public health (except where animal by-products, including processed products are destined for incineration, landfilling or use in biogas or composting plant).

### 3.2 The waste framework directive and waste hierarchy

Fig. 7 depicts the current version of the waste hierarchy, initially set out in Directive 75/442/EEC[50] (amended by 91/156/EC and re-cast as 2006/12/EC), and most recently revised through Directive 2008/98/EC (the 'rWFD').

The hierarchy places priority on preventing waste arising in the first instance and relegates disposal, a term that encompasses landfilling to the least favoured waste management option. Of the intermediate waste management options, reuse and recycling (*i.e.* for instance into chemicals and materials) is preferred to energy recovery in that it is more environmentally sound.

The introduction of a policy approach to waste management that takes account the whole life-cycle of products and materials,[51] not just the waste phase, was a significant development in the 2008 revision of the WFD, along with an emphasis on managing wastes so as to conserve natural resources and strengthen the economic value of waste.

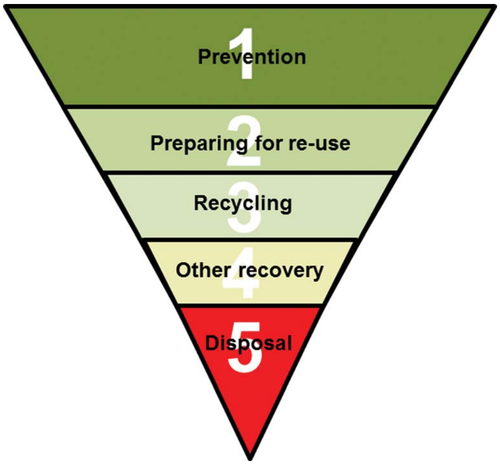


**Fig. 7** The waste hierarchy.

'Biowaste', a term which includes FW, was also singled out in rWFD for the first time as a special case, with the Commission being tasked to carry out an assessment of biowaste and, if appropriate, to bring forward proposals for legislative measures.[52] This assessment focused on three points: the separate collection of biowaste with a view to its composting and digestion; the treatment of biowaste so as to ensure a high level of environmental protection; and the use of environmentally safe materials (in particular compost and digestate) produced from biowaste. A Green Paper has been published on biowaste management in the EU[53] and various studies have been carried out to support an Impact Assessment of a potential legislative proposal.[54]

Member States are required under the rWFD to draw up waste prevention programmes by the end of 2013 with a view to breaking the link between economic growth and waste generation.[55]

EU guidelines on the preparation of food waste prevention programmes identify two main approaches to FW prevention:

- behavioural change (following a motivate, enable, engage, exemplify, encourage model); and
- sectoral based approaches (targeted at: food manufacturing and processing; food retailing and distribution; food services, restaurants, caterers; businesses and institutions, hospitals, schools; and households).

The lowest priority afforded in the waste hierarchy to disposal by landfill is reflected in the Landfill Directive (99/31/EC), one aspect of which seeks to divert biodegradable municipal waste (*i.e.* mainly waste of household origin) away from landfill through imposing stringent reduction targets on Member States (65% by weight by 2016 against 1995 levels with intermediate reduction targets).[56] FW is considered as biodegradable waste for the purpose of the Directive. Another factor driving the diversion of biodegradable/FW from landfill towards other waste management options, particularly towards AD with biogas recovery, is the imperative of reducing greenhouse gas (GHG) emissions.

### 3.3 Future practices towards valorisation of biowaste/FSCW

The valorisation of biowaste (or any waste) is not explicitely mentioned or defined in the WFD, but the concept of transforming waste into valuable materials and energy is within the spirit of the Directive's policy objectives.[57] In a later communication of 18 May 2010 on future steps in bio-waste management in Europe, the Commission concluded that composting and AD offered the most promising environmental and economic results for biowaste that cannot be prevented. At present, the majority of FW produced in the UK is either landfilled, composted or incinerated. AD is a methodology that is still in its commercial infancy, with only three dedicated AD food waste treatment plants presently operating in the UK treating catering wastes and waste from food retailers and manufacturers.

However, the first small-scale commercial AD system for domestic, localised FW treatment, which creates heat, power and bio-fertiliser, has recently been unveiled and there are plans for it to provide a template for similar developments elsewhere.[58]

In relation to the waste hierarchy, the status of 'composting' has been a matter of uncertainty. It appears that the Commission is heading towards regarding only compost and digestate that meet 'end-of-waste' criteria as having undergone 'recycling'. A Compost Quality Protocol (CQP) and a Digestate Quality Protocol (DQP) have been notified by the UK to the European Commission under the Technical Standards Directive (98/34/EC) further to the end-of-waste criteria in the rWFD.[59] These Protocols require compliance with an "approved standard". At present, the only approved standard for source-separated biowaste in the UK is PAS 100 (for compost) and PAS 110 (for digestate).[21] Only compost and digestate that meets those standards can be properly regarded as fully recycled waste. Until CQP or DQP certification is achieved, treated biowaste therefore remains 'waste' and accordingly continues to be subjected to waste controls.

The Quality Protocol approach has been adopted in relation to other (non-bio) forms of waste as a means of enabling businesses to demonstrate to customers and regulators alike that waste has been fully recycled and that waste regulations cease to apply.[60] This can have very significant commercial implications, and the extension of the Quality Protocols approach would be a positive step towards strengthening the economic potential of waste where there is uncertainty over end-of-waste status.

### 3.4 Legislation issues

**3.4.1 Biowaste treatment – feedstock supply.** In its aforementioned 2010 Communication, the Commission also noted the importance of "good quality input into these processes".[61] According to the Commission, this could be best achieved by separate collection, and Member States were recommended to "make the fullest possible use" of the options provided by Articles 11 and 22 of the WFD to "introduce separate collection systems as a matter of priority in line with the competition rules of the Treaty on the Functioning of the European Union".

Where international transportation is contemplated for the treatment of waste (which includes transportation to other EU Member States), transfrontier shipment of waste rules will also need to be considered (further to the Basel Convention).[62] In general, most shipments of waste for disposal are prohibited. The rules applicable to shipments of waste for recovery depend on the classification of the waste concerned and its destination. Waste from agro-food industries is generally found on the 'green list' subjected to the conditions that it is not infectious.[63] Examples include wine lees, dried and sterilised vegetable waste, residues and by-products and cocoa shells, husks, skins and other cocoa waste. In broad terms, only certain specified non-hazardous wastes can be exported to non-OECD countries under 'green list' controls. For example, whilst 'green list' controls would apply to the export of vegetable waste to Ireland, they would not apply if the country of export was Romania (and full prior notification procedures need to be followed).

**3.4.2 End-of-waste and chemicals regulation.** A potential policy and regulatory disincentive to the reprocessing of food wastes into chemical substances is the dovetailing of end-of-waste status and chemical substances legislation, most notably through Regulation (EC) no. 2006/1907 on the Registration Evaluation Authorisation and Restriction of Chemicals (REACH).[64] This requires all those who manufacture in the EU in quantities of one tonne or more per annum per manufacturer (or who meet the threshold criteria in an importer capacity) to obtain a registration for the chemical concerned, without which the substance cannot be placed on the market within the EU. Despite provisions that enable producers/importers to share the cost of obtaining all the necessary hazard and risk data required to register the same substance, the testing and administrative costs of achieving a registration are nonetheless considerable. Small(er) scale producers in the EU, particularly of any novel substances/mixtures resulting from food waste reprocessing, may ultimately find the compliance costs of REACH legislation a major barrier to the commercial viability of the process. With other major economies outside the EU also showing interest in adopting similar legislation to REACH (including the US and China),[65] even manufacturing and distribution outside of the EU may at some point become unfeasible.

The situation in the EU with regard to FW/Biowaste/FSCW exemplifies the potential impact that research in the area may have into the development of future policies in directions that favour a move away from current practices (AD, composting, animal feed and energy recovery) towards the valorisation of FSCW. There would though be many challenges to overcome in order to favour such a change in policy, in view of, for example, "grey areas" such as the distinction between waste and by-products, strong political drives for the diversion of FW into AD and the disincentive of REACH legislation to the application of the waste hierarchy and the full recovery of waste.

## 4 Classification of food waste and roadmap for valorisation

A multidisciplinary classification that takes into consideration the limitations and opportunities for FW valorisation at various supply chain levels, based on various pieces of legislation, waste properties and scientific literature, is proposed for FW, FSCW and domestic waste[12,14,28,50,51,66–69] (Fig. 8). This classification establishes an increasing potential to utilise different FW feedstocks, deeply rooted in the Landfill Directive Hierarchy (see Section 3.2) giving some guidelines for responsible and sustainable practice, primarily for FSCW. The understanding of this rWFD hierarchy and of the proposed classifications are key aspects in order to set up roadmaps for food waste minimisation and valorisation, in the EU and worldwide.

Co-products with a high potential for valorisation are vegetable-derived waste, due to regulatory and technical reasons (consistency, traceability, health and safety issues).[16,20a,b] Valorisation routes include extraction of valuable components for nutraceutical applications or conversion to co-products into chemicals, materials or biofuels.[16] Catering waste and animal by-products are highly regulated in the EU[50] with justified

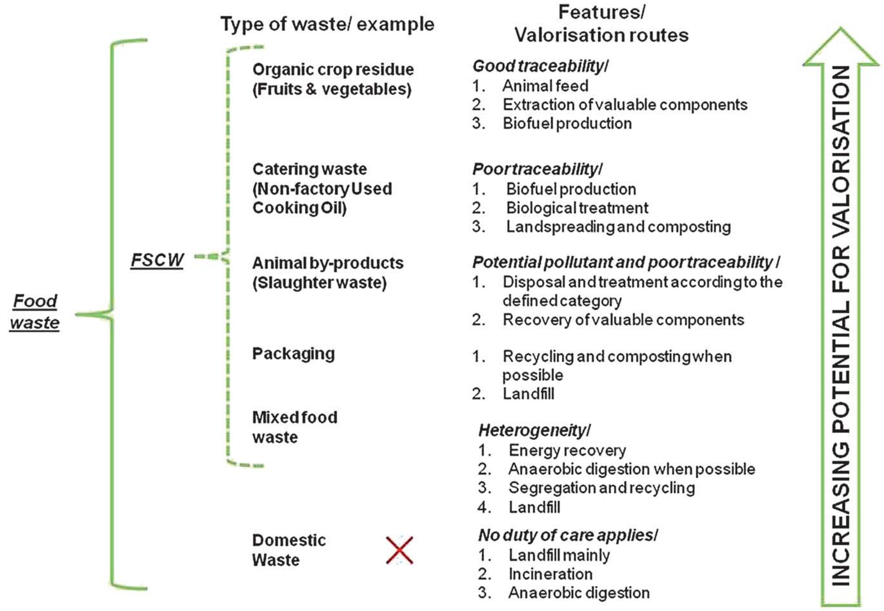


**Fig. 8** Classification of FW types.

concerns, limiting their valorisation potential to non-feed/non-pharma applications. The focus for packaging and household waste valorisation should be recycling, volume reduction, composting or conversion into biogas *via* AD.

From the proposed classification, a series of FW streams and general valorisation strategies have been identified, which will be described in subsequent sections.

### 4.1 Organic crop residues

Organic crop residues include grain, fruit and vegetable harvested feedstocks and processing by-products such as husks, straw, stover, peels, pomace, stones, factory vegetable oil and oleochemical residues. Off-spec production, packaging, canning, freezing, frying and drying operations are mostly responsible for the production of those residues.[10] These fractions comprise important sources of sugars, lipids, carbohydrates, mineral acids, inorganic compounds (*i.e.* silica), dietary fibres or phytochemicals including phenolics, carotenoids and tocopherols. Phytochemicals represent a particularly promising opportunity as highly demanded compounds for the food, pharmaceutical and cosmetic sectors.[70]

The beverage industry, for example, generates large quantities of fruit pomace (5 to 9 million and 3 to 4.2 million tonnes per year from grapes and apples, respectively) on the basis of percentage of by-product generated upon crop processing.[70] As these types of waste are prone to microbial spoilage, drying operations are required prior to the implementation of further valorisation strategies. Alternatively, the residues can be immediately valorised after waste generation using clean technologies compatible to high moisture content. Organic crop residues are often used as animal feed[14] as transport and refining costs render any other alternative use economically ineffective.

Attempts to valorise organic crop residues for the production of chemical compounds have also been reported. The two examples below describe the development of an integrated wheat straw biorefinery, with the aim of maximising the valorisation of side-streams.

The slag and fly ash originating from the combustion of wheat straw have been extracted to yield solubilised $K_2O$ and $SiO_2$ (up to 24%). The latter can be used in formulations for bio-derived adhesives utilised in bio-boards, offering an alternative to formaldehyde-based adhesives, and meeting at the same time all the specifications in terms of fire and moisture resistance for that application.[71] Wheat straw surface waxes can also be extracted using supercritical $CO_2$ (1 wt% yield). The process can be followed by char production (29 wt%, $CV = 27.2$ kJ $g^{-1}$) by low temperature microwave pyrolysis, also yielding a bio-oil (21 wt%) and a gaseous fraction (14 wt%) composed of CO and $CH_4$.[72]

Bio-derived surfactants from sugars, peptides, amino acids, fatty acids, hydroxy acids and lipids can all be derived from FSCW including agricultural residues and food processing waste. Some commercialised surfactants (*e.g.* pentose sugars combined with fatty alcohols) are already derived from agricultural residues such as wheat bran and straw.[73] Amino acids are also used for the synthesis of agrochemicals as well as for the production of bio-compatible and biodegradable surfactants.[74] The combination of amino acids with hydrocarbon chains found in fatty acids, alcohols or amines has been proposed as an alternative to common sodium lauryl sulphate (SLS) fossil oil-derived surfactants used in home and personal care products. Lysine derived surfactants ($N^{\alpha}$,$N^{\varepsilon}$-dioctanoyl lysine) show no phytotoxicity and less cytotoxicity than that of SLS, so that these can offer an excellent alternative in specialty applications where toxicity is regulated (*e.g.* pharmaceuticals). Ethyl lauroyl arginate (ethyl-*N*-lauroyl-L-arginate HCl or LAE) is another bio-derived surfactant from arginine. This cationic surfactant has antimicrobial properties against Gram positive and negative bacteria, yeasts and moulds[75] and has been commercially employed in the cosmetics and pharmaceutical industries as a replacement to antimicrobials such as cetyl trimethyl ammonium bromide (CTAB) and preservatives including sulphites, benzoates and sorbates.[76]

Sugar-based surfactants (*e.g.* alkyl polyglucosides, APGs) are another family of renewable surfactants with good detergent properties and low toxicity as compared to traditional fossil oil-derived surfactants.[77] Starch and vegetable oils are among the main feedstocks from which these can be derived. APGs have been extensively utilised for many years but their stability in acidic environments as well as the expensive nature of their synthetic pathways still need to be addressed.

## 4.2 Catering waste and derivatives

Catering waste comprises residues generated in restaurants, pubs, coffee shops and certain food production facilities, no longer intended for human consumption.[78] 90% of catering waste produced in these facilities is potentially recyclable.[79] Nonetheless, due to various reasons including logistics, operations within business, and health and safety issues, they may be regarded as poorly traceable and quantifiable. Catering waste (Fig. 9) is broadly composed of:

- used cooking oil (UCO),
- mixed waste from food preparation, packaging and servicing and
- separated waste, organic, glass, cardboard and plastic.

The valorisation of catering waste focuses on three key areas, namely the utilisation of used cooking oil in non-feed/technical applications (conversion into biofuels and other products), treatment of organic waste and animal by-products (generally by microbiological means for composting and/or AD) as well as recycling of clean packaging waste.[78,80]

**4.2.1 Used cooking oil (UCO).** The worldwide production of virgin oils and fats has a total market volume of *ca.* 160 million tonnes per year (Fig. 10, breakdown of oil types).[81]

Fats and oils are mainly dedicated for human food consumption (80% of the total).[82] The remaining 20% is essentially devoted for animal feed (5–6%), production of oleochemicals (surfactants, coatings and lubricants)[83] and biodiesel[84] (16.2 million metric tonnes per year produced worldwide). These figures illustrate the quantities of waste oils that may be potentially generated from food processing facilities in processes including frying or fat rendering. Estimations on the amounts of annually generated UCO worldwide have proven to be difficult but previous reports indicate 0.7–1 million tonnes per year generated at the EU,[85] with 75–150 000 tonnes per year coming from the UK.[86] According to the University of Minnesota, the US alone roughly produces 1.5 million tonnes per year (including yellow and brown grease)[87] and reports estimate a 2–3 million tonnes per year UCO generated in China.[88] These figures would account for a total UCO generation worldwide of *ca.* 5 million tonnes per year.

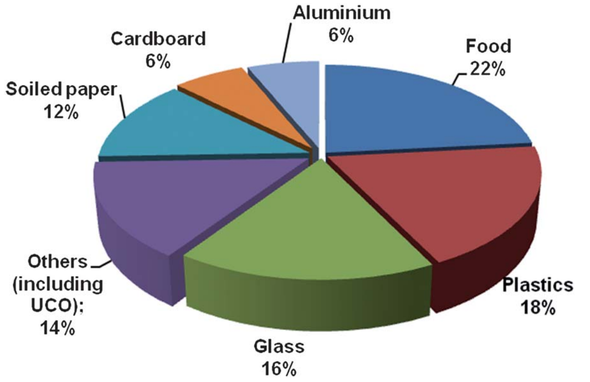


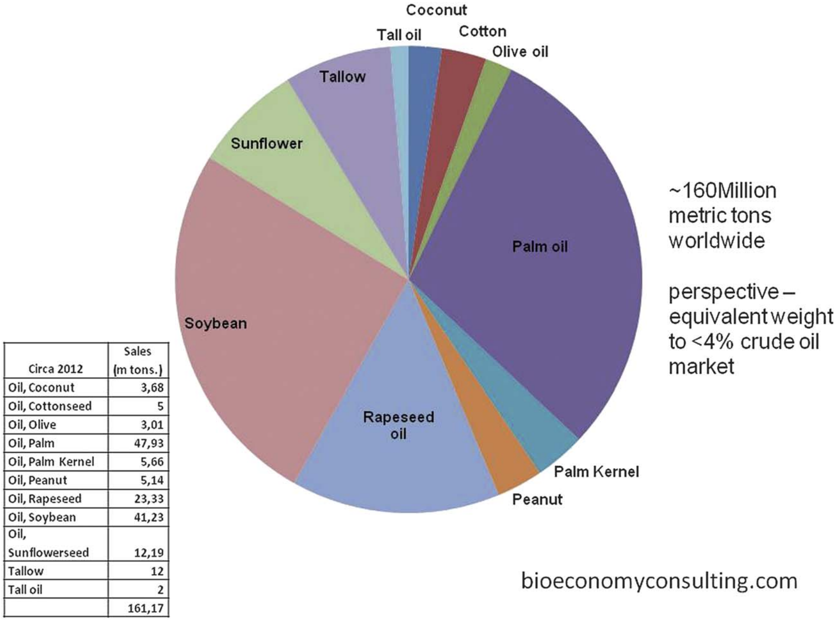
**Fig. 9** Breakdown of the type of waste generated in catering facilities.

Frying used cooking oil has been traditionally valorised into animal feed products. This is still the case only in fully traceable types of oils such as those which have not been in contact with meat products (generally known as factory vegetable oil (FVO) in contrast to catering oils which also generally designed as UCO). This differentiation is a consequence of animal by-product regulations which led to radical changes in legislation for the reutilisation of catering UCO.[50,89] Consequently, UCO have to be valorised to non-feed applications different from the human food supply chain. Current and potential applications of this promising FW feedstock include its utilisation in fuel boilers, lubricants/surfactant precursors and biodiesel production.[90] UCO conversion to biodiesel is the most economical from the feedstock viewpoint; it can be sold at £550–750 per tonne to large biofuel producers, as compared to the product (biodiesel) which can be marketed at £1000 per tonne.[91]

**4.2.2 Used cooking oil: transformation into fatty acid methyl esters and valorisation of glycerine.** The use of virgin oils for biofuel production has generated in past years a significant controversy known as "food *versus* fuel issue".[3] In this regard, recovered oils and fats as feedstock for biodiesel can offer an interesting alternative to achieve a more sustainable biodiesel production worldwide,[92] avoiding the use of food virgin crops in fuel applications. However, the potential for biodiesel production from UCO is still limited, as UCO valorisation can meet less than 30% of the world's biodiesel demand, with the remaining amounts having to be sourced from other feedstocks.

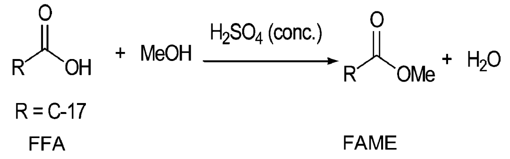
UCO mainly comprise triglycerides, monoglycerides, diglycerides and variable quantities of free fatty acids (5–20% w/w) generated during the frying process.[93] Waste oils can be effectively converted, *via* transesterification with methanol or ethanol, into fatty acid methyl esters (FAME; biodiesel) (Schemes 1 and 2) using a range of catalysts including solid acids and bases. UCO has a much larger free fatty acids (FFAs) and water content than those of virgin oils, both of which are detrimental in FAME production.[94] The most widely extended biodiesel production process from UCO is the homogeneous based catalysed transesterification of glycerides, which requires a pre-treatment of the FFA with $MeOH/H_2SO_4$ (Fig. 11).

There are also literature reports on the use of heterogeneous catalysts which can efficiently catalyse the simultaneous esterification of the FFA as well as the transesterification of the triglycerides present in the waste oils.[95,96] Heterogeneous catalysts such as alkaline oxides,[97] supported enzymes and

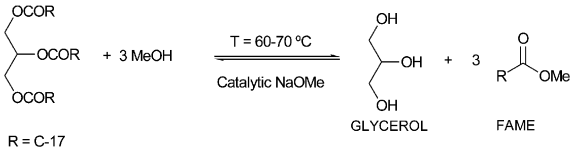


| Circa 2012 | Sales (m tons.) |
|---|---|
| Oil, Coconut | 3,68 |
| Oil, Cottonseed | 5 |
| Oil, Olive | 3,01 |
| Oil, Palm | 47,93 |
| Oil, Palm Kernel | 5,66 |
| Oil, Peanut | 5,14 |
| Oil, Rapeseed | 23,33 |
| Oil, Soybean | 41,23 |
| Oil, Sunflowerseed | 12,19 |
| Tallow | 12 |
| Tall oil | 2 |
|  | 161,17 |

**Fig. 10** World market of oils and fats.



**Scheme 1** Esterification reaction for acid pretreatment.



**Scheme 2** Transesterification reaction of triglycerides.

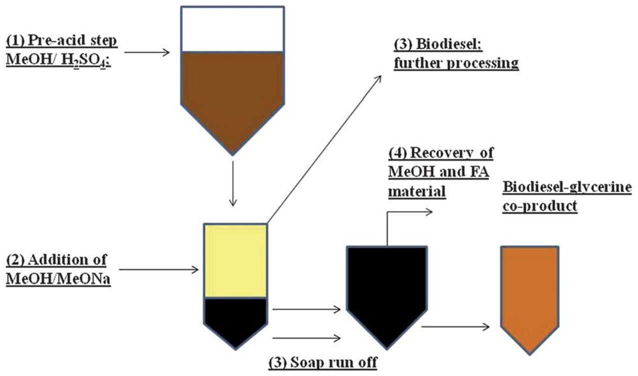


**Fig. 11** Biodiesel production from UCO.

carbonaceous materials have also received increasing attention in recent times due to the more environmentally sound credentials than their homogenous equivalent.[98] The major issues with the utilisation of heterogenous catalysts for biodiesel production from UCO are linked to lower conversion, deactivation of active sites due to the presence of FFA and moisture and reusasility issues, which is one of the major drawbacks of the most widely utilised heterogeneous catalyst for biodiesel production (CaO).

An interesting example reported in the literature obtained CaO from FW (*e.g.* eggshell and mollusc shells by calcination) which could catalyse the production of FAME from pre-esterified UCOs into biodiesel.[99] The use of an inexpensive source for the production of an active catalyst can improve the cost-competitiveness of the process. Enzymatic conversion has also been successfully evaluated showing a great potential for the development of commercially available lipase-based processing for the conversion into biodiesel of high FFA content UCOs.[100]

Employed feedstocks include waste frying, olive, rapeseed or sunflower oil, rendered animal fats as well as others sourced from food industries,[101] restaurants and catering facilities which are largely exposed to air, high temperatures and moisture,[102] all parameters which increase FFA content in oil.[103]

In summary, UCO is currently one of the most attractive feedstocks for the production of biodiesel. Lower market value in comparison with virgin oils and recovered factory oil, favourable government incentives[104] plus the possibility to recycle waste from the catering sectors make UCO derived FAME a commercially and environmentally acceptable feedstock for biofuel production.[105]

**4.2.3 Biodiesel glycerine.** Glycerol generated as a by-product in conventional biodiesel production emulsifies with soaps, methanol, esterifiable fatty material (FA material) and

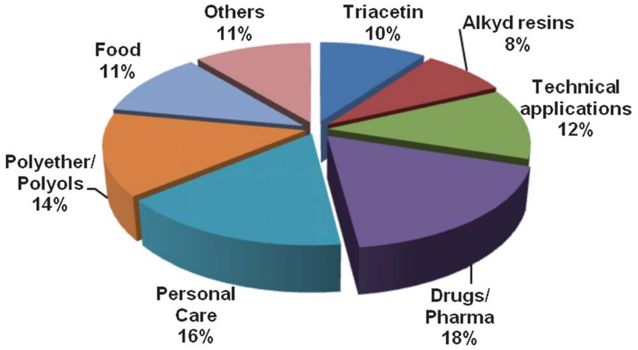


**Fig. 12** Different uses of glycerol by market volumes.

water to form a denser phase known as biodiesel soapstock.[106] FA material and methanol might be recovered from soapstock for reprocessing.[94,107] The remaining mixture is generally known as glycerine, effectively another food co-product. The quality of glycerine will largely depend on the feedstock and the type of biodiesel processing employed.[108] UCO-derived biodiesel glycerine can be refined into commercial grades (above 60 wt% of glycerol content) to be primarily employed in non-food, non-pharma applications, due to regulatory provisions in the EU/UK. This valorisation route is favoured because of its availability from biodiesel producers and the low cost of the raw material (about £100 per tonne). By contrast, other highly refined grades of glycerine (derived from soap/FFA production, synthetic glycerol) are employed in a broader range of applications (Fig. 12).[109]

**4.2.4 Glycerine applications.** Glycerine, as a catering oil by-product, has found treatment routes as a land spread agent. Although environmentally acceptable, this is a costly activity. In the UK, the type of glycerine most suitable for this purpose should contain less than 3% methanol (above this threshold, methanol glycerine will be considered as toxic and flammable)[110] and contains potassium phosphates as the major inorganic component, derived from the use of KOH as a homogeneous catalyst in the transesterification reaction and phosphoric acid in the purification of biodiesel.[111] Despite these limitations, there are a number of possibilities for glycerine which have been increasingly attractive in recent years including its use as a co-substrate for AD, combustion in combined heat and power (CHP) engines, a cement additive or as a co-substrate for fermentation bioreactions.

### 4.3 Animal by-products

The meat, poultry and fish industries produce the largest quantities of waste within the food industry.[80] Waste from these industries varies in type and composition but in general it is highly polluting (*e.g.* blood, fats, residues from intestines, partially digested grass or manure). In addition, industrial processing water is discharged as a liquid effluent which may have high nitrogen content or high levels of BOD/COD (Biological and Chemical Oxygen Demands, respectively). Various treatments for pathogens and pollutant removal are required for these streams, with common processes including thermal, biological or chemical treatments.[112] For some animal by-products, it may be challenging to develop routes toward recycling or reutilisation due to health and environmental concerns. The regulation on the use of animal derived by-products is very strict in the EU, establishing three different categories which define the fate of most of these co-products (Table 3).[50]

### 4.4 Mixed domestic waste and waste packaging

Organic waste and packaging from catering and domestic waste have been subjected to biological treatment, composting or eventually ended up in landfill sites. However, there is an increasing trend to their reutilisation either by the extraction of valuable components, packaging recycling or production of biogas for AD in the case of organic waste.[42,116] Food and packaging waste constitute respectively 73% and 71% of household waste (as compared with the total of food and packaging wastes generated).[36] The variable proportion packaging waste (*i.e.* plastics and cardboard) and FW in municipal solid waste hinders the use of this particular waste stream compared to concentrated pre-consumer waste streams issued from the food processing sector. At the retail and distribution stage, packaged surplus production that cannot be sold elsewhere contributes to a significant proportion of FW; however, the food and drinks sector efficiently manages to reuse a large proportion of FW generated.[25]

## 5 Overview of current uses of food supply chain waste in different areas around the globe

The following case-studies are snapshots of the situation in different countries around the globe and recent developments

**Table 3** Description of animal by-products

| Category/risk | Definition/type of waste | Prescribed treatment |
|---|---|---|
| Category 1 (very high risk) | Animal parts or animal types unsuitable for human consumption (carcasses and BSE/other disease-infected materials) | Destruction by incineration, recovery of valuable components for fuel applications, (rendered fat)[113] |
| Category 2 (high risk) | Dead animals, manure and digestive material, other materials different to categories 1 and 3 | Biological treatment, Anaerobic digestion,[114] recovery of valuable inorganic and organic components[115] |
| Category 3 (low risk) | Suitable for human consumption but discarded for commercial reasons (packaging, wrong transport, expire date, *etc.*) | Recovery of valuable components for a range of applications: pet food, biofuel production and cosmetics |

in the area of FSCW valorisation. Some examples of accumulative types of waste, common to several regions around the globe and related to current or planned valorisation strategies, are discussed.

### 5.1 Citrus peel residues

Citrus fruits are considered as commodity products similar to coffee and tea in terms of international trade. Citrus fruits mainly include oranges, lemons, limes, grapefruits and tangerines. Major citrus producing countries include the US, Brazil, China, India, Japan, Spain, Italy, Egypt, South Africa, Turkey and Morocco, with Brazil being the world leader in citrus production. These countries account for over 70% of the world's supply of citrus fruits. Processing operations are important for citrus fruits, with residual peels accounting for 50 wt% of the fruit.[117,118] With high volumes of citrus production (over 94.8 million tonnes globally[118]), it is estimated that 31.2 million metric tonnes of citrus fruits are processed every year in the world, yielding 15.6 million metric tonnes of waste annually (50 wt%, wet basis of waste).[84]

Major components of wet waste orange peels are water (80 wt%), soluble sugars, cellulose and hemicellulose, pectin and D-limonene, highlighting an interesting market for future development around waste valorisation practices, especially targeting 2nd generation FSCW valorisation strategies.[119] Several attempts have been made to fully valorise citrus peels, especially concerning orange peels. The major environmental problem associated with citrus peel is its highly fermentable carbohydrate content,[120] which accelerates its degradation when not carefully managed.[121] Citrus peel residues can be employed as cattle feed, upon drying, but with a protein content of only 6 wt%, this not a high protein source feedstock.[122] Additionally, decreasing its moisture content from 80 to 10 wt% is highly energy-intensive and costly, rendering feed applications for waste citrus peels only marginally profitable.[122,123]

Several valorisation strategies have been reported for citrus peel waste. Existing valorisation strategies include:

- Pectin extraction by acid hydrolysis and production of activated carbon,[124]
- Pectic enzyme production[117]
- Dietary fibre extraction[123]
- Methane (biogas) production[125]
- Fermentation substrate for single-cell protein production[126]
- Bio-ethanol production by a variety of microorganisms and including simultaneous saccharification and fermentation[117,119,127] and
- Succinic acid production.[128]

D-Limonene (3.8 wt% of dry weight, \$1–2 kg$^{-1}$)[123] can be used as a building block to generate compounds with similar structures (*i.e.* carveol, carvone, α-terpineol, perrillyl alcohol and perillic acid). D-Limonene is also a valuable renewable bio-solvent that can be used as an alternative environmentally unacceptable halocarbon solvent.[129] D-Limonene is mainly used as a flavour and fragrance compound for the production of adhesive terpene resins *via* polymerisation.[130] This compound can be distilled off from the essential oil found in the peel which is currently performed on-site in large scale citrus juicing operations in Brazil or Florida.[131] Extraction of D-limonene by steam distillation (90% of D-limonene extracted)[128] or microwave assisted steam diffusion[132] has also been reported. Pectin (\$10–12 kg$^{-1}$), one of the most important food additives, is a complex structural heteropolysaccharide found in non-woody plant tissues. It is used as a gelling agent and a thickener. Citrus fruits contain roughly 20–30% extractable pectin (10–15% for dry apple).[133] Pectin is traditionally extracted by acidic hydrolysis using nitric, sulphuric or hydrochloric acid, between 50 and 100 °C and at pH 2–3 for several hours, with a final precipitation step using isopropanol, generally yielding 3% pectin in relation to the peel weight.

Two unique examples of an integrated approach to the valorisation of citrus peel have been recently reported.[134,135] Pourbafrani *et al.* demonstrated that bio-ethanol, methane and D-limonene could be produced upon sulphuric acid treatment of orange peels at 150 °C, using a cost-effective biorefinery process.[134] Balu *et al.* have also recently developed a microwave-assisted approach to valorise orange peel residues into a range of valuable products ranging from chemicals (D-limonene and α-terpineol) and polysaccharides (pectin) to a novel and most unique form of mesoporous cellulose.[135] The advantage and superiority of the microwave protocol compared to other techniques lies in the ability to simultaneously produce several valuable products coupled with a unique *in situ* flexibility. Other valorisation strategies have always focused on the production of one single component from orange peel, while these two examples are the only cases of an integrated biorefinery using citrus peels (Fig. 13). These examples highlight the need for a sustainable and integrated process for the combined extraction of citrus peel components using clean, green and transportable technology, such as microwaves.

Transformation of citrus peel residues into higher value products would allow companies to increase competitiveness by generating additional profits and reducing disposal costs together with improving the resource efficiency of the citrus supply chain. Novel processes could further benefit the valorisation, especially a fast and one-step process that allows for *in situ* transformation of limonene to higher value products (*i.e.* α-terpineol). Citrus fruits are grown around the globe in the region of the equator, and even though the harvesting season is

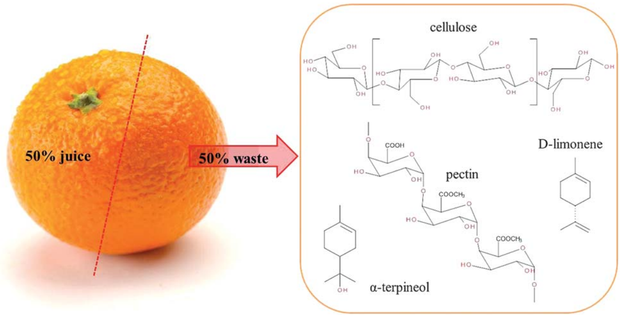


**Fig. 13** Valorisation of orange residues to valuable products.

fixed in specific locations around, they spread around the globe throughout the year, ensuring a constant supply of citrus and citrus waste for valorisation purposes.[136]

Citrus fruits constitute by large the principal group of fruits in Spain in terms of cultivated land (over 60% of the total fruit crops, almost 1% of the total geographic surface of Spain).[137] From these, oranges (50%) and mandarins (36%) account for the majority of the citrus fruit crops, as compared to lemon (13%). Around 6 million tonnes of citrus fruits were produced in Spain during the 2010/2011 campaign, ever increasing figures compared to the past few years, with over a 25% estimated increase for the 2015/2016 campaign.[137] 40% of the aforementioned citrus fruits production goes to the food industry, mostly for the production of juice.[137] However, less than half of the raw material is utilised in the juice industry, leaving largely underutilised citrus peel, pulp and pith, which at this point become a residue and thus a problem for the food industry and society. In Spain alone, over 600 000 tonnes of citrus waste (with over 500 000 tonnes corresponding to orange residues) were generated in 2010.[137] The disposal of such residues is also highly regulated at both European and national levels.

Morocco is the third largest exporter of citrus fruits after Spain and the USA. Morocco's total citrus production for 2010/11 was estimated to be around 1.7 million million tonnes. The average citrus fruit yield is estimated at 21 million tonnes per year. Morocco's citrus production continues to be dominated by the traditional clementine, navels and specific varieties of the country. Moroccan government policy predicted a 70 percent increase over current production level by 2018. The citrus processing sector in Morocco is facing stiff competition in sourcing raw materials in the fresh citrus market. This is mainly due to the low prices offered by orange juice processors compared to prices offered in the fresh market. There are four citrus processing plants currently operating in Morocco, three of which are producers of single strength orange juice that can hardly meet demand from local market buyers. Fresh oranges delivered to juice processors are currently estimated at about 40 000 million tonnes annually.[138] Factories work at 20% of their production capacities and operators even fear for the future of the sector.

Waste valorization for this industry in Morocco focuses on two approaches: (i) the extraction of essential oils, which are utilised in the food industry or cosmetics, and (ii) animal feedstuffs (cattle or sheep). The differences in processing, source and variety of fruit as well as type of canning may produce a variation in the physical characteristics and nutritive value of citrus pulp.[136,139,140] The utilisation of agro-industrial by-products is economically worthwhile and would increase the revenue of the citrus juice industry in Morocco, especially since conventional feedstuffs are often expensive in this country.

In view of the case-studies and the potential of the feedstock, we can conclude that citrus residues are currently very promising biowaste feedstocks which can potentially have many ways to be valorised to high added value chemicals and biofuels.[141,142] Currently, most of the proposed valorisation technologies are under development but some interesting results have been already reported for each one of them. In the particular case of orange waste residues, the company Citrotecno at Comunidad Valenciana in Spain has developed a revolutionary and unique cascade-type valorisation approach aimed to convert 120–150 000 tonnes of citrus residues into cattle feed pellets (containing over 40 wt% fibre and 8 wt% proteins), essential oils (limonene from the peel, which the company plans to market as solvents, fragrances, food additives and semiochemicals), biofuels (second generation bioethanol *via* fermentation of the sugars from the pith and pulp, which could produce over 100 000 $m^3$ bioethanol per year) and purified water from the process *via* a pervaporation/condensation approach.[141]

### 5.2 Cashew, cashew nut shell oil and derivatives. The African case

Cashew (*Anacardium occidentale* L.) is indigenous to Brazil, but has spread to other parts of tropical South and Central America, Mexico and the West Indies[143] and currently widely cultivated in the coastal regions of South Africa, Madagascar, Mozambique, the Ivory Coast, Nigeria, Guinea Bissau, Tanzania as well as in South Asia (from Sri Lanka to the Philippines) and India. Currently, the four main cashew producing regions are India, Brazil, Nigeria and Tanzania with India accounting for about 40 percent of the International market in cashew production. About ten years ago, the world production of cashew nuts was close to 2 million tonnes of nuts-in-shell with an estimated value in excess of $2 billion US dollars. India and Brazil are the major cashew exporters, with 60 percent and 31 percent respectively of world market share.

Cashew nut farming has always been a small holder activity in Kenya and Tanzania. Culturally, cashew nuts are intercropped with mangoes, coconuts, or food crops such as millets and maize. During the 1970s, Kenya produced over 22 000 tonnes of cashews, but unlike its neighbours, which has never recovered production since the decline in the 1980s. The implementation of the Cashew Productivity Enhancement Program in Kenya led to a cashew nut production reaching 14 000 tons in 2007, later declining to 8000 tons in 2010.[144] A production of 40 000 tonnes is however projected by 2015.

In Tanzania, cashew is the fourth most valuable export crop after coffee, cotton and tea, in spite of a considerable fluctuation of its production.[145] The area under production ranges from 80–90 000 hectares during the past years, accounting for a total production of raw cashew nut in Tanzania above 100 000 tonnes per annum (Fig. 14). With around 20% recovery by weight of cashew nut shell liquid (CNSL), the production potential for CNSL is estimated to be about 20 000 tonnes per year. Interestingly, the past two years seem to have marked a substantial upward trend.

High cashew prices are one of the reasons for increased production of these valuable fruits, but such production would dramatically increase if additional revenues and value added products were to be obtained by processing the raw cashew. In general, there are a number of systemic constraints which prevent Tanzania from increasing its cashew production. These include complex socio-economic factors such as high levels of taxation at the farmgate and on processed cashews, low farmer profitability leading to a lack of investment in the crop, limited

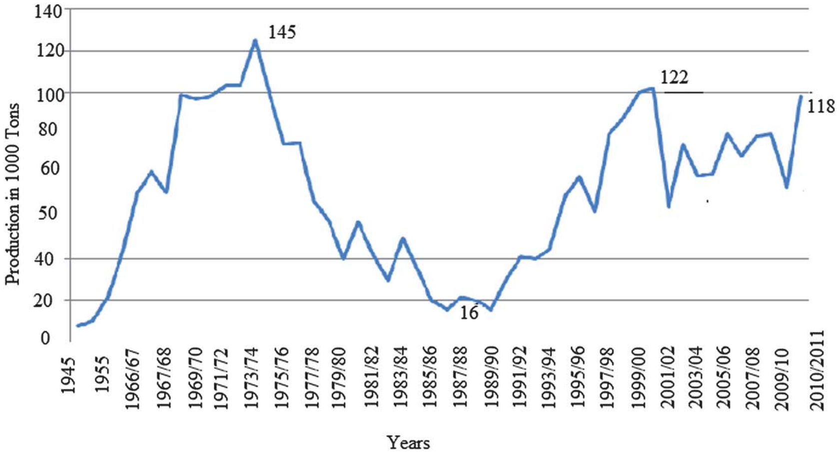


**Fig. 14** Production of raw cashew nuts in Tanzania (1961–2010). Source: Cashew nut Board of Tanzania (CBT).

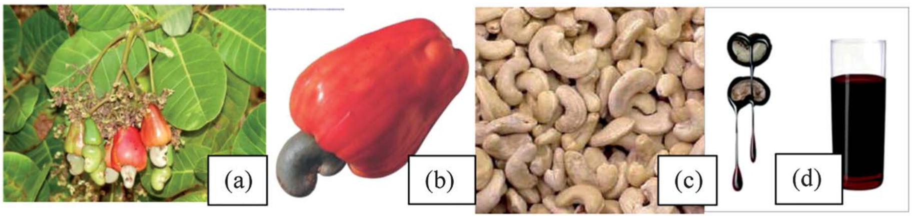


**Fig. 15** Cashew (a), cashew apple (b), cashew nut (c) and cashew nut shell liquid (d) obtained from cashew nut shells.

processing experience and a lack of an established international reputation for Tanzanian processed kernels.[145] Moreover, a lack of financing for raw material purchases as well as a lack of kernel buyers are some additional problems the industry is currently facing.

Four main products (Fig. 15) can be obtained from cashew, namely raw nuts, cashew kernels, cashew apple (apple shaped swollen peduncle) and cashew nut shell liquid (CNSL).

Harvesting of cashew nuts in Tanzania is generally done manually on a daily basis over a period of 60 days. The tree also produces an edible false fruit, the cashew apple to which the nut is attached (Fig. 15b). The apple ferments within 24 hours of harvesting and leads to the production of local brews by cashew growers. Five tonnes of cashew apple are roughly harvested for every tonne of cashew nut obtained. Based on this estimate, Tanzania produces about 500 000 tonnes of cashew apples per annum. Despite the large amounts produced, most of this product is wasted, although the fruits can be made suitable for consumption by removing the undesirable tannins to produce juice, syrup, squish, pickles, jam, chutneys, candy and canned fruit jelly. The waste derived from such rich nutritious cashew apples is a significant economic loss. The production of ethanol from cashew apples appears to be an attractive strategy to valorise this important FW in Tanzania.

**5.2.1 Cashew nut shell liquid (CNSL).** In the search for cost effective modern materials from renewable resources, CNSL and derived products may have a significant role to play. CNSL is a versatile renewable material and offers interesting opportunities for the production of speciality chemicals, high value products and polymers. Recent research and findings have shown that the constituents of CNSL possess special structural features to be transformed into speciality chemicals including keiromone and high value polymers.[146–149] The world availability of CNSL is about 50 000 tonnes per year with India being the main producer.[150]

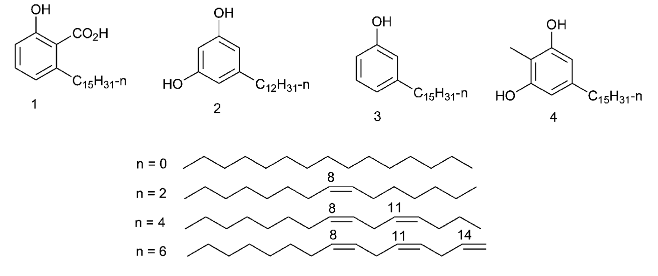
CNSL is a dark reddish brown viscous liquid (pericap fluid) found in the soft honeycomb structure of the cashew nut. It is a by-product of the cashew industry, often considered as an optimum and cheaper natural source of unsaturated phenols (*ca.* 30–35 wt%). CNSL has multiple applications in polymer based industries including friction linings, clutch disks, paints and varnishes, laminating resins, rubber compounding resins, cashew cements, polyurethane based polymers, surfactants, epoxy resins, foundry chemicals and intermediates for the chemical industry.[151–153] In tropical medicine, CNSL has traditionally been used in treating leprosy, elephantiasis, psoriasis, ringworm, warts and corns.

On the basis of the mode of extraction from cashew nut shell, CNSL can be classified into two types, solvent-extracted CNSL and technical CNSL (Table 4 and Scheme 3).

A novel and cheaper liquid crystalline polyester has been synthesised from CNSL, to substitute polymer fibres and films in speciality applications. Generally, liquid crystalline polymers have attracted much attention in recent years because of their potential use as high performance materials and their low carbon footprint.[155]

**Table 4** Description of solvent extracted and technical CNSL[154]

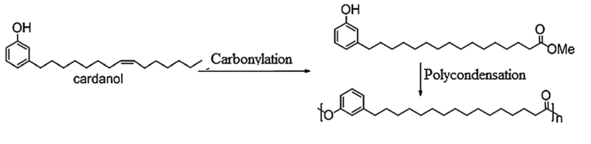
| | Solvent-extracted CNSL | Technical CNSL |
|---|---|---|
| Production method | Solvent extraction | Shell roasting |
| Anacardic acid content (%) | 60–65 | None or traces of polymeric material |
| Cardol content (%) | 15–20 | 15–20 |
| Cardanol content (%) | 10 | 60–65 |
| Methylcardol (%) | Traces | Traces |



**Scheme 3** Major components of CNSL.

CNSL has also been tested as a structure directing agent to develop silica-based supports for invertase and trypsin enzymes as well as for novel heterogeneous copper(II) Schiff base catalysts. Catalysts prepared using CNSL templates were more efficient than those prepared using the commercially available templates.[156] In addition, Spherical Polymeric Particles (SPP) have been prepared from Tanzanian CNSL by means of a suspension-polymerization technique involving either step-growth or chain growth polymerization mechanisms. 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 $m^2 g^{-1}$. Particles were found to exhibit Langmuir-type adsorption isotherms with a saturation capacity of about 9.0 and 44.2 mg $g^{-1}$ for $Na^+$ and $Ca^{2+}$, respectively.[157]

Cardanol has also been polymerized using an Fe–salt complex as the catalyst to give a soluble polyphenol containing the unsaturated alkyl group in the side chain. The polymer was subjected to hardening by a cobalt naphthenate catalyst[158] or by thermal treatment, yielding crosslinked films with a high gloss surface.[159] Similar polymers from cardanol have been recently synthesized, which are expected to be biodegradable.[160] The monomers were synthesized using an appropriate catalytic system which involved carbonylation to move the double bonds of cardanol followed by the introduction of the methoxycarbonyl group to the terminal end of a molecule. Monomers having an ester group at one end and a hydroxyl at the other end were easily polymerized (Scheme 4).



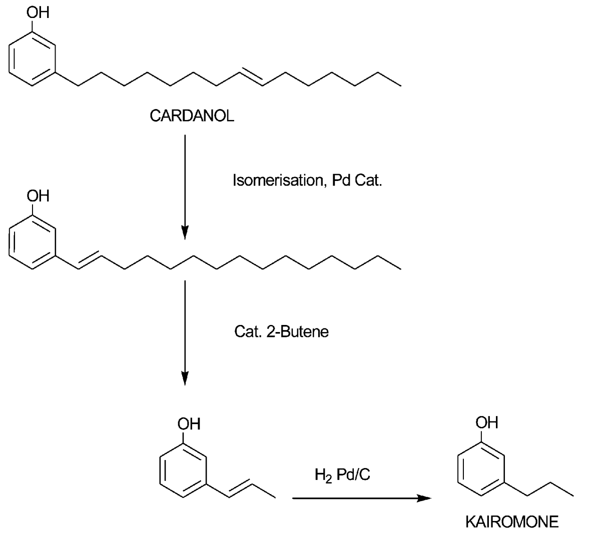
**Scheme 4** Synthesis of renewable biodegradable polymers from cardanol.

The synthesis of polyesters using cardol and a monomer, 8-(3-hydroxyphenyl) octanol (HPO) derived from cardanol, has also been recently attempted.[161] Preliminary results on these synthesized polymers indicate they may be promising candidates to substitute polymer fibres and films currently produced from non-renewable sources in speciality applications.

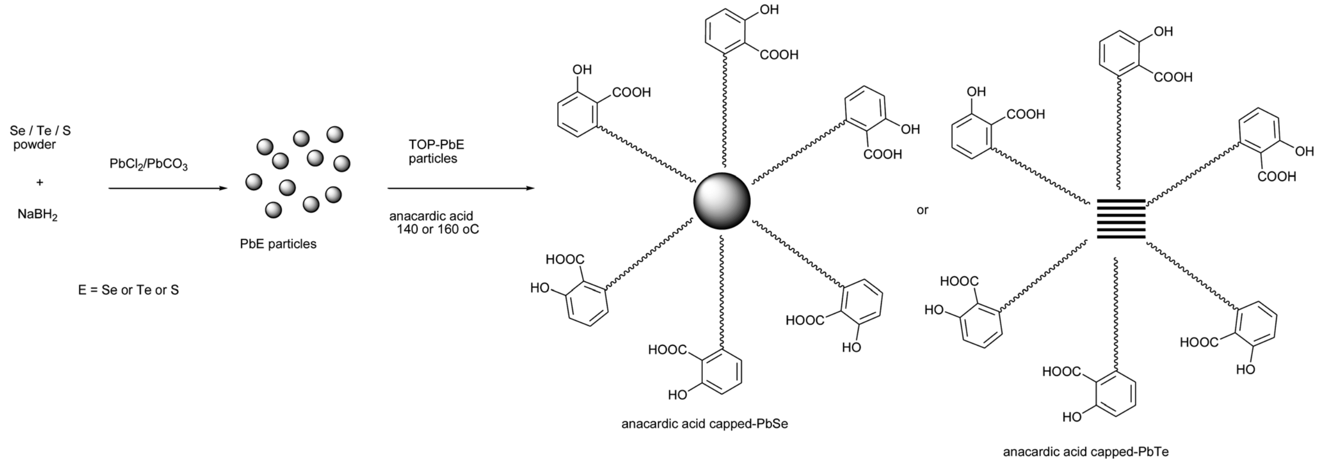
Fine chemicals have also been synthesised starting from CNSL. Sodium cardanol sulfonate as a renewable surfactant has been synthesized from cardanol contained in CNSL. The surfactant properties of cardanol sulfonate were determined and compared with dodecylbenzene sulfonate. Comparatively, the relative detergency of cardanol sulfonate was calculated to be 93.7%. Results suggested that cardanol sulfonate can be potentially utilised as an alternative anionic surfactant.[162] In another development, novel important target chemicals such as a kairomone component of the tsetse fly and a detergent precursor [3-(non-8 enyl) phenol] have been synthesized from CNSL renewable components.[163] Kairomone (3-propylphenol), a component of the natural tsetse fly attractant, was obtained *via* hydrogenation of 3-(prop-1-enyl) phenol synthesized from the metathesis of monoene cardanol (Scheme 5). These promising compounds are currently in the process of commercialisation and production at an industrial scale.

Eco-friendly wood preservatives have also been developed from CNSL formulations with sulfited wattle tannin and copper(II) chloride.[164] CNSL and Neem seed oil have also been used as wood preservatives by other researchers.[165] In this formulation, copper was incorporated into CNSL and Neem seed oil. Rubber wood samples were treated with these solutions utilising dipping and pressure techniques with different levels. Final materials were found to be effective as wood preservatives against fungi and termites. The combinations of copper/CNSL and copper/Neem in pressure treatment have resulted in interesting high protection against wood termites.

Soft nanomaterials of various shapes and forms have also been prepared from cashew nut shell liquid (CNSL) by various



**Scheme 5** A synthetic route to Kairomone (a tse-tse fly attractant) from cardanol.



**Scheme 6** A facile route for semiconductor quantum dots (QDs) synthesis using anarcadic acid as a capping agent.

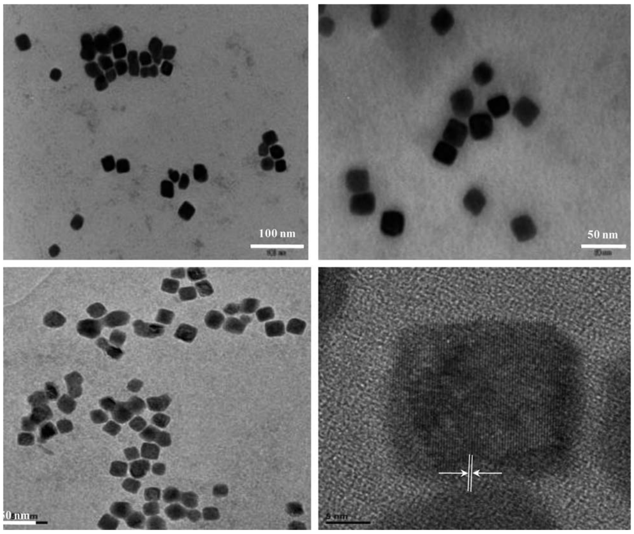


**Fig. 16** TEM and HRTEM images of anacardic acid capped PbTe nanoparticles synthesised at 160 °C when PbCl2 was used as a lead source (1 h).

researchers.[166–168] The amphiphiles produced from CNSL are soft nanoarchitectures including lipid nanotubes, twisted or helical nanofibers, low-molecular weight hydro- or organogels, and liquid crystals which are promising for their industrial use as well as a range of applications. More recently, a facile route for semiconductor quantum dots (QDs) synthesis involving the use of anacardic acid, a component of cashew nut shell liquid (CNSL) as a capping agent, has also been accomplished (Scheme 6).[169]

Anacardic acid could be employed as a capping agent to efficiently generate nanoparticles with improved properties behaving in a quantum manner, of comparable structural quality to that of pure nanocrystals (Fig. 16).

From these examples, the potential to develop novel methodologies to convert naturally occurring oils (in this case obtained from cashew nut shells) into building blocks for pharmaceuticals, agrochemicals, paints and plastics, speciality chemicals and other functional materials has been clearly highlighted to be extremely high and offers many different possibilities for a range of chemistries and products.

### 5.3 Valorization of oils and fats from food waste in the UK and Spain

**5.3.1 Food waste in Spain: focus on food UCOs and enzymatic transesterification.** Taking Spain as a case study, the different types of waste can be categorised into industrial, agricultural, sanitary and solid urban residues depending on their origin. Solid urban residues can at the same time be subdivided into glass, paper, plastics, metals, organic matter and others. Their distribution is presented in Fig. 17. Currently, around 15 million tonnes of FW residues are generated per year in Spain. This figure includes expired products, residues and FW itself but more and more frequently foodstuffs that have either been badly labelled or with similar issues completely unrelated to their quality.

Generally, the most widely exploited and extended way to deal with FW residues in Spain is the use of composters in order to minimize the amount of waste for disposal. Several composting plants can be found all over Spain but these are generally considered as first generation recycling and/or reuse of organic matter. In terms of FW feedstocks in Spain, waste oils

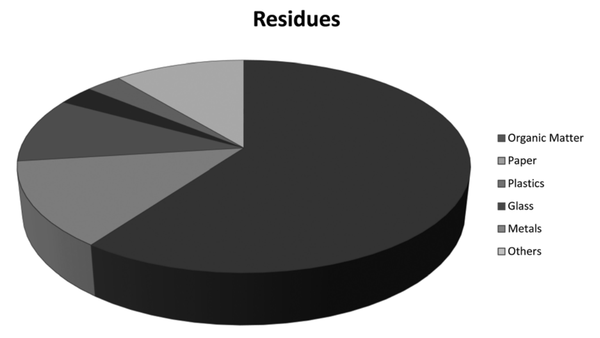


**Fig. 17** Percentage distribution of waste residues in Spain. Organic matter (60%), paper (13%), plastics (10%), glass (3%), metals (3%) and others (11%).[170]

(from both households and restaurants) can be considered as one of the main and most interesting FW residues in Spain. The country is indeed, together with Greece and Italy, a leading worldwide producer and consumer of vegetable oils (*e.g.* olive and sunflower), with its production accounting for a third (>30%) of the total olive oil production worldwide. Particularly, the south part of Spain (Andalucia) is one of the major producers and exports olive oil to many countries worldwide.[171]

Traditionally, this olive oil finds several uses in the food industry but it is also widely consumed for cooking purposes (*e.g.* frying). Upon frying, the waste oil becomes a problem in society as until very recently it was disposed as such, without finding any alternative uses for further valorisation. The inherent issues in the management of these residues have caused significant pollution in rivers and inland waters. Few initiatives have been ongoing to collect some of the waste oils from restaurants and houses but this requires an important infrastructure and logistics which in turn makes it difficult unless some sort of high added value products can be derived from the oil residues. A proof of concept of the aforementioned principle was demonstrated by SENECA Green Catalyst S.L. (Fig. 18), a spin-off company created in 2007 from Departamento de Quimica Organica at Universidad de Cordoba in Spain to valorise waste frying oils into biodiesel.[172]

**Fig. 18** Biofuel pilot plant at Seneca Green Catalyst.

The company uses a novel dual technology which can combine work under conventional homogeneous conditions (NaOH, MeOH), implementing a pre-esterification step to convert the FFA into FAME and then subsequently to carry out the transesterification process, with the use of an enzymatic methodology which allows the simultaneous esterification/transesterification of the waste oils. This novel approach facilitates the implementation of either technology depending on several factors including the quality and variability of the waste feedstocks (analysis is always carried out prior to reaction), industry and market demands, cost-competitiveness of the process, *etc.* The company is able to work on a multiton scale (3–5 tonnes biodiesel per day) and it is likely to expand in the next few years depending on market needs. Furthermore, the company has also developed an adsorbant which can be used to clean the final biodiesel to remove all impurities without the need of any washing with water, considered as precious in a dry region such as the south of Spain.

**5.3.2 Food waste in the UK: focus on recovery of fats and oils from food waste for biodiesel production.** Around 3 million tonnes per annum of rendered animal fat and grease, mainly obtained from animal by-products, are being produced in the EU.[173] Traditional uses for these tallow and lard included fuel, cosmetic precursors and components of pet food supplements. Due to changing regulations, biofuel production from rendered

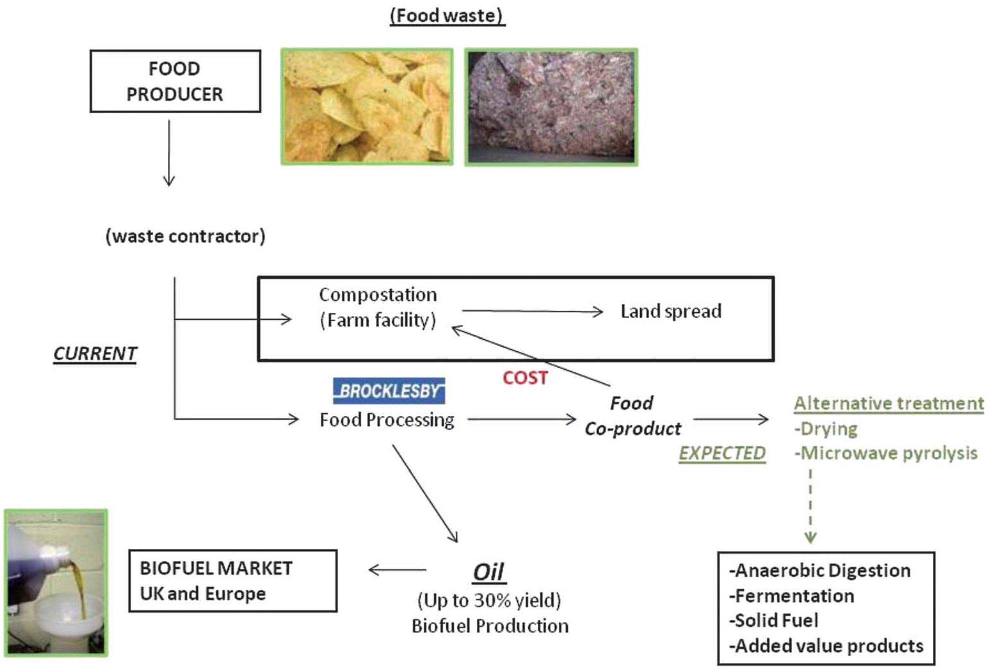


**Fig. 19** Business model scheme for food waste processing.

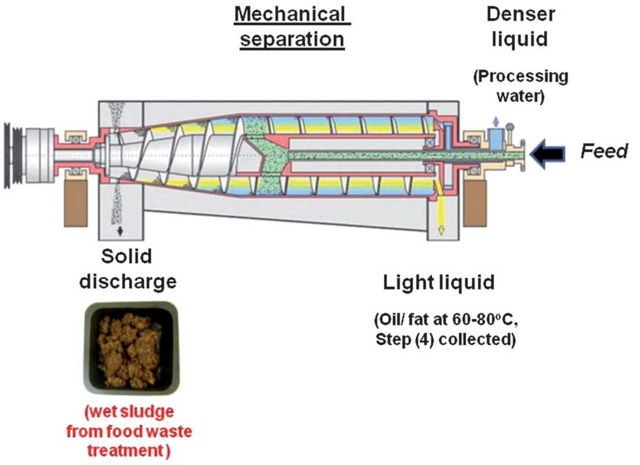


**Fig. 20** Centrifuging step for oil recovery.

fats has recently increased in importance in the EU and the UK.[174] Brocklesby Ltd is a UK company based in North Cave, East Yorkshire that has developed a process which recovers oil and fats from miscellaneous FW (Fig. 19), including animal by-products employed in biodiesel production with up to 30% triglyceride content. The process currently under operation has the potential to process 2000 metric tonnes per year of FW sources (solid waste, triglyceride rich waste, processed as Category 3 animal by-products). The recovery of triglycerides is carried out under a process largely based on wet rendering technologies,[175] with high efficiencies (up to 98% yields). The novelty of the process is the flexibility of the approach where a number of various products can be processed due to the possibility to work under wet and semisolid conditions. Despite the high process efficiency, a starchy/fibrous co-product is sent off-site for composting. The company is currently working on the reduction of the waste volumes through various alternative treatments including the use of microwave pyrolysis, with a significant potential to employ the co-products as solid fuels. The extraction process involves particle reduction in a first stage by means of mincing, followed by thermal treatment at temperatures below 100 °C, in order to break down the fibrous/lipid cells, freeing the melted oil adsorbed/present inside the cells. This is followed by a mechanical separation *via* tricanter centrifuge (Fig. 20) where the oil/fat is separated from the solids (wet sludge) and the processing water, which is recirculated in the system.

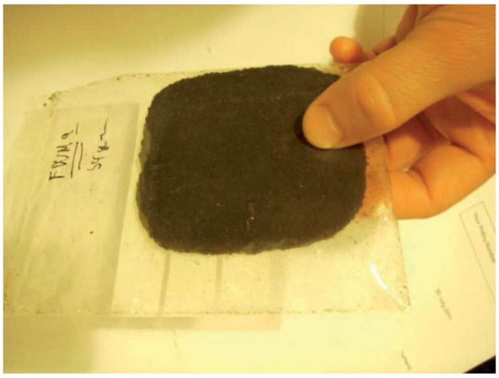


**Fig. 21** Compacted waste sludge.

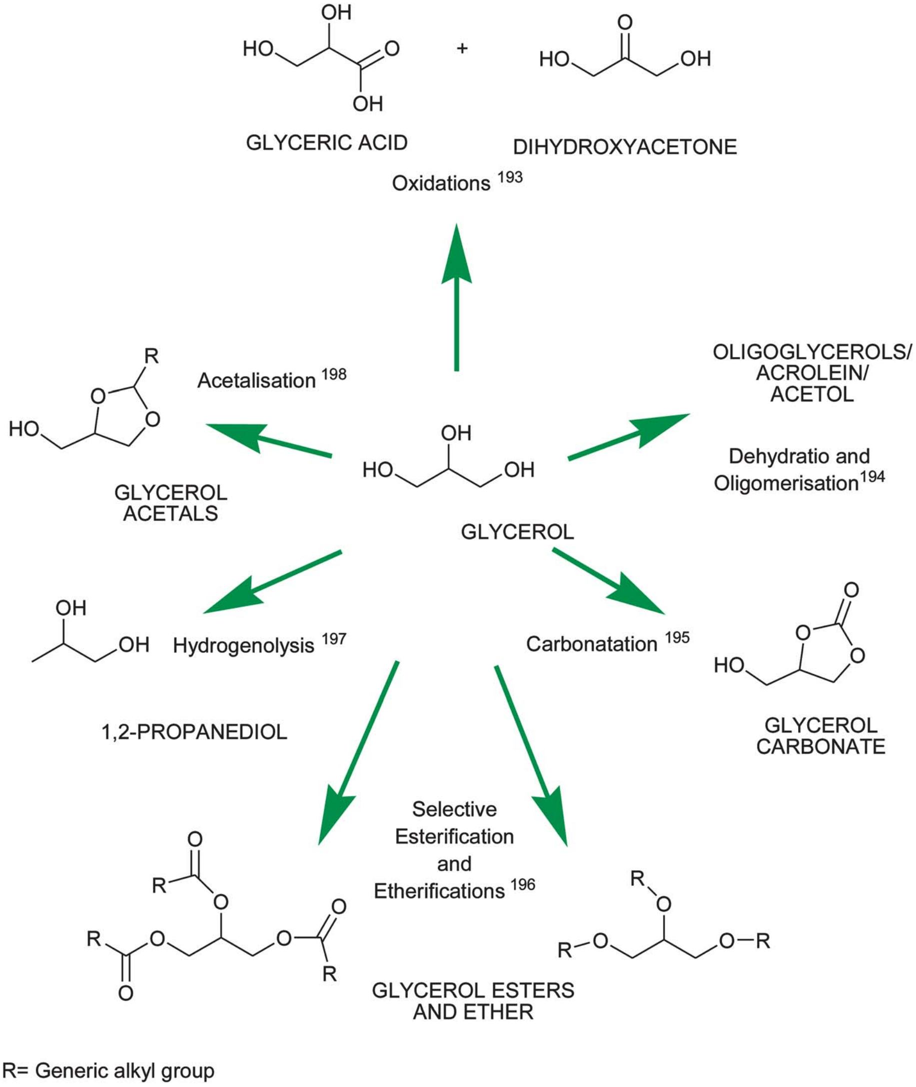
Applications for the wet residue are currently being investigated, with possible uses as substrate for fermentations and feedstocks for microwave pyrolysis. The latter have the potential to produce biofuel and chemicals.[176] Preliminary work looked into the possibility to combine an effective way of drying waste from oil extraction (Fig. 21) with a simultaneous methodology to obtain bio-oil and a high calorific value biochar. For instance, the gross calorific value found in the dried char was 27.4 kJ $g^{-1}$, 22% higher to that of the dried parent material. The main components found in the bio-oil were levoglucosan and FFAs, showing the potential of microwave pyrolysis as a suitable treatment for oil extraction, homogenisation and conversion of FW into added value chemicals.

**5.3.3 Chemical conversions of glycerine.** The mentioned applications for biodiesel glycerine allow various stakeholders (catering producers, biofuel companies and end users) to develop supply chains based on UCO. A more challenging and exciting area of research is the conversion of glycerine into high added value products as a long term objective for the biodiesel industry. In 2004, the US DOE designated glycerol as one of the top 10 platform chemicals for the production of added value chemicals, which repeated in a revisited version of the platform chemical list.[177] The structure of the compound, versatility of its chemistry and potential for bio-transformations make this molecule a versatile raw material for the chemical industry since its availability, quality and consistency are increasing.

A number of processes and transformations are described in the literature and are summarised in Scheme 7.[178–183] The most successful processes developed with UCO-derived glycerine are the Solvay process (Epicerol®) for the production of epichlorohydrin[184] based on a chlorination process using HCl and its hydrogenolysis to 1,2-PDO using Cu catalysts.[185]

In addition, biosynthesis of 1,3-propanediol, butanol and succinic acid amongst other chemicals from glycerine are generally another interesting area of research currently under development (Scheme 8)[186] to biobased commercial routes including that patented by the company Bioamber for succinic acid.[187] This process employs agricultural and FW residues as raw materials for the bioconversion of glucose into succinic acid.

**5.3.4 Alternative biofuels: hydrotreatment of UCOs.** Apart from biodiesel related research, there are some other interesting catalytic routes to biofuels from waste oils. One of them is the production of bio-hydrogenated diesel.[188–190] These routes involve the treatment of oils with hydrogen using heterogeneous catalysts (typically Ni–Mo and/or Co–Mo and related desulfurised catalysts) as well as solid acid catalysts to generate a paraffin mixture upon removal of oxygen and hydrogenation of all C=C double bonds. Preliminary reports in the field have looked into the utilisation of low quality oil feedstocks for the production of gasoline (>30%) and gas oil (>30%) using heterogeneous catalysis including zeolites (HZSM-5) and sulphated zirconias.[191–193] Optimum yields of gasoline were obtained between 400 and 430 °C, at a pressure of 10 bar of



**Scheme 7** Summary of key chemistries for glycerol.

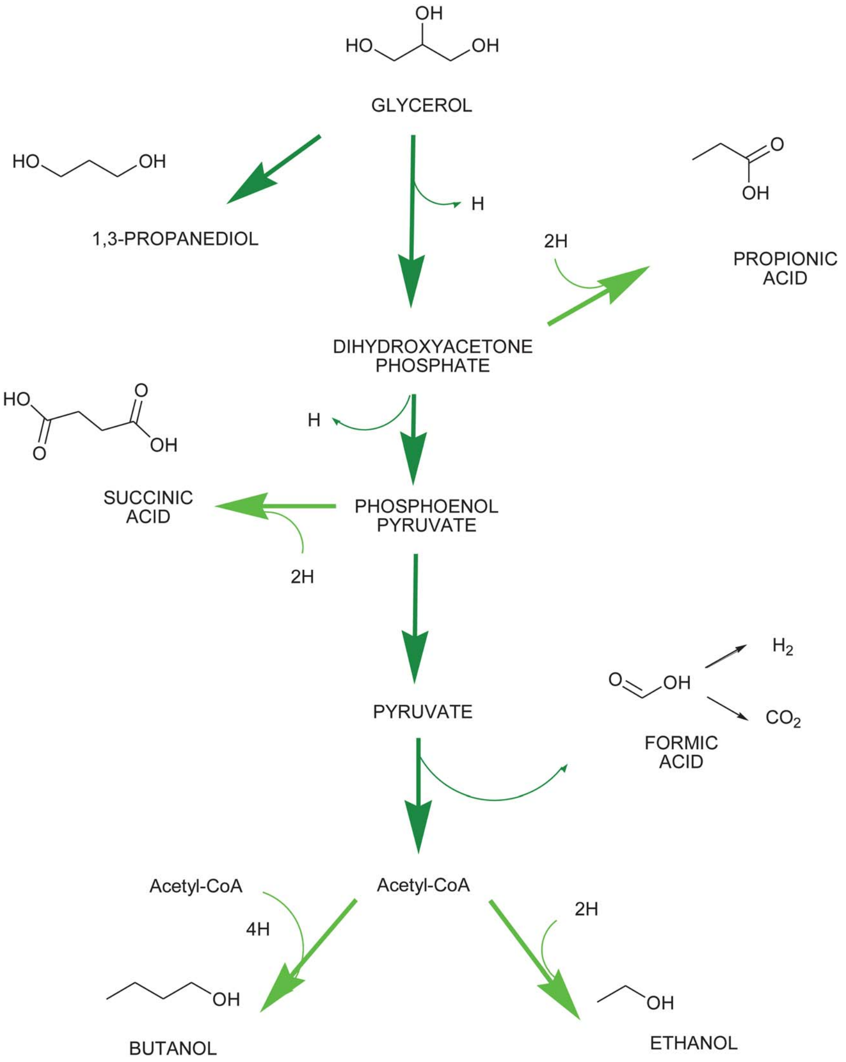
hydrogen and 90 minutes of reaction in a batch reactor. This route is particularly interesting as glycerin is not generated as a co-product in the systems, with all the triglycerides and FFA being converted into hydrocarbons. Biohydrogenated diesel has been proposed as the next generation biodiesel and has been commercially demonstrated by Neste Oil.[194,195]

A recent study from Norwegian researchers reviewed and compared the environmental impact, life cycle assessments and costs between different bio-diesel fuels (transesterified lipids, hydrotreated vegetable oils and woody biomass-to-liquid Fischer-Tropsch diesel). The conclusion of this work pointed out that hydrotreated oils from waste or by-products including tall oil, tallow or waste cooking oils outperform any other diesel products in terms of environmental LCA impact and costs.[196]

In Greece, Bezergianni *et al.* have recently described how the production of hydrogenated green diesel from waste oils can take place in high yields (>95%) using typical commercially sulfided Ni–Mo catalysts.[197] Low pressure values generally maximise bio-hydrogenated diesel production as opposed to high temperatures, which favour cracking reactions. In all cases, the heteroatom removal in the systems was efficient, exceeding 99% for sulphur and nitrogen and over 90% for oxygen (Fig. 22).[195]

The main drawback of this methodology is the use of hydrogen in the systems (Scheme 9) which generally require high pressures. Unless it can be obtained from a renewable resource (*e.g. via* aqueous phase reforming of another waste residue/renewable feedstock), the proposed approach cannot be commercially feasible. In this regard, coupling an APR approach with oil hydrotreatment processes could be the ideal sustainable solution for the valorisation of waste oils.

**5.3.5 Non-fuel applications of UCOs.** A range of sophisticated production lines have been recently developed based on oils and fats. Products include surfactants, lubricants, coatings, polymers from either food and non-food triglycerides and fatty acids. Selected examples reported the use of vegetable oils and fats in lubrication,[198] paints and drying applications,[199] which can potentially be economically attractive and sustainable



**Scheme 8** Key biotransformation from glycerol.

"end-of-waste" routes for UCO and recovered fats[200] in addition to their conversion into biofuels.

*Vegetable oil, fats and UCOs as lubricants.* Bio-renewable, non-hazardous and biodegradable components for lubrication are expected to considerably increase in future years, driven by environmental and health concerns (toxicity, not being readily biodegradable, *etc.*) as well as by the large demand of mineral-based lubricants worldwide (37.5 million tonnes per year).[200,201]

Vegetable oils, greases and fats either as neat, in blends as well as chemically modified or with additives have become a promising alternative to mineral and synthetic based oils, with a large number of examples reported in the literature.[202] The preferred applications for vegetable oils in lubrications are those in which thermal/oxidative stability is not a critical issue. These include cutting fluids,[203] low working temperature hydrolic fluids[204] and others. The reported examples for UCO as lubricant are in any case limited[205] due to their physico-chemical properties particularly related to thermal and oxidative stabilities. These properties have been found to be acceptable for high oleic acid-containing varieties of sunflower oil (HOSO)[206] or corn oil and its derivatives.[207] HOSO and corn oil are rich in monounsaturated fatty acids (primarily oleic), conferring them a good thermal and oxidative stability with a suitable lubricity to be employed as base oils for a certain type of lubrication uses.

However, additives are required to improve their oxidative stability and viscosity at high and low temperatures to achieve a similar performance to those of their synthetic/mineral equivalents.[198] These include anti-wearing agents (zinc dialkyldithiophosphates: ZDDPs), antioxidants (hindered phenols, aromatic amines and others), detergents/dispersants (sulphonates, salicylates and others), chemical modification[208] (*i.e.* improvements in thermal/oxidative stability, viscosity modification boundary lubrication, *etc.*), deodorisation[209] (*via* distillation to improve flash point properties) or/and blending with mineral products to meet the specifications.[210]

A large scope for research in the area is therefore needed to achieve further developments in this field. For instance, the free fatty acids available in large contents on acid oils/UCOs could be rectified by conversion into soaps, amides (*i.e.*, partial

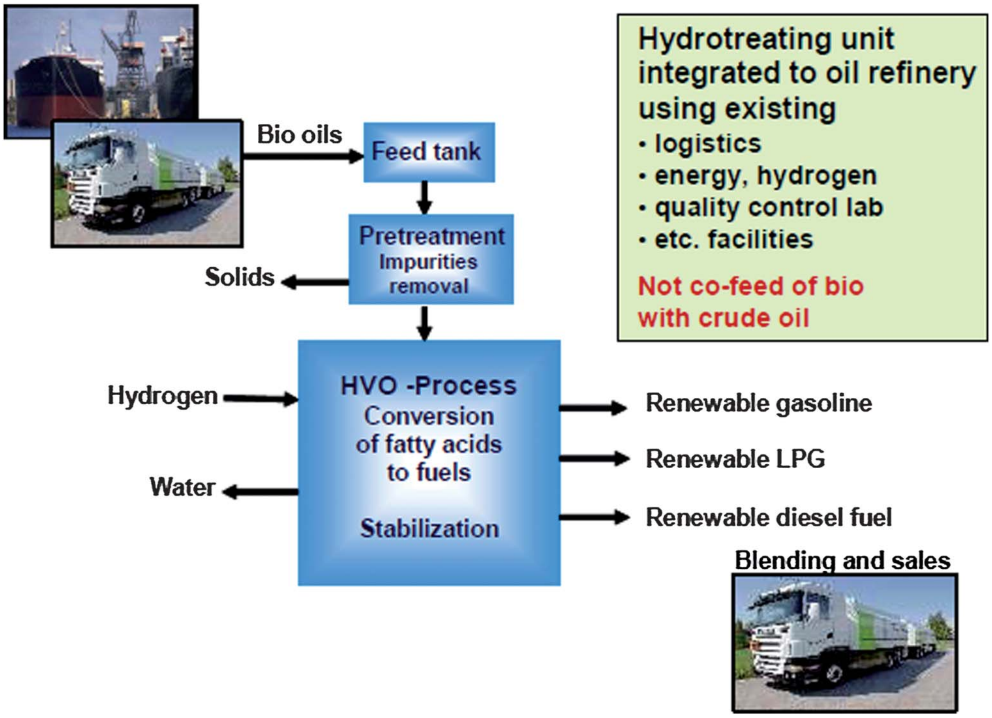


**Fig. 22** Hydrotreatment concept – from waste oils to valuable products. Reproduced with permission from ref. 195.

$$C_xH_yO_z \rightarrow a\,C_{x\text{-}b\text{-}d\text{-}e}\,H_{y\text{-}2c}\,O_{z\text{-}2b\text{-}c\text{-}d} + b\,CO_2 + c\,H_2O + d\,CO + e\,C$$

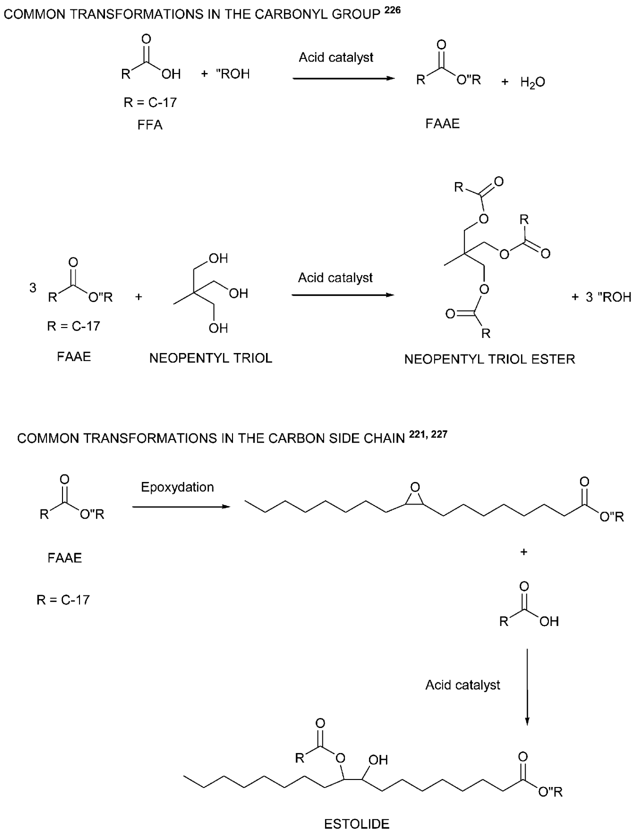
**Scheme 9** General reaction pathway for the catalytic cracking of oils to gasoline and gas-oil type products.

emulsification of water in cutting fluids),[208a] fatty acid alkyl esters (FAAE) or neopentyl triol esters (resulting in increased thermal/oxidative stability in hydrolic fluids) (Scheme 10).[211] Other modifications likely to improve properties such as viscosity index or oxidative stability are the conversion into estolides,[212] epoxidation and partial oxidation.[206]

In summary, UCOs and derivatives have a significant potential to become environmentally friendly alternatives to mineral-based lubricants, with low volatility, high viscosity index, high biodegradability and lower production costs. The utilisation of UCO in this area is however not exempt of challenges, due to variability of composition and lower oxidative and thermal stability in comparison to currently available virgin oils and mineral products.

*Potential for the use of UCO in other applications.* UCOs have also been proposed for the production of bio-derived coatings, paints and varnishes. These industries are moving towards safer (*i.e.* non-flammable, non-VOC containing) alternatives as the mineral base of those products is a large source of contaminants. Most varnishes are a blend of resin, drying oil and volatile solvent, from which alkyds are the most important class of resin in the coatings industry.

Alkyds are made of an alcohol such as glycerol, a dibasic acid and oils including castor, coconut, linseed or soybean. Vegetable oils with high levels of unsaturated fatty acids have been



**Scheme 10** Useful conversions in lubrication chemistry.

tested as varnish agents (*i.e.* linseed, soy bean, high linoleum sunflower and castor oil), by chemical tranformations under controlled mechanisms of polymerisation.[213] Condensation with polyols for the formation of alkyd resins, radical polymerisation and oxidation are required to form a solid polymerised matrix from UCOs. The main challenge with the use of these types of UCOs within these applications is their relatively low shell life and poor oxidative stability. Oils degrade upon frying leading to an increase in the FFA content and polymerisation reactions, which could be overcome by the introduction of functionalities in the carbon chain of the parent oil (epoxydation,[214] ozonolysis/introduction of carboxylic groups to increase hydrophilic properties of paints, insertion of olefins, *etc.*).[215]

### 5.4 Food waste and legislation in Greece

The food industry in Greece includes enterprises that manufacture meat, fisheries, fruits and vegetables, dairy, grain mill based products as well as animal food, sugar based foods, coffee and beverages such as wines, beers and soft drinks. In order to estimate the production of wastewater from food industries, data from the Hellenic Statistical Authority were used concerning the production quantities of food products in 2007 and the emission inventories adjusted to the local conditions (as reported in the deliverables of the aforementioned project) as summarized in Table 5.

Anaerobic digestion (AD) is a mature technology to convert biodegradable organic matter of waste into biogas. Generally, anaerobic digestion in Greece is considered to be a treatment method rather than an energy producing process. As a result, AD has not been extensively applied for energy production and use of the digestate as a soil conditioner. Biogas can be utilized for electricity co-production and thermal energy in Combined Heat Power units as well as fed directly into the natural gas grid if the required specifications are met. The obstacles to the widespread use of AD are summarised in Fig. 23, which highlight the reluctancy of food producers to utilise this technology.

**Table 5** Production quantities of food products (rounded numbers as reported from the Hellenic Statistic Authority for the year 2007) and the relevant emission inventories for liquid and solid waste production

| Product | Quantity of production (tonnes, tn) | Unit (U) | Production of waste ($m^3\ U^{-1}$) | $BOD_5$ ($kg\ U^{-1}$) | TSS ($kg\ U^{-1}$) | Tot. N ($kg\ U^{-1}$) | Tot P (kg/U) | Fats and oil ($kg\ U^{-1}$) | Putrescible waste ($kg\ U^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| Meat from cattle, pigs, sheep | 40 000 | tn living weight per year | 5.3–7.4 (6.9) | 6–10.9 (9) | 5.6–9.6 (7.7) | 0.7–0.84 (0.75) | 0.05–0.33 (0.14) | 2.1–5.9 (4) | 35[a] |
| Meat from chicken | 81 300 | 1000 heads per year | 37.5 | 11.9–17 | 12.7 | N/A | N/A | 5.6 | 35[b] |
| Fish and fishery products, (processed/preserved) | 11 700 | tn product per year | 24 | 7.3 | 9.4 | 0.65 | N/A | 4.7 | 280–570[c] |
| Processed fruit and vegetables | 645 000 | tn raw material per year | 0.43–89.4 (17.5) | 1.2–43.7 (11.8) | 0.2–19.4 (4.2) | N/A | N/A | N/A | 80–660[d] |
| Virgin olive oil | 13 100 | tn product per year | 7 | 95 | 455 | N/A | N/A | N/A | N/A |
| Refined oil and fats | 206 500 | tn product per year | 3.4 | 12.45 | 12.3 | N/A | N/A | 14.05 | N/A |
| Dairy (liquid) products | 470 300 L | tn product per year | 3.1 | 3.21 | 1.5 | 0.31 | 0.68 | N/A | N/A |
| Butter | 900 | tn product per year | 2.6 | 1.1 | 0.4 | 1.95 | 0.42 | N/A | N/A |
| Yogurt | 139 600 | tn product per year | 3.9 | 3.21 | 1.5 | 0.31 | 0.68 | N/A | N/A |
| Cheese | 111 000 | tn product per year | 2.3–7.7 | 2.2–21.7 | 0.2 | 1.56 | 0.34 | N/A | N/A |
| Grain mill products | 773 500 | tn product per year | 0.29–1.5 (0.750) | 0.1–1.8 | 0.2–1.6 | N/A | N/A | N/A | N/A |
| Sugar production of beets | 170 000 | tn product per year | 23 | 20 | 75 | N/A | N/A | N/A | N/A |
| Beverages (distillation) | 29 700 $m^3$ | $m^3$ alcohol per year | 36–63 | 210–216 | 75–257 | N/A | N/A | N/A | 300[e] |
| Wines | 150 000 $m^3$ | tn grapes per year | 2 | 1.6 | 0.3 | N/A | N/A | N/A | N/A |
| Beer | 435 200 $m^3$ | $m^3$ product per year | 5.4–11 | 10.5–18.8 | 3.9–7.3 | N/A | N/A | N/A | 20[f] |
| Soft drinks | 556 200 $m^3$ | $m^3$ product per year | 2.15–6.4 | 2.1–3.1 | 0.7–4.3 | N/A | N/A | N/A | N/A |

[a] Blood, hooves, paunch, *etc.* [b] Feathers, hooves, and inedible parts. [c] Inedible fish part. [d] Peels, cores, and seeds. [e] Spent resins, figs, and canes. [f] Spent hops, grain, residues, and yeast.

Table 6 lists the biogas plants operating in Greece as recorded by the Centre for Renewable Energy Sources and Saving (CRES) in 2007. The biogas plants treating landfill leachate accounted for 75% of the installed electrical power, while 25% came from sewage sludge treatment. In the case of thermal energy, 6% of the installed thermal energy power was produced from FW, while the remaining 94% was produced in sewage treatment plants.[216]

FW can also be valorised to marketable products *via* bioconversion. Table 7 presents the approximate composition of specific industrial food waste streams. The classification is based on major components (*i.e.* carbohydrates, protein, oil or fat) in each type of FW. Carbohydrate and protein-rich FW streams could be employed for the production of generic fermentation media that may contain sufficient amounts of nutrients to consequently reduce the use of commercial nutrient supplements. The production of crude hydrolysates from FW will be based on the utilisation of commercial enzyme formulations or the production of crude enzymes *via* solid state or submerged fermentations. Many FW may contain directly assimilable mono- or di-saccharides. However, most FW contain polysaccharides that should be hydrolysed in order to be used in fermentation processes. Ongoing research at the Agricultural University of Athens (Greece) focusses on the bioconversion of flour-rich waste streams from confectionary industries for the production of single cell oil that can be used as raw material for biodiesel and oleochemical production. In addition, protein-rich food waste could be used for the production of media rich in sources of nitrogen (*e.g.* amino acids, peptides) using proteolytic enzymes. For instance, oilseed meals produced as by-products from biodiesel production plants could be hydrolysed into a nutrient rich supplement for various microbial fermentations using crude enzymes produced by solid state fermentation.[217] Ongoing research at the Agricultural University of Athens focusses on the valorisation of crude glycerol and protein-rich sunflower meal generated from a biodiesel production plant for the production of an antioxidant fraction, a protein isolate fraction for application as adhesive and polyxydroxybutyrate (PHB) for packaging applications. Wheat flour milling by-products have also been employed for the production of succinic acid after enzymatic hydrolysis of starch and protein.[218]

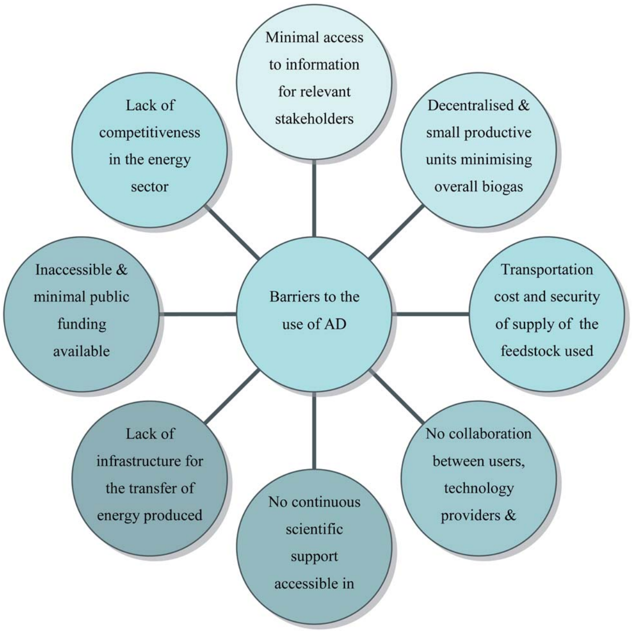


**Fig. 23** Barriers to the use of anaerobic digestion (AD).

### 5.5 Food waste in Hong Kong

Hong Kong is one of the most densely populated places in the world and has an average population density of about 6480 people per km$^2$ in 2009.[235] In some urban districts, the population density reaches 50 000 people per km$^2$. With such high

**Table 6** Biogas plants in Greece (2007)

| | Waste type | *Biogas production*, kNm$^3$ per annum | *Capacity* | |
|---|---|---|---|---|
| ZANAE | Food wastes | 396 | 0.64 | MW$_{th}$ |
| Tasty foods | Food wastes | 91 | 0.76 | MW$_{th}$ |
| Landfill in Tagarades | Municipal wastes | 666 | 5.28 | MW$_e$ |
| Sewage treatment plant (STP) in Larisa | Activated sludge | 350 | 0.57 | MW$_{th}$ |
| STP in Patras | Activated sludge | 505 | 1.05 | MW$_{th}$ |
| STP in Chalkida | Activated sludge | 310 | 1.50 | MW$_{th}$ |
| STP in Alexandroupolis | Activated sludge | 300 | 0.33 | MW$_{th}$ |
| STP in Rodos | Activated sludge | 90 | 0.35 | MW$_{th}$ |
| STP in Heraklion | Activated sludge | 1.042 | 0.19/0.53 | MW$_{e/th}$ |
| STP in Chania | Activated sludge | 420 | 0.17/0.29 | MW$_{e/th}$ |
| STP in Psitalia | Activated sludge | 20.501 | 10.35/7.14 | MW$_{e/th}$ |
| Landfill in Ano Liosia | Municipal wastes | 67.613 | 23.5 | MW$_e$ |
| STP in Metamorphosis | Activated sludge | 1.647 | 1.63 | MW$_{th}$ |
| STP in Volos | Activated sludge | 590 | 0.35/0.70 | MW$_{e/th}$ |
| STP in Thessaloniki | Activated sludge | 2.200 | 2.5/6.74 | MW$_{e/th}$ |
| Landfill in Xanthi | Municipal wastes | Under construction | 9.5 | MW$_e$ |
| Landfill in Volos | Municipal wastes | Under construction | 1.72 | MW$_e$ |
| STP in Larisa | Activated sludge | Under construction | 0.6 | MW$_{th}$ |

**Table 7** Composition of major food processing and municipal wastes and by-products

| Type of food waste | Water content (%) | Carbohydrate content (%) | Protein content (%) | Oil/fat content (%) | References |
|---|---|---|---|---|---|
| **Carbohydrate-rich wastes** | | | | | |
| Molasses, beet | 23 | 65.1 | 6.7 | — | Greasham, 1993 (ref. 219) |
| Spent grains from breweries | 80–83 | 9–11.6 | 3.2–4.6 | 1.5–2.4 | Russ and Meyer-Pittroff, 2004 (ref. 220) |
| Whey | 92.7 | 4.9 | 0.9 | 0.9 | Waldron *et al.*, 2004 (ref. 221) |
| Apple pomace | 3.9–10.8 | 48–62 | 2.9–5.7 | 1.2–3.9 | Bhushan *et al.*, 2008 (ref. 222) |
| Orange waste (peel, pulp and seeds) (dry basis) | 79 | 47 | 6.5 | — | Mahmood *et al.*, 1998 (ref. 223) |
| Cassava pulp (dry basis) | 6.8 | 69.9 | 1.55 | 0.12 | Sriroth *et al.*, 2000 (ref. 224) |
| Waste bread (whole wheat and white bread) | 33–43 | 41–51 | 8–13 | 3 | Lin *et al.*, 2012 (ref. 225) |
| Rice flour (*e.g.* waste streams from confectionary industries originally produced as food for infants) | 5 | 86.1 | 7.3 | 1.1 | Lin *et al.*, 2012 (ref. 225) |
| Wheat bran (crude) | 11 | 64.5 | 15.5 | 4.2 | Du *et al.* 2009 (ref. 226) |
| Pear pulp (dry matter) | | 62.8 | 5.1 | 1 | El Kossori *et al.*, 1998 (ref. 227) |
| Tomato pomace (dry basis) | | 25.4–50 (fiber) | 15.4–23.7 | 5.4–20.5 | Del Valle *et al.*, 2006 (ref. 228) |
| Grape pomace without seeds (dry basis) | 58.2–78.9 | 12.5–48.8 | 11.0–11.4 | 4.47–5.19 | Saunders *et al.*, 1982 (ref. 229) |
| Lees from sherry wine | | 4.1 (sugars) | 15.1 | 5.4 | Gomez *et al.*, 2004 (ref. 230) |
| Potato peel (dry basis) | 85 | 69.7 | 8 | 2.6 | Arapoglou *et al.*, 2010 (ref. 231) |
| Potato tuber | 83.3 | 12.5 | 2.6 | 0.1 | USDA, 2008 (ref. 232) |
| **Protein- and/or fat/oil rich wastes** | | | | | |
| Municipal meat waste (dry basis) | 41 | | 24.6 | 69.9 | Garcia *et al.*, 2005 (ref. 233) |
| Municipal fish waste (dry basis) | 73.9 | | 57 | 19.1 | Garcia *et al.*, 2005 (ref. 233) |
| Soybean meal | 10 | 29.9 | 42 | 4 | Greasham, 1993 (ref. 219) |
| Linseed meal | 8 | 38 | 36 | 0.5 | Greasham, 1993 (ref. 219) |
| Yeast from breweries | 5 | 39.5 | 43 | 1.5 | Greasham, 1993 (ref. 219) |
| Yeast, hydrolysate | 5.5 | — | 52.5 | — | Greasham, 1993 (ref. 219) |
| Corn steep liquor | 50 | 5.8 | 24 | 1 | Greasham, 1993 (ref. 219) |
| Dried distillers soluble | 8 | 45 | 26 | 9 | Greasham, 1993 (ref. 219) |
| Fish meal (anchovy), 65% | 8 | — | 65 | 3.8 | Greasham, 1993 (ref. 219) |
| Blood | 86 | — | 12 | 0.3 | Russ and Meyer-Pittroff, 2004 (ref. 220) |
| Meat and bone meal | 8 | — | 50 | 8 | Kampen, 1997 (ref. 234) |
| Pharmamedia (derived from cottonseed embryo) | 1 | 24.1 | 59.2 | 4 | Kampen, 1997 (ref. 234) |
| Peanut meal and hulls | 9.5 | 23 | 45 | 5 | Kampen, 1997 (ref. 234) |
| Slaughterhouse waste | 74 | — | 9 | 14 | Russ and Meyer-Pittroff, 2004 (ref. 220) |

**Table 8** Types of waste disposed at landfills in Hong Kong in 2010 (adapted from the Advisory Council on the environment[238])

| Waste | Volume (tonnes per day) |
|---|---|
| Municipal solid waste | 4942 |
| Food waste | 3237 |
| Construction waste | 3584 |
| Sludge | 935 |
| Other waste | 1119 |
| Total | 13 817 |

compactness, the majority of households in Hong Kong are resided in multi-storey multi-tenant buildings. Similar to many other metropolitan cities, Hong Kong is facing an imminent waste management problem.

Table 8 and Fig. 24 show the types of commercial and industrial waste disposed at landfills in Hong Kong in 2010.[236] Among the 13 817 tonnes of waste disposed daily, 3237 tonnes are FW, constituting about 23% of the waste disposed, and it is the second largest waste category. Of the 3237 tonnes of FW generated daily, around 960 tonnes originate from commercial and industrial food production operations (*i.e.* bakery industry, bean curd industry, catering industry, food production industry, hotels, wholesale market, yard waste and restaurants).[237] In recent years, the amount of FW arising from the commercial and industrial sectors has been steadily increasing, as seen in Fig. 25. The quantities of FW in 2010 were doubled as compared to the amount in 2002.

According to the Policy Framework for the Management of Municipal Solid Waste (2005–2014), the Government of Hong Kong SAR has suggested to adopt an integrated waste

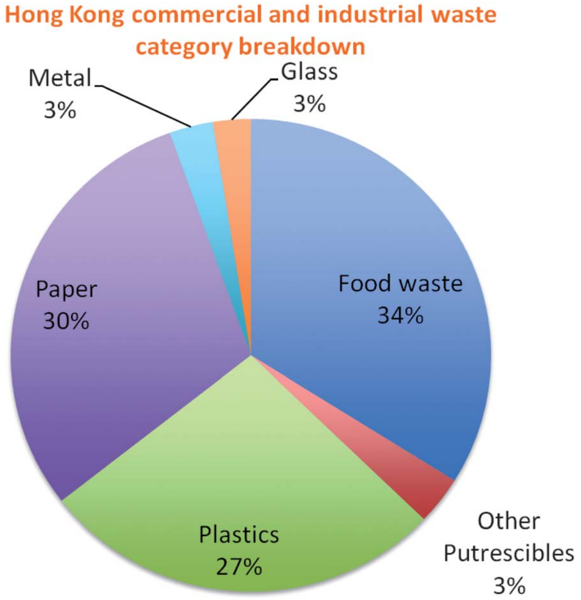


**Fig. 24** Types of commercial and industrial waste disposed at landfills in Hong Kong (2010).

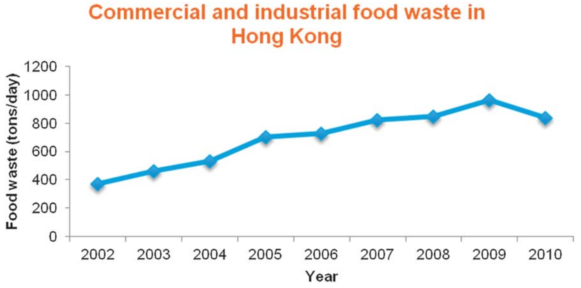


**Fig. 25** Evolution of food waste production from commercial and industrial sectors from 2002 to 2010.

management facility for waste treatment, including FW. Alternative options including a centralized plant have been considered to treat FW to be generated in Hong Kong but the transportation of FW in large quantities across the territory for treatment may not be viable due to the high transportation costs, as well as the possible odour and leachate contamination issues during transportation. At the moment, Hong Kong relies mainly on landfills for waste disposal. However, these three landfills will reach full capacity by 2014, 2016 and 2018.[239] In the light of these important issues, there is an imminent need to reduce the quantity of organic waste disposal to landfills. At the same time, the development of effective FW conversion processes/technologies aiming at waste processing at the source is highly desirable, particularly in a densely populated state such as Hong Kong.

In Hong Kong, restaurants as well as the food and beverage industries have employed composters to treat FW in order to minimize the amount of waste for disposal (Fig. 26). Continued

**Fig. 26** Food composters to handle food waste.

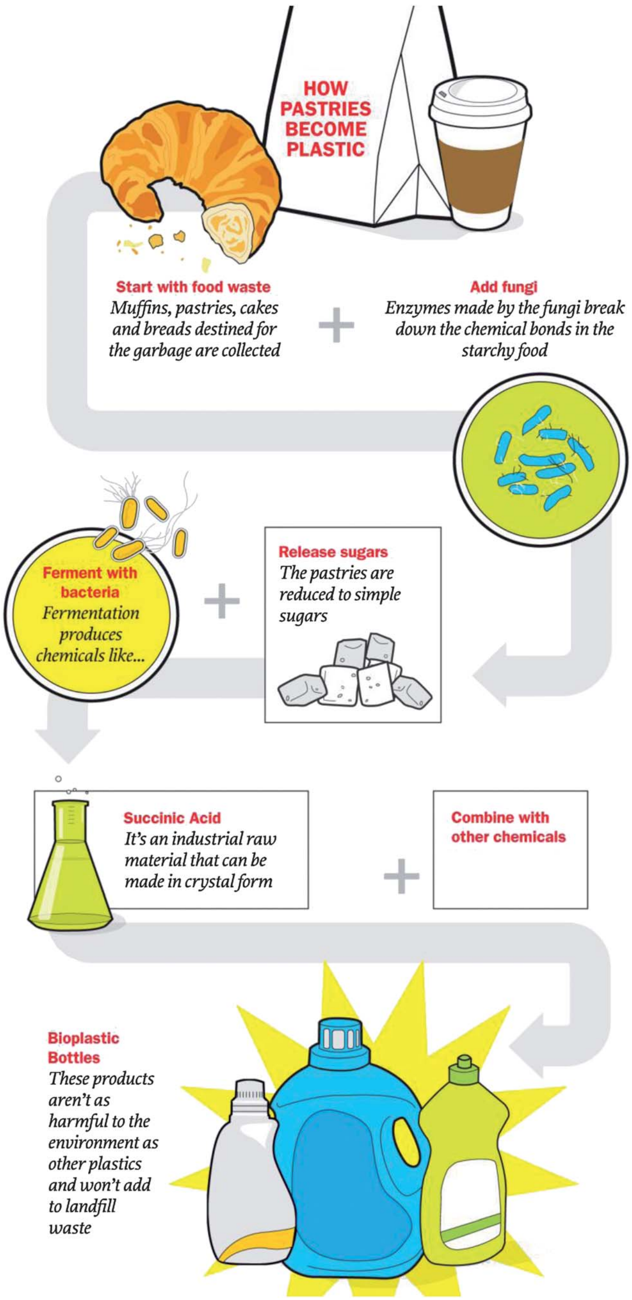


**Fig. 27** Biorefinery concept for the fermentative succinic acid production from bakery waste.[237]

education and publicity efforts have been devoted to encouraging further household FW reduction. Collection of FW from domestic households for treatment is difficult at this stage. As previously mentioned, the majority of households in Hong Kong reside in multi-storey multi-tenant buildings which lack available space for dedicated FW containers at both household and building levels. Furthermore, these issues add to the hot and humid weather in Hong Kong that could easily cause potential hygiene and odour problems, making the whole scenario even more complicated. In view of the above difficulties, targets have been aimed at source separated FW from the commercial and industrial sectors, as the separation of food waste can be much easier done. Nevertheless, the Hong Kong Government is currently dealing with the FW issue in the domestic sector and would work closely with the relevant stakeholders, including the domestic sector, property management companies and green groups, to encourage households to generate less FW and to develop trial schemes to explore how FW could be effectively collected and disposed through on-site FW treatment facilities.

The School of Energy and Environment at the City University of Hong Kong has been recently started collaborating with the coffee retailer giant 'Starbucks Hong Kong' from March 2012.[240] The partnership, facilitated by the NGO Climate Group Hong Kong, focuses on the valorisation of spent coffee grounds and unconsumed bakeries to valuable products *via* bio-processing. The collaboration is based on a support scheme as part of the "Care for Our Planet" campaign from April 2012 consisting in a donation of HK$8 (US$1) for every set of Care For Our Planet Cookies Charity Set sold to support research on valorisation of FW for the sustainable production of chemicals and materials. This project was cocurrently funded by the Innovation and Technology Commission from the Government of HKSAR.[241]

Research has been focused on the production of bio-plastics and detergents from unconsumed bakeries *via* enzymatic hydrolysis of non pre-treated bakery waste, followed by fungal solid state fermentation to break down carbohydrates into simple sugars for subsequent succinic acid fermentation (Fig. 27). A mixture of fungi comprising *Asperillus awamori* and *Asperillus oryzae* was utilised for the production of amylolytic and proteolytic enzymes, respectively. Macromolecules including starch and proteins contained in bakery waste were then hydrolysed into a bakery hydrolysate enriched in glucose and free amino nitrogen (FAN). This hydrolysate was subsequently employed as generic feedstock in a bioreaction to produce succinic acid (SA) by *Actinobacillus succinogenes*. Fig. 28 shows the isolated succinic acid crystals from the fermentation broth which utilised the bakery hydrolysate from FW.[241] Succinic acid crystals were separated using a novel resin based distillation-crystallisation method previously developed by Lin *et al.*[242]

**Fig. 28** Succinic acid crystals (left: pointed with red arrow) produced from Starbucks bakery waste (right: in a glass beaker).[238]

In summary, this project is currently mediating in the development of advanced FW valorisation practices used in Hong Kong to valuable products, reducing at the same time the release of GHG and other air pollutants into the atmosphere. Such a synergistic solution can then be adopted by the Hong Kong Government as part of their strategy for tackling the FW issue and for the environmentally friendly production of alternative platform chemicals.

## 6 Valorisation of food supply chain waste: towards integrated biorefineries

The implementation of the biorefinery concept is an essential part of the successful valorisation of FSCW. Phase III or "product-driven" biorefinery targets the production of several product outputs (chemicals and energy) using a range of combined technologies.[243] Typically, Phase III biorefineries focus on valorising a whole crop for example (*i.e.* Miscanthus) by extracting surface waxes as well as using the residue to generate energy *via* pyrolysis or gasification. Such a concept should not however be focused on the single valorisation of dedicated biorefinery crops. Phase III biorefineries also have a role to play in valorise FSCW.

In the case of industrial FW, suitable processing schemes that valorise waste into added-value products should be integrated into existing food industry facilities. Technologies already implemented in the food industry are preferred including microwave heating (used for commercial pasteurisation and sterilisation[244] of prepared food) or supercritical $CO_2$ (used for the decaffeination of coffee[245]). These strategies aim to maximise profits from different process outputs reducing in parallel long term production costs. Process integration is obviously a preferred alternative to setting up a new plant, where some technologies still entail a significant capital investment.

In some cases, the exploitation of local or regional food industries may lead to decentralisation of biofuels, chemicals and biomaterials production and could therefore offer a solution to specific local demands, lowering associated transport costs and emissions. In the case of biofuels production from FW (including other biomass feedstocks), a local food industry could exploit its waste for biofuel production (*i.e.* biogas production from effluent and solid waste in the food industry), in order to serve the needs of the plant, a local or regional agricultural community.[246] This proposed bio-economy can significantly contribute to the future development of rural, coastal and industrialised regions by improving the sustainable exploitation of their natural and industrial resources, by creating supply chains for residues and waste as feedstock or setting up of networks of biorefineries.

### 6.1 Integrated biorefineries based on specific food waste

For biorefineries to be successful, they have to adapt to the needs of international markets as well as bulk chemical production being strongly driven by supply demand issues and "economies of scale". In many cases, the production of commodity products from specific FW may not be economically feasible as low market prices of commodity products require large production capacity industrial plants. The establishment of such industries may not be feasible in many cases because large quantities of specific types of FW should be transported to a central location. This concept will be hindered by major disadvantages of specific FW including widespread distribution of FW, high water content and fast deterioration due to contamination. These important drawbacks could be solved through the development of a generic processing scheme for bulk FW similar to that developed by Brocklesby Ltd (Section 5.3.2).

Specific types of FW should be treated either on-site by the same producing industry or at least on a local/regional industrial site. Minimising FW transportation should be one of the main targets of FW based biorefineries. Novel processes could be developed combining extraction of high-value products with subsequent fermentations (or green chemical conversions) for the production of chemicals, materials and fuels to minimise production costs. For instance, the utilisation of olive pulp waste and orange processing waste streams for bioethanol production could become feasible only in the case that they are combined with the production of other added-value products (*e.g.* extraction of limonene and pectin from orange processing wastes) and integrated with current food production.[247,248] Fractionation of whey into a lactose-rich and a protein-rich fraction could also be employed for the production of high-value whey protein hydrolysates with various applications (*e.g.* protein source for individuals with reduced capacity of digestion, or with genetic metabolic disorders), while lactose could be used as a carbon source for the production of various chemicals *via* fermentation.[249]

The minimisation and valorisation of these wastes has a double advantage. It reduces pollutant loadings of agro-food industries as well as contributing to the sustainable development of the agro-food sector through a rational use of FW bio-derived containing compounds.

### 6.2 Evaluation of food supply chain waste for the production of chemicals, materials and fuels using the biorefinery concept

In a local or regional integrated process in an existing food industry, initial processing steps will extract high value constituents from FW (proteins, oils, sugars, vitamins, waxes, colorants and flavour and fragrance compounds) while the majority of FW will subsequently be processed for the production of case-specific fermentation media or treated using chemical or thermochemical methods. Apart from minor constituents (*e.g.* antioxidants), even major components including oils and fats could be used in several applications as previously described in this perspective article. Oil-rich fractions extracted from FW could substitute for plant oils as raw materials of the chemical industry for chemical conversions and synthesis of chemically pure compounds. Oil extracted from FW could be employed for the production of fatty acid esters, surfactants (*e.g.* sorbitan ethoxylates), stabilisers, fatty amines, dicarboxylic acids, resins, plasticizers, soaps, lubricants and polyols.[250–252] Additionally, oils extracted from FW (*e.g.* fish processing wastes) could be used as raw material for biofuel production.[253]

Bioprocessing technologies could be employed for the production of bio-energy, platform chemicals and biomaterials. Platform chemicals could be subsequently converted *via* clean and green chemical technologies into high added value chemicals and polymers. Fermentation media should contain major and minor nutrients including sources of carbon, nitrogen, minerals vitamins and trace elements. Specific types of FW may not provide all these nutrients. For this reason, it may be desirable to combine different types of FW that contain complementary nutrient composition. It should be stressed that enzymatic hydrolysis of polysaccharides and protein contained in FW should be achieved by mixed enzyme consortia produced on-site *via* solid state fermentations. Crude protein-rich wastes or hydrolysates have been utilised as substitutes for commercial nutrient supplements for the production of bio-based polymers, chemicals or even speciality products.[254–260] Carbohydrate- and protein-rich fractions produced in the above processing schemes could be employed for the formulation of fermentation media *via* enzymatic hydrolysis. This concept has not been applied extensively yet. However, all chemicals produced from purified carbon sources *via* fermentation could be in principle produced from FW hydrolysates.

Most future platform chemicals (*i.e.* succinic, fumaric, malic, 3-hydroxypropionic, glutamic and itaconic acids as well as sugars including xylitol and arabinitol) could be produced *via* fermentation of sugars[192,261–263] and subsequently converted into valuable products such as specialty chemicals, biofuel-precursors and biodegradable polymers. Fermentation processes can also be employed for the production of bio-based polymers either through the synthesis of monomers (*e.g.* lactic acid, succinic acid) or through direct production of biodegradable polymers (*e.g.* polyhydroxyalkanoates, bacterial cellulose).[264–272]

Fermentations of FW hydrolysates could be also used for the production of single cell oil (SCO) using various oleaginous microorganisms. The fatty acid composition of SCO depends on the selected microorganism. SCO produced by many yeast strains could be used as a substitute for plant oils due to their similar fatty acid composition[273] or alternatively as raw material for biodiesel production.[274] Another potential application is the production of oleochemicals either as multi-purpose feedstocks or case-specific feedstocks. Multi-purpose feedstocks include oils that contain common fatty acids (*e.g.* oleic and linoleic acids) compared to case-specific feedstocks that contain uncommon fatty acids with special properties derived from their unique molecular structure.[275]

Table 9 summarises the potential for the production of major biofuels, chemicals and biopolymers from FW. Calculations were based on carbon source requirements (mainly glucose equivalent) for the production of selected compounds using conversion yields of 90% of the theoretical value (except lactic acid and succinic acid). For instance, 0.08 million tonnes

**Table 9** Carbon source requirements for the fermentative production of various chemicals

| Chemical product | Current and future industrial applications | Worldwide production[a] ($10^6$ tonnes) | Production yield[a,b] (kg $kg^{-1}$ glucose) | Quantity of glucose required ($10^6$ tonnes) | Quantity of food waste required |
|---|---|---|---|---|---|
| Ethanol | For industrial use as solvent, disinfectant, preserving agent and building block for chemical synthesis | 31[c] | 0.46 | 67.39 | 61.26 million tonnes of starch[d] that is contained in various food wastes |
| 1,3-Propanediol | Polymeric applications (*e.g.* polytrimethylene terephthalate), malonic acid, polyurethans, copolyester ethers | 0.08 | 0.54[e] | 0.148 | 0.148 million tonnes of crude glycerol or approximately 1.48 million tonnes of waste cooking oil |
| Lactic acid | Additive in foods and beverages, industrial applications, PLA production, pharmaceuticals and personal care products | 0.15 | 0.95[f] | 0.158 | 0.319 million tonnes of waste bread (45% starch content on average)[d] |
| Succinic acid[276] | Platform molecule for the production of 1,4-butanediol, γ-butyrolactone, tetrahydrofuran, pyrrolidinones, polybutylene succinate, succinic esters, polyamides, *etc.* | 0.015 | 1.16 | 0.013 | 27 million kg of waste bread (based on an overall conversion yield of 0.55 g succinic acid per g bread)[d] |
| Fumaric acid | Food acidulant and beverage ingredient. Platform molecule for the production of unsaturated polyester resins, tetrahydrofuran, 1,4-butanediol, γ-butyrolactone, L-aspartic acid *etc.* | 0.012 | 1.16 | 0.01 | 0.021 million tonnes of waste bread (45% starch content on average)[d] |
| PHB | Bio-based polymers, medical applications, biocomposites, food packaging materials, use of the monomers as platform chemical | ≈0.4[g] | 0.43 | 0.93 | 1.879 million tonnes of waste bread (45% starch content on average)[d] |

[a] Taken from Patel *et al.* (2006).[261] [b] 90% of theoretical conversion yield. [c] Utilisation of starch and sucrose as carbon sources. [d] A starch to glucose conversion yield of 1.1 has been assumed. [e] The carbon source is glycerol. [f] A 95% conversion yield may be feasible for lactic acid in the future. [g] Projected worldwide production capacity for 2013.[277]

of 1,3-propanediol could be produced from approximately 1.48 million tonnes of waste cooking oil. The annual worldwide production of waste cooking oil is approximately 0.7–1 million tonnes.[85] This means that the crude glycerol generated during biodiesel production from waste cooking oil could provide up to 67.6% of the raw material required for 1,3-propanediol worldwide production. The annual production of household waste from bakery products and dried food is more than 1 million tonnes only in the UK.[42] According to Table 9, significant quantities of lactic acid, fumaric acid, succinic acid and/or polyhydroxybutyrate (PHB) could be produced *via* fermentation from only bakery products and dried food that are disposed as waste from households. These examples highlight the potential of platform chemical production in future biorefineries utilising exclusively starch-based FW.

## 7 How can our society's attitude be changed towards the use of food supply chain waste as a resource?

At the global level, waste will increasingly be used as inputs into other processes, by either composting or through energy recovery and recapture of all non-biodegradable material. Achieving zero waste will not be dependent on regulations alone; consumer demand and markets for recycled material will combine to ensure that products, processes, and business models are designed around maximum efficiency and minimal waste, regardless of the geographic location or cultural context.[278]

A significant potential for the reduction of FW in the developed world lies within retailers, food services and consumers. Consumers and businesses need to realise how our resources are constrained and comply with the reality of our situation. Cultural shifts in the way consumers value food, stimulated through education, increased awareness of the food supply chain and FW impact on the environment have a significant potential to reduce waste production, at least for food wasted at the post-consumer stage. Improved food labelling and a better consumer understanding of labelling and food storage will have a high potential to reduce the produced quantities of FW.

An example of a leading practice to improve sustainability of the food industry is the Waste and Resources Action Programme (WRAP), a UK government initiative to reduce FW which has focused mainly on waste packaging. As a result of the 'love-food hate-waste' campaign launched by WRAP, 22% of households store more food in the refrigerator rather than in fruit bowls and 14% waste less food due to improved storage.[42]

Similarly the Courtauld Commitment is a voluntary agreement in the UK between WRAP and major retailers that is leading to new solutions and technologies to reduce food, packaging and household waste entering landfill.

Food supply chains will continue to be developed in response to the continuous increase in new challenges posed by the development of new technologies at the manufacturing and retail end (*e.g.* identification and labelling of products and better demand forecasting).[279] For example, Norway's largest food supplier, Nortura, is using radio frequency identification (RFID) technologies to trace poultry and meat products from farm to supermarket shelves, ensuring that meat and poultry products are kept in optimal conditions minimising waste along the supply chain.

It is quite evident that the manufacturing and retailer end of the food supply chain have been working on reducing waste in their operations. However, there are foods and food products that are still being wasted but not counted in traditional waste disposal streams. Government policies and regulations can also act as barriers. For example, European Food Information Regulations on date labelling do not necessarily balance the health regulations with environmental factors. It is essential that businesses engage and collaborate with Governments throughout the whole lifecycle of products and services.

At the consumer end of the food supply chain, consumers often lack the knowledge to consume in a less wasteful manner. Given the consumers' current relationship with FW, a package of measures including effective communication or intensive personal engagement may serve as a way forward to bring behaviour change in the absence of motivation or consciousness on FW issues. WRAP believes that "the way forward is to create a positive climate around encouraging good behaviours in relation to food management" and to "provide persuasive arguments for a change in behaviour together with simple but effective steps and tools to manage our food better".[280] They also highlight the importance of making consumers aware of the environmental impacts of FW, and in particular its contribution to carbon emissions. People need to be educated about the resource-constrained world we live in today.

A study conducted by Thøgersen and Ölander examining the impact of recycling on the values and behaviours of Danish consumers confirmed that behaviour is driven by the values people hold and 'behavioural inertia', created by forces (such as established habits) that are independent of values.[281]

Changing consumer behaviour can therefore be challenging for most stakeholders in a supply chain as they face a difficult task if they are to influence environmentally friendly behaviour without first addressing values. While attempts to shift consumer behaviour may result in reduction in FW in developed countries, changes in legislation and business behaviour towards more sustainable food production and consumption will be necessary to reduce waste from its current high levels.

## 8 Concluding remarks and future prospects

This contribution has been aimed to demonstrate the potential of advanced FW valorization practices for our current society. FW is inevitable, especially at a pre-consumer stage, but the environmental damage caused by GHG emissions and ground water contamination *via* FW decomposition in landfill sites, to name only one, can largely be avoided. Nevertheless, in this perspective article we have highlighted the complexity to tackle this important problem of the current society that involves governments, policies, regulations, stakeholders, companies, products and most importantly consumers and public opinion. Several strategies to valorize FW have been implemented including recycling, composting and related practices, which however cannot achieve a sufficient processing of FW residues, being in all cases of limited value.

In this regard, advanced FW valorization practices aiming to achieve sustainable development and a circular economy should focus on innovative low environmental impact legislation-compliant technologies able to convert waste into value-added products. These include AD (hailed as the future of FW management), low environmental impact chemical technologies (including smart chemical separation technologies), integrated bio-chemical processing approaches (*e.g.* fermentation and chemical transformations of converted platform molecules to high-added value chemicals and biofuel precursors), extractive processes for the recovery of valuable compounds (*e.g.* antioxidants, terpenes) using benign methodologies including the use of microwave irradiation and related approaches. A multidisciplinary approach is necessary to fully understand these processes, allowing us to reach the level of innovation necessary to achieve a zero-waste economy and a more sustainable bio-based society. Among these, cross-industry and public-private collaborations are needed along the food supply chain but also between industries given the potential of FSCW to be used as a feedstock for different industries, ensuring that this strategy has a maximal impact. Since data on FW generation from public research are limited, collaboration and investment in monitoring would be a good starting point, allowing scientific, industrial and governmental bodies to interact from the start. This first step is especially important when selecting types of FSCW to focus on for valorisation, availability, location and chemical content being crucial to set up a profitable biorefinery.

Steering changes that can have wide sustainable impacts on the environment will require several approaches to lead to sufficiently rapid changes and legislation can certainly support these efforts. Legislation can have a powerful impact on driving positive behaviour change along with another essential approach (education) which is a valuable agent to facilitate the proposed change. Findings reported in this manuscript clearly show how this area is attracting increasing interest. However, policy makers must play a full role in this, especially with regard to restrictions on the transport of bioresources, which coud become an important feedstock in the future. We envisage an increasing awareness of the valorisation of FW feedstocks worldwide. FSCW will play a key role in the near future around the biorefinery concept to contribute to a greener and more sustainable future society.

In any case, the aforementioned complexity of the FW issue should not however restrict the development of innovative practices to deal with this important under-utilised source of

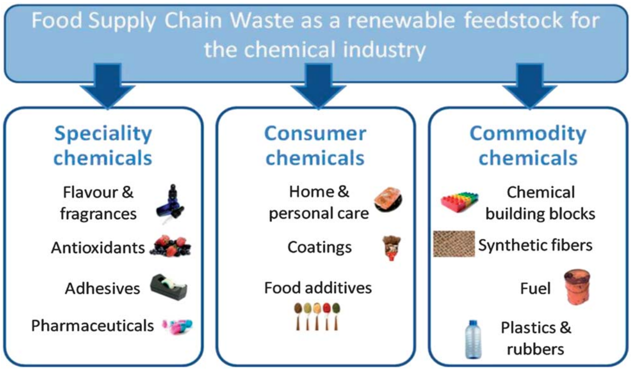


**Fig. 29** Sectors of the chemical industry that could benefit from the use of FSCW as a raw material.

valuable compounds. In contrast, it should encourage every single institution involved in any part of the food supply chain to redouble efforts aiming to minimize FW production in each step of the chain, maximizing at the same time the value of products and additional revenues that can be obtained by means of a rational and well understood utilisation of raw materials and feedstocks. Such a strategy would benefit the chemical industry by allowing it to increase its use of renewable raw material, helping the food and chemical industry to form a symbiotic relationship. The diversity of compounds found in FSCW reflects the variety of sectors in the chemical industry that could benefit from using such a renewable feedstock, improving its green credentials (Fig. 29).

All of these should be done in parallel to well designed re-education and awareness campaigns throughout the world's population in order to change the perception of FW as a problem instead of a valuable resource to produce chemicals, materials and fuels.

It is possible that through the increased and well-publicised use of FW for non-food applications such as chemicals, the consumer may learn to overcome any behaviour inertia and help establish the new supply chains we need to achieve for a future sustainable society.

A new European COST Action led by the York team will start at the end of the year 2012 (http://www.cost.eu/domains_actions/fa/Actions/TD1203) and will help us to move towards the new supply chains by bringing together industry and academia from a range of disciplines with technology and policy experts.

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## References

1 J. H. Clark, F. E. I. Deswarte and T. J. Farmer, *Biofuels, Bioprod. Biorefin.*, 2009, **3**, 72–90.
2 F. Cherubini, *Energy Convers. Manage.*, 2010, **51**, 1410–1421.
3 R. Luque, L. Herrero-Davila, J. M. Campelo, J. H. Clark, J. M. Hidalgo, D. Luna, J. M. Marinas and A. A. Romero, *Energy Environ. Sci.*, 2008, **1**, 542–564.
4 R. Dobbs, J. Oppenheim, F. Thompson, M. Brinkman and M. Zornes, *Resource Revolution: Meeting the World's Energy, Materials, Food and Water*, McKinsey & Company, 2011, http://www.mckinsey.com/features/resource_revolution, accessed 6 July 2012.
5 A. Schieber, F. C. Stintzing and R. Carle, *Trends Food Sci. Technol.*, 2001, **12**, 401–413.
6 WRAP, *2009 Gate Fee Report*, 2009, http://www.wrap.org.uk/downloads/W504GateFeesWEB.c640bae1.7613.pdf, accessed 23 March 2012.
7 WRAP, *2011 Gate Fee Report*, 2011, http://www.wrap.org.uk/recycling_industry/publications/wrap_gate_fees.html, accessed 23 March 2012.
8 United Nations Industrial Development Organization, *Food Wastes*, http://www.unido.org/fileadmin/import/32068_35FoodWastes, accessed 2 February 2012.
9 B. I. Service, *Preparatory Study on Food Waste across E.U.-27 for the European Commission*, 2010, p. 14, http://ec.europa.eu/environment/eussd/pdf/bio_foodwaste_report.pdf, accessed 6 July 2012.
10 G. T. Kroyer, *Lebensm.-Wiss. Technol.*, 1995, **28**, 547–552.
11 C. A. Zaror, *Food Control*, 1992, **3**, 190–199.
12 A. Segrè and S. Gaiani, in *Transforming Food Waste into a Resource*, RSC Publishing, Cambridge, 1st edn, 2012, ch. 2, pp. 42–96.
13 J. Parfitt, M. Barthel and S. Macnaughton, *Philos. Trans. R. Soc., B*, 2010, **365**, 3065–3081.
14 J. Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijk and A. Meybeck, *Global Food Losses and Food Waste. Extend, Causes and Prevention*, Food and Agriculture Organization of the United Nations, 2011.
15 A. Gomez, J. Zubizarreta, M. Rodrigues, C. Dopazo and N. Fueyo, *Resour., Conserv. Recycl.*, 2010, **54**, 972–984.
16 G. Laufenberg, B. Kunz and M. Nystroem, *Bioresour. Technol.*, 2003, **87**, 167–198.
17 Directive 1999/31/EC of 26th April 1999 on the landfill of waste.
18 C. M. Galanakis, *Trends Food Sci. Technol.*, 2012, **26**, 68–87.
19 World Economic Forum, *Driving Sustainable Consumption, Value Chain Waste*, 2010, http://www.members.wef

orum.org/pdf/sustainableconsumption, accessed 2 July 2012.

20 (*a*) Regulation 1831/2003 of the 22nd, September 2003, on additives for use in animal nutrition; (*b*) Directive 2002/32/EC of 7th, May 2002, on undesirable substances in animal feed; (*c*) Directive2008/38/EC of 5th, March 2008, establishing a list of intended uses of animal feedingstuffs for particular nutritional purposes.

21 (*a*) British Standard Association, *PAS 110:2010, Specification for Whole Digestate, Separated Liquor and Separated Fibre Derived from the Anaerobic Digestion of Source-segregated Biodegradable Materials*, BSI, February 2010; (*b*) British Standards Institution's Publicly Available Specification (PAS) 100, available from WRAP, http://www.wrap.org.uk.

22 http://www.stockfeed.co.nz/Poultry_Feed.html, accessed 28 August 2012.

23 http://www.vervaet.nl/content_uk.php?menu=112, accessed 28 August 2012.

24 http://www.treehugger.com/corporate-responsibility/are-local-incinerators-just-a-load-of-hot-air.html, accessed 28 August 2012.

25 (*a*) Oakdene Hollins, *Mapping Waste in the Food Industry for Defra and the Food and Drink Federation*, August 2008; (*b*) Oakdene Hollins, *Mapping Waste in the Food Industry for Defra and the Food and Drink Federation*, November 2010.

26 (*a*) Directive 2000/76/EC of 4th of December 2000 on the incineration of waste; (*b*) Directive 96/61/EC, 1996 of 24th September 1996 concerning the Integrated Pollution Prevention and Control (IPPC).

27 Directive (COM(2006) 232),of 22th of September 2006 on the Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC.

28 C. O. Tuck, E. Perez, I. T. Horvath, R. A. Sheldon and M. Poliakoff, *Science*, 2012, **337**, 695–699.

29 J. H. Litchfield, *Food Biotechnol.*, 1987, **1**, 29–57.

30 M. Poeschl, S. Ward and P. Owende, *Renewable Sustainable Energy Rev.*, 2010, **14**, 1782–1797.

31 *The food we waste*, Banbury, UK, WRAP, 2008, http://www.ns.is/ns/upload/files/pdf-skrar/matarskyrsla1.pdf, accessed 9 July 2012.

32 L. S. Kantor, K. Lipton, A. Manchester and V. Oliveira, Estimating and addressing America's food losses, *Food Rev. Int.*, 1997, **20**, 2–12.

33 A. Segrè and S. Gaiani, in *Transforming Food Waste into a Resource*, RSC Publishing, Cambridge, 1st edn, 2012, ch. 1, pp. 1–41.

34 A. A. Kader, *Acta Hortic.*, 2005, **682**, 2169–2175.

35 T. Garnett, *Fruit and Vegetables and UK Greenhouse Gas Emissions: Exploring the Relationship, UK: Food and Climate Research Network*, University of Surrey, 2006.

36 FDF, Environment Agency, WRAP, Eurostat, http://www.wrap.org.uk, accessed 28 August 2012.

37 ENDS Report 294, Environmental Data Services, 1999.

38 *United Kingdom food and drink processing mass balance: a Biffa award Programme on sustainable resource use*, C-Tech, 2004, http://www.massbalance.org/downloads/projectfiles/2182-00335.pdf, accessed 9 July 2012.

39 Understanding Food Waste – Research Summary, WR1204 Household Waste Prevention Evidence Review, l1m2-Executive Report, WRAP, 2009, http://randd.defra.gov.uk/Document.aspx?Document=WR1204_8365_FRP.pdf, accessed 5 September 2012.

40 P. Tucker, P. Douglas, *Understanding Household Waste Prevention Behaviour, Technical Report No. 1: A Critical Review of the Literature*, 2006.

41 *Lifestyle Scenarios: the Futures for Waste Composition*, Brook Lyndhurst, Summary report, March 2007, http://randd.defra.gov.uk/Document.aspx?Document=WR0104_7293_FRP.pdf, accessed 5 September 2012.

42 WRAP, Household food and drink waste in the UK, Banbury, 2009, http://www.wrap.org.uk/sites/files/wrap/Household%20food%20and%20drink%20waste%20in%20the%20UK%20-%20report.pdf, accessed 5 September 2012.

43 The Basel Convention on the Control of the Transboundary Movements of Hazardous Wastes and Their Disposal, adopted 22 March 1989, as subsequently amended.

44 Directive 75/442/EEC, OJ L194, of 15th July 1975 on waste pp. 39–41.

45 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, "Roadmap to a Resource Efficient Europe", COM (2011) 0571, final, 20 September 2011.

46 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the "Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan", COM (2008) 0397, final (25 June 2008). "Delivering More Sustainable Consumption and Production": http://ec.europa.eu/environment/consultations/sustainable.htm, accessed, 28 August 2012.

47 K. Biedenkopf, The Diffusion of EU Environmental Legislation: *Why Do Third Countries Voluntarily Follow EU Leadership?*, http://glogov.org/images/doc/Biedenkopf.pdf, accessed 28 August 2012.

48 Directive 2008/98/EC of 19 November 2008, OJ L312, Article 3(1), pp. 3–30.

49 Regulation (EC) No. 1069/2009 of the European Parliament and the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No. 1774/2002 (Animal By-Products Regulation), OJ L300, 14 November 2009, p. 1–33.

50 Directive 775/442/EEC on waste, OJ L194, 25 July 1975, pp. 39–41.

51 Recital 8, Directive 2008/98/EC.

52 Article 22, Directive 2008/98/EC.

53 Green Paper on the Management of Biowastes in the European Union, COM (2008) 811, final, 3 December 2008.

54 "Assessment of the Options to Improve the Management of Biowaste in the European Union", Arcadis, Commission Study Contract No. 07.0307/2008/517621ETU/G4. See http://ec.europa.eu/environment/waste/compost/pdf/ia_biowaste%20-%20final%20report.pdf, accessed 28 August 2012.

55 Article 29, Directive 2008/98/EC.

56 Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, OJ L182, 16 July 1999, pp. 1–19.

57 Article 28, Directive 2008/98/EC.

58 Pioneering development set to increase food recycling in the UK, Association for Organics Recycling, News 2012, http://www.organics-recycling.org.uk/page.php?article=2379&name=Pioneering+development+set+to+increase+food+waste+recycling+in+the+UK, accessed 29 August 2012.

59 (*a*) Environment Agency for England and Wales and the Northern Ireland Environment Agency, The Quality Protocol for the Production and Use of Quality Compost from Source-Segregated Biodegradable Waste, 1 August 2012; (*b*) *Anaerobic Digestate Quality Protocol – End of Waste Criteria for the Production and Use of Quality Outputs from Anaerobic Digestion of Source-segregated Waste*, Environment Agency for England and Wales and the Northern Ireland Environment Agency, 1 June 2010.

60 Waste Protocol Project, UKEnvironment Agency, http://www.environment-agency.gov.uk/business/topics/waste/32154.aspx, accessed 29 August 2012.

61 Communication from the Commission to the Council and the European Parliament on Future Steps in Bio-waste Management in the European Union, COM(2010) 235, final, 18 May 2010.

62 Regulation (EC) No. 1013/2006 of the European Parliament and the Council of 14 June 2006 on shipments of waste, OJ L190, 12 July 2006, pp. 1–98.

63 Annex III of Regulation (EC) No. 1013/2006, http://www.environment-agency.gov.uk/static/documents/Business/Consolidated_waste_list_ver5.pdf, accessed 28 August 2012.

64 Regulation (EC) No. 1907/2006 (as amended) of the European Parliament and the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).

65 (*a*) China – Order No. 7 "Provisions on the Environmental Administration of New Chemical Substances" 15 October 2010 (known as "China REACH") and Decree 591, "Regulations on the Safe Management of Hazardous Chemicals in China" (2011), effective 1 December 2011; (*b*) US – (i) the proposed reform of the Toxic Substances Control Act (TSCA) through a bill to amend it to ensure the risks from chemicals are adequately understood and managed (known as the Safe Chemicals Act 2011) (see Library of Congress, S.847 – as of 25 July 2012, before the Committee on Environment and Public Works); (ii) California's proposals for a 'green chemistry' law, more specifically Assembly Bill 1879 and Senate Bill 509; (iii) the Environmental Protection Agency's list of chemicals posing the greatest risk to health and the environment and a chemicals action plan to address those risks.

66 M. R. Kosseva, *Adv. Food Nutr. Res.*, 2009, **58**, 57–136.

67 Scottish Environment Protection Agency, National Best Practice Project Phase 1, *Used Cooking Oils*, 6 of September 2005.

68 Directive 2006/12/EC of 5 April 2006 on waste.

69 Household Food and Drink Waste in the UK, WRAP, UK, November 2009, http://www.wrap.org.uk/sites/files/wrap/Household%20food%20and%20drink%20waste%20in%20the%20UK%20-%20report.pdf, accessed 5 September 2012.

70 S. Djilas, J. Canadanovic-Brunet and G. Cetkovic, *Chem. Ind. Chem. Eng. Q.*, 2009, **15**, 191–202.

71 J. R. Dodson, A. J. Hunt, V. L. Budarin, A. S. Matharu and J. H. Clark, *RSC Adv.*, 2012, **1**, 523–530.

72 V. L. Budarin, P. S. Shuttleworth, J. R. Dodson, A. J. Hunt, B. Lanigan, R. Marriott, K. J. Milkowski, A. J. Wilson, S. W. Breeden, J. Fan, E. H. K. Sin and J. H. Clark, *Energy Environ. Sci.*, 2011, **4**, 471–479.

73 Sugar-based surfactant development gains ground, riding on the success of growing demand for APG, ICIS, May 2011, http://www.icis.com/Articles/2011/05/09/9457923/development-and-demand-for-sugar-based-surfactants-are-on-the.html, accessed, 17 July 2012.

74 C. Moran, L. Perez, R. Pons, A. Pinazo and M. R. Infante, in *Surfactants from Renewable Resource*, ed. M. Kjellin and I. Johansson, Wiley-Interscience, Weinheim, 1st edn, 1999, ch. 5, pp. 85–107.

75 M. R. Infante, personal communication.

76 Vedeqsa Inc., Cosmetic sector, http://www.lamirsa.com/vedeqsa_inc_productos_cosmetico.php?idioma=uk, accessed 17 July 2012.

77 P. M. Foley, A. Phimphachanh, E. S. Beach, J. B. Zimmerman and P. T. Anastas, *Green Chem.*, 2011, **13**, 321–325.

78 UK Environment Agency, Catering waste, 2012, http://www.environment-agency.gov.uk/netregs/62521.aspx, accessed 18 July 2012.

79 Sustainability Victoria, "*Waste wise catering toolkit; Small changes big difference*", 2005, Victoria State Goverment Australia.

80 (*a*) P. Gale "*Risk assessment: Use of composting and biogas treatment to dispose and of catering waste containing meat*", 2002, Department for environment, food and rural Affairs, UK Goverment; (*b*) *Greening Up Our Catering*, Monash University, Office of Environmental Sustainability, Australia, June 2009.

81 Courtesy of Mr Alistair Reed from Bioeconomy Consulting, http://bioeconomyconsulting.com, accessed 12 June 2012.

82 F. Rosillo-Calle, L. Pelkmans and A. Walter, *A Global Overview of Vegetable Oils, with Reference to Biodiesel, A Report for the IEA Bioenergy Task 40*, Imperial College London UK, VITO Belgium and UNICAMP Brazil, June 2009.

83 (*a*) F. D. Gunstone, in *Oleochemical Manufacture and Applications*, ed. F. D. Gunstone and R. J. Hamilton, Taylor & Francis, 2001, ch. 1, pp. 1–22; (*b*) K. Hill and

R. Höfer, in *Sustainable Solutions for Modern Economies*, ed. R. Höfer, RSC Publishing, Cambridge, 1st edn, 2009, ch. 9.1, pp. 167–228.

84 BP Statistical Review of World Energy, June 2012, http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2012.pdf, accessed 5 September 2012.

85 M. G. Kulkarni and A. K. Dalai, *Ind. Eng. Chem. Res.*, 2006, **45**, 2901–2913.

86 A. D. Stevens, *Waste vegetable oil recycling for biodiesel production in Essex and Cambridgeshire*, Waste WISE Overview Report, 2 May 2003.

87 D. G. Tiffany, *The Growth of Alternative Fuels: Minesota and U.S. Perspectives, Submitted for a Joint Conference of the University of Minnessota*, University of Padova and University of Bologna, Wisconsin, 2002.

88 (*a*) W. Jinfu, in Better Engines than Table, China Daily, 31 October 2011, http://www.chinadaily.com.cn/opinion/2011-10/31/content_14004907.htm, accessed on 1 September 2012; (*b*) D. Barboza, in Recycled Cooking Oil Found to Be Latest Hazard in China, The New York Times, 31 March 2010, http://www.nytimes.com/2010/04/01/world/asia/01shanghai.html?_r=1, accessed 1 September 2012.

89 *Landfill Directive Regulatory Guidance Note 14 (version 2.4) on the The Duty of Care and the European Waste Catalogue*, UK Environment Agency, 20 August 2007.

90 ADAS UK Ltd., *West Midlands Non-Food Crops Opportunities/Mapping Study*, 15th October 2007.

91 F.O. Licht's World Ethanol and Biofuels Report, weekly on-line, http://www.agra-net.com/portal2/showservice.jsp?servicename=as072#, accessed 12 August 2012.

92 J. Janaun and N. Ellis, *Renewable Sustainable Energy Rev.*, 2010, **14**, 1312–1320.

93 (*a*) M. J. Haas, *Fuel Process. Technol.*, 2005, **86**, 1087–1096; (*b*) A. L. Tiwari, A. Kumar and H. Raheman, *Biomass Bioenergy*, 2007, **31**, 569–575.

94 M. Cetinkaya and F. Karaosmanoglu, *Energy Fuels*, 2004, **18**, 1888–1895.

95 (*a*) R. Luque and J. H. Clark, *ChemCatChem*, 2011, **3**, 594–597; (*b*) J. A. Melero, J. Iglesias and G. Morales, *Green Chem.*, 2009, **11**, 1285–1308; (*c*) R. A. Arancon, H. R. Barros, A. M. Balu, C. Vargas and R. Luque, *Green Chem.*, 2011, **13**, 3162–3167.

96 (*a*) Q. Shu, Z. Nawaz, J. X. Gao, Y. H. Liao, Q. Zhang, D. Z. Wang and J. F. Wang, *Bioresour. Technol.*, 2010, **101**, 5374–5384; (*b*) W. Y. Lou, M. H. Zong and Z. Q. Duan, *Bioresour. Technol.*, 2008, **99**, 8752–8758; (*c*) M. G. Kulkarni, R. Gopinath, L. C. Meher and A. K. Dalai, *Green Chem.*, 2006, **8**, 1056–1062.

97 M. Kouzua and J. Hidaka, *Fuel*, 2012, **93**, 1–12.

98 (*a*) R. Jothiramalingam and M. Kuang Wang, *Ind. Eng. Chem. Res.*, 2009, **48**, 6162–6172; (*b*) A. P. Singh Chouhan and A. K. Sarma, *Renewable Sustainable Energy Rev.*, 2011, **15**, 4378–4399.

99 N. Viriya-Empikul, P. Krasae, W. Nualpaeng, B. Yoosuk and K. Faungnawakij, *Fuel*, 2012, **92**, 39–244.

100 B. Zhang, Y. Weng, H. Xu and Z. Mao, *Appl. Microbiol. Biotechnol.*, 2012, **93**, 61–70.

101 S. Kent Hoekman, A. Broch, C. Robbins, E. Ceniceros and M. Natarajan, *Renewable Sustainable Energy Rev.*, 2012, **16**, 143–169.

102 M. V. Ruiz-Méndez, S. Marmesat, A. Liotta and M. C. Dobarganes, *Grasas Aceites*, 2008, **59**, 45–50.

103 *Rancidity of Foods*, ed. J. C. Allen and R. J. Hamilton, Elsevier Applied Sciences, Amsterdam, The Netherlands, 2nd edn, 1989.

104 *RFA Report on YearTwo of the RTFO*, and verified Data from 2009/2010, Renewable Fuels Agency, UK Goverment, 2010.

105 N. Zyaykina, V. Van Hoed, W. De Greyt and R. Verhé, *Lipid Technol.*, 2009, **21**, 182–185.

106 P. Felizardo, M. J. Neiva Correia, I. Raposo, J. F. Mendes, R. Berkemeier and J. Moura Bordado, *Waste Management*, 2006, **26**, 487–494.

107 P. A. Eaves, J. J. Spadaro and E. A. Gastrock, *J. Am. Oil Chem. Soc.*, 1959, **36**, 230–234.

108 K. Narashimharao, A. Lee and K. Wilson, *J. Biobased Mater. Bioenergy*, 2007, **1**, 19–30.

109 http://www.novaol.it/novaol/cms/index.html, accessed, 23 August 2012.

110 List of hazardous wastes, EN Official Journal of the European Communities L 226/3, 6.9.2000, (2000/532/EC).

111 E. Ahn, M. Koncar, M. Mittelbach and R. Marr, *Sep. Sci. Technol.*, 1995, **30**, 2021–2033.

112 R. G. Cooper and J. M. Rusell, in *The New Zealand Meat Processing Industry, Present Effluent Treatment Practice and Future Directions, Proceedings of the 1992 Food Industry and Environmental Conference*, The Georgia Tech Research Institute, Atlanta, p. 95.

113 L. C. Meher, D. Vidya Sagar and S. N. Naik, *Renewable Sustainable Energy Rev.*, 2006, **10**, 248–268.

114 http://www.clearfleau.com/, accessed 12 August 2012.

115 M. R. Kosseva, C. A. Kent and D. R. Loyd, *Biochem. Eng. J.*, 2003, **15**, 125–130.

116 Diverting waste from landfill; Effectiveness of waste-management policies in the European Union, EEA Report No 7/2009, ISSN 1725–9177, European Environmental Agency, 2009, http://www.eea.europa.eu/publications/diverting-waste-from-landfill-effectiveness-of-waste-management-policies-in-the-european-union, accessed on 5 June 2012.

117 J. A. Siles Lopez, Q. Li and I. P. Thompson, *Crit. Rev. Biotechnol.*, 2010, **30**, 63–69.

118 FAOSTAT online database, Food and Agriculture Organization of the United Nations, http://faostat3.fao.org/home/index.html#VISUALIZE_BY_DOMAIN, accessed, 9 July 2012.

119 W. Zhou, W. Widmer and K. Grohmann, *Proc. Fla. State Hortic. Soc.*, 2008, **121**, 307–310.

120 V. Ferreira-Leitão and L. M. Fortes Gottschalk, *Waste Biomass Valorization*, 2010, **1**, 65–76.

121 K. Grohmann, R. Cameron, Y. Kim, W. Widmer and G. Luzio, *J. Chem. Technol. Biotechnol.*, 2012, DOI: 10.1002/jctb.3859.

122 V. A. Bampidis and P. H. Robinson, *Anim. Feed Sci. Technol.*, 2006, **128**, 175–217.

123 F. R. Marin, C. Soler-Rivas, O. Benavente-Garcia, J. Castillo and J. A. Perez-Alvarez, *Food Chem.*, 2007, **100**, 736–741.

124 E. Ma, Q. Cervera and G. M. M. Sanchez, *Bioresour. Technol.*, 1993, **44**, 61–63.

125 P. Ozmen and S. Aslanzadeh, *Master of Science*, University of Boras, 2009.

126 K. L. Kalra, H. S. Grewal and S. S. Kahlon, *MIRCEN J. Appl. Microbiol. Biotechnol.*, 1989, **5**, 321–326.

127 W. Widmer, W. Zhou and K. Grohmann, *Bioresour. Technol.*, 2010, **101**, 5242–5249.

128 Q. Li, J. A. Siles and I. A. Thompson, *Appl. Microbiol. Biotechnol.*, 2010, **88**, 671–678.

129 F. M. Kerton, in *Alternative Solvents for Green Chemistry*, RSC, London, 1st edn, 2009, ch. 5, pp. 97–117.

130 R. J. Braddock, in *Handbook of Citrus By-Products and Processing Technology*, Wiley-Interscience, Weinheim, 1999, ch. 12, p. 186.

131 D. A. Kimball, in *Citrus Processing, A Complete Guide*, Aspen Publishers, Gaithersburg, 2nd edn, 1999.

132 A. Farhat, A. S. Fabiano-Tixier, M. El Maataoui, J. F. Maingonnat, M. Romdhane and F. Chemat, *Food Chem.*, 2011, **125**, 255–261.

133 M. C. Ralet, E. Bonnin and J. F. Thibault, in *Polysaccharides and Polyamides in the Food Industry: Properties, Production, and Patents*, ed. A. Steinbüchel and S. Ki Rhee, Wiley-VCH, Weinheim, 2005, vol. 1, ch. 10, pp. 351–386.

134 (*a*) M. Pourbafrani, *Doctor of Philosophy*, Chalmers University of Technology, 2010; (*b*) M. Pourbafrani, G. Forgacs, I. S. Horvath, C. Niklasson and M. Taherzadeh, *Bioresour. Technol.*, 2010, **101**, 4246–4250.

135 A. M. Balu, V. Budarin, P. S. Shuttleworth, L. A. Pfaltzgraff, K. Waldron, R. Luque and J. H. Clark, *ChemSusChem*, 2012, **5**, 1694–1697.

136 M. S. Ladaniya, in *Citrus Fruit Biology, Technology and Evaluation*, Academic Press, 1st edn, 2008.

137 J. M. Gil Roig and F. Lambarra, MEDFROL – *Market and Trade Policies for Mediterranean Agriculture: The case of fruit/vegetable and olive oil*, CREDA-UPC-IRTA http://medfrol.maich.gr/documentation/view/reports/wp1-asr/Spain.pdf, accessed 24 July 2012.

138 Data communicated by the Ministry of Industry, Trade and New Technologies in Morocco.

139 S. Fazlollah-Ghoreishi, R. Pirmohammadi and A. Teimouri-Yansari, *J. Anim. Vet. Adv.*, 2007, **6**, 1074–1078.

140 A. G. Silva, R. C. Wanderley, A. F. Pedroso and G. Ashbell, *Anim. Feed Sci. Technol.*, 1997, **68**, 247–257.

141 http://citrotecno.com/noticia.php?id=15, accessed 12 July 2012.

142 F. M. Demirbas, M. Balat and H. Balat, *Energy Convers. Manage.*, 2011, **52**, 1815–1828.

143 J. F. Morton, in *Fruits of Warm Climates*, ed. Julia F. Morton, Cashew Apple, Miami, 1987, pp. 239–240.

144 A. Leny, in *Kenya's Drive to Revive Cashew Nut Industry*, 2011.

145 P. J. Martin, C. P. Topper, R. A. Bashiru, F. Boma, D. De Waal, H. C. Harries, L. J. Kasuga, N. Katinila, L. P. Kikoka, R. Lamboll, A. C. Maddison, A. E. Majule, P. A. Masawe, K. J. Millanzi, N. Q. Nathaniels, S. H. Shomari, M. E. Sijaona and T. Stathers, *Crop Prot.*, 1997, **16**, 5–14.

146 J. Philip, J. Buchweishaija, L. L. Mkayula and L. Ye, *J. Agric. Food Chem.*, 2007, **55**, 8870–8876.

147 O. O. Llomo, Y. M. M. Makame and L. L. Mkayula, *Bull. Chem. Soc. Ethiop.*, 2005, **19**, 9–16.

148 J. Mmongoyo, MSc Chemistry dissertation, University of Dar es Salaam, 2010.

149 W. Johnson, MSc Chemistry thesis, University of Dar es Salaam, 2003.

150 G. Bertogli in Tanzania's Cashew Value Chain: A diagnostic, United Nations Industrial Development Organization, Vienna, Austria, 2011, http://www.unido.org/fileadmin/user_media/MDGs/IVC_Diagnostic_Tool.pdf, accessed 11 July 2012.

151 H. P. Bhunia, G. B. Nando, A. Basak, S. Lenka and P. L. Nayak, *Eur. Polym. J.*, 1999, **35**, 1713–1722.

152 P. L. Nayak, *J. Macromol. Sci., Rev. Macromol. Chem. Phys.*, 2000, **40**, 1–21.

153 O. A. Attanasi, S. Berretta, C. Fiani, P. Filippone, G. Mele and R. Saladino, *Tetrahedron*, 2006, **62**, 6113–6120.

154 P. P. Kumar, *J. Agric. Food Chem.*, 2002, **50**, 4705.

155 S. H. Azam-Ali and E. C. Judge,ITDG Schumacher Centre for Technology and Development Bourton on Dunsmore, Rugby, Warwickshire, UK, "*Small-scale cashew nut processing*", 2001, FAO.

156 F. B. Hamad, E. B. Mubofu and Y. M. M. Makame, *Catal. Sci. Technol.*, 2011, **1**, 444–452.

157 L. L. Mkayula, Y. M. M. Makame and T. H. Matechi, *Tanz. J. Sci.*, 2004, **30**, 1–10.

158 H. P. Bhunia, G. B. Nando, A. Basak, S. Lenka and P. K. Nayak, *Eur. Polym. J.*, 1999, **35**, 1381–1391.

159 R. Ikeda, H. Tanaka, H. Uyama and S. Kobayashi, *Macromol. Rapid Commun.*, 2000, **21**, 496–499.

160 J. Mgaya, E. B. Mubofu and D. J. Cole-Hamilton, personal communication.

161 A. K. Miza, MSc Chemistry dissertation, University of Dar es Salaam, 2012.

162 P. Peungjitton, P. Sangvanich, S. Pornpakakul, A. Petsom and S. Roengsumran, *J. Surfactants Deterg.*, 2009, **12**, 85–89.

163 J. A. Mmongoyo, Q. A. Mgani, S. J. M. Mdachi, P. J. Pogorzelec and D. J. Cole-Hamilton, *Eur. J. Lipid Sci. Technol.*, 2012, **114**, 1183–1192.

164 G. C. J. Mwalongo, L. L. Mkayula, B. Dawson-Andoh, E. B. Mubofu, J. Shields and B. A. Mwingira, *Green Chem.*, 1999, **35**, 13–16.

165 D. Venmalar and H. D. Nagaveni, in *Evaluation of Copperised Cashew Nut Shell Liquid and Neem Oil as Wood Preservatives*, Institute of Wood Science and Technology, Bangalore, India, 2011.

166 G. John and P. Kumar Vemula, *Soft Matter*, 2006, **2**, 909–914.

167 P. K. Vemula and G. John, *Acc. Chem. Res.*, 2008, **41**, 769–782.

168 G. John, B. V. Shankar, S. R. Jadhav and P. K. Vemula, *Langmuir*, 2010, **26**, 17843–17851.

169 S. Mlowe, V. S. R. Rajasekhar Pullabhotla, E. B. Mubofu, F. N. Ngassapa, P. O'Brien and N. Revaprasadu, *Anacardic Acid Capped PbE (S, Se, and Te) Nanoparticles*, unpublished work.

170 Los residues urbanos y su problematica, UNED, http://www.uned.es/biblioteca/rsu/pagina1.htm, accessed 29 August 2012.

171 US Library of Congress, Crops, http://countrystudies.us/spain/58.htm, accessed 11 July 2012.

172 Seneca Green Catalysts, http://www.uco.es/senecagreencat/Quienes_somos.html, accessed 11 July 2012.

173 PDM Group, Tallow and rendered animal fat, News Report, 2008, http://www.pdm-group.co.uk/news/2008/tallow_rendered_animal_fats.html, accessed 11 July 2012.

174 (*a*) DIRECTIVE 2008/98/EC of the European Parliament and of the council of the 19 November 2008 on waste and repealing certain Directives; (*b*) UK Enviroment Agency, WRAP, March 2011.

175 S. Woodgate and J. van der Veen, *Biotechnol., Agron., Soc. Environ.*, 2004, **8**, 283–294.

176 (*a*) V. L. Budarin, J. H. Clark, B. Lanigan, P. Shuttleworth, S. W. Breeden, A. J. Wilson, D. J. Macquarrie, K. Milkowski, J. Jones, T. Bridgeman and A. Ross, *Bioresour. Technol.*, 2009, **100**, 6064–6067; (*b*) P. Shuttleworth, V. Budarin, M. Gronnow, J. H. Clark and R. Luque, *J. Nat. Gas Chem.*, 2012, **21**, 270–274.

177 T. Werpy and G. Petersen, in *Top Value Added Chemicals from Biomass*, U.S. Renewable Energy Laboratory (NREL), Oak Ridge, TN, USA, 2004(*a*) J. J. Bozell and G. R. Petersen, *Green Chem.*, 2010, **12**, 539–554.

178 (*a*) R. Garcia, M. Besson and P. Gallezot, *Appl. Catal., A*, 1995, **127**, 165–176; (*b*) S. Carrettin, P. McMorn, P. Johnston, K. Griffin, C. J. Keily and G. J. Hutchings, *Chem. Phys.*, 2003, **5**, 1329–1336.

179 (*a*) S. Cassel, C. Debaig, T. Benvegnu, P. Chaimbault, M. Lafosse, D. Plusquellec and P. Rollin, *Eur. J. Org. Chem.*, 2001, 875–896; (*b*) A. Corma, G. W. Huber, L. Sauvanaud and P. O'Connor, *J. Catal.*, 2008, **257**, 163–170.

180 (*a*) S. C. Kim, Y. H. Kim, H. Lee, D. Y. Yoon and B. K. Song, *J. Mol. Catal. B: Enzym.*, 2007, **49**, 75–78; (*b*) J. W. Yoo and Z. Mouloungui, *Stud. Surf. Sci. Catal.*, 2003, **146**, 757–760; (*c*) C. Vieville, J. W. Yoo, S. Pelet and Z. Mouloungui, *Catal. Lett.*, 1998, **56**, 245; (*d*) M. Aresta, A. Dibenedetto, F. Nocito and C. Pastore, *J. Mol. Catal. A: Chem.*, 2006, **257**, 149–153.

181 (*a*) F. Jerome and J. Barrault, *Eur. J. Lipid Sci. Technol.*, 2011, **113**, 118–134; (*b*) J. A. Melero, G. Vicente, M. Paniagua, G. Morales and P. Muñoz, *Bioresour. Technol.*, 2011, **103**, 141–151; (*c*) J. A. Melero, R. Van Grieken, G. Morales and M. Paniagua, *Energy Fuels*, 2007, **21**, 1782–1791.

182 (*a*) Prof. G. J. Suppes awarded with 2006 Presidential Green Chemistry Challenge Awards, http://www.epa.gov/greenchemistry/pubs/pgcc/winers/aa06.htmL, accessed 12 July 2012; (*b*) B. Delfort, I. Duran, A. Jaecker, T. Lacome, X. Montagne and F. Paille, *US pat.*, US6890364, 2005.

183 (*a*) G. Vicente, J. A. Melero, G. Morales, M. Paniagua and E. Martín, *Green Chem.*, 2010, **12**, 899–907; (*b*) C. X. A. da Silva, V. L. C. Gonçalves and C. J. A. Mota, *Green Chem.*, 2009, **11**, 38–41.

184 (*a*) D. Schreck, W. J. Kruper, R. D. Varjian, M. E. Jones, R. M. Campbell, K. Kearns, B. D. Hook, J. R. Briggs and J. G. Hippler, WO2006020234, 2006; (*b*) P. Krafft, C. Franck, I. De Andolenko and R. Veyrac, WO2007054505, 2007.

185 (*a*) Michael William Marshall Tuck, Simon Nicholas Tilley, Int. pat. WO2007010299, 2007; (*b*) Davy Process Technology Limited , UK pat. GB0514593, 2005.

186 S. S. Yazdani and R. Gonzalez, *Curr. Opin. Biotechnol.*, 2007, **18**, 213–219.

187 http://www.bioamber.com/bioamber/en/products/succinic_acid, accessed 5 September 2012.

188 (*a*) K. Murata, Y. Liu, M. Inaba and I. Takahara, *Energy Fuels*, 2010, **24**, 707–717; (*b*) G. W. Huber, P. O'Connor and A. Corma, *Appl. Catal., A*, 2007, **329**, 120–129.

189 R. Sotelo-Boyas, Y. Liu and T. Minowa, *Ind. Eng. Chem. Res.*, 2011, **50**, 2791–2799.

190 (*a*) I. Kubickova and D. Kubicka, *Waste Biomass Valorization*, 2010, **1**, 293–308; (*b*) Fortum OYJ, *US Pat.*, 7 232 935, 2007; (*c*) J. A. Melero, M. Clavero, G. Calleja, A. Garcia, R. Miravalles and T. Galindo, *Energy Fuels*, 2010, **24**, 707–717.

191 W. Charusiri, W. Yongchareon and T. Vitidsant, *Korean J. Chem. Eng.*, 2006, **23**, 349–355.

192 W. Charusiri and T. Vitidsant, *J. Energy*, 2003, **5**, 58–68.

193 W. Charusiri and T. Vitidsant, *Energy Fuels*, 2005, **19**, 1783–1789.

194 Fortum OYJ, *US Pat.*, 7 232 935, 2007.

195 H. Aatola, M. Larmi, T. Sarjovaara and S. Mikkonen, *Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOx, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine*, 2008, http://www.biofuelstp.eu/downloads/SAE_Study_Hydrotreated_Vegetable_Oil_HVO_as_a_Renewable_Diesel_Fuel.pdf, accessed 5 September 2012.

196 K. Sunde, A. Brekke and B. Solberg, *Energies*, 2011, **4**, 845–877.

197 (*a*) S. Berzegianni, A. Dimitriadis, A. Kalogianni and K. G. Knudsen, *Ind. Eng. Chem. Res.*, 2011, **50**, 3874–3879; (*b*) S. Berzegianni, A. Dimitriadis, A. Kalogianni and P. Pilavachi, *Bioresour. Technol.*, 2010, **101**, 6651–6656; (*c*) S. Berzegianni, A. Dimitriadis and A. Kalogianni, *Bioresour. Technol.*, 2010, **101**, 7658–7660.

198 (*a*) S. Boyde, *Green Chem.*, 2002, **4**, 293–307; (*b*) R. Garcés, E. Martínez-Force and J. J. Salas, *Grasas Aceites*, 2011, **62**, 21–28.

199 (*a*) J. Bentley, in *Oleochemical Manufacture and Applications*, ed. F. D. Gunstone and R. J. Hamilton, Sheffield Academic Press, 1st edn, 2001, ch. 6, pp. 164–193; (*b*) U. Konwar, N. Karak and M. Mandal, *Prog. Org. Coat.*, 2010, **68**, 265–273.

200 C. Herrmann, J. Hesselbach, R. Bock, A. Zein, G. Öhlschläger and T. Dettmer, *Clean: Soil, Air, Water*, 2007, **35**, 427–432.

201 F. D. Gunstone, *Lipid Technol.*, 2012, **24**, 96.

202 P. Nagendramma and S. Kaul, *Renewable Sustainable Energy Rev.*, 2012, **16**, 764–774.

203 Y. M. Shashidhara and S. R. Jayaram, *Tribol. Int.*, 2010, **43**, 1073–1081.

204 G. Mendoza, A. Igartua, B. Fernandez-Diaz, F. Urquiola, S. Vivanco and R. Arguizoniz, *Grasas Aceites*, 2011, **62**, 29–38.

205 A. A. Hayder, M. Y. Rosli, H. N. Abdurrahman and M. K. Nizam, *Int. J. Phys. Sci.*, 2011, **6**, 4695–4699.

206 L. Lazzeri, *Ind. Crops Prod.*, 2006, **24**, 280–291; (*a*) T. Regueira, L. Lugo, O. Fandiño, E. R. López and J. Fernández, *Green Chem.*, 2011, **13**, 1293–1302.

207 (*a*) L. Pop, C. Puşcaş, G. Bandur, G. Vlase and R. Nuţiu, *J. Am. Oil Chem. Soc.*, 2008, **85**, 71–76; (*b*) G. B. Bantchev, G. Biresaw, A. Mohamed and J. Moser, *Thermochim. Acta*, 2011, **513**, 94–99.

208 (*a*) F. D. Gunstone, J. Alander, S. Z. Erham, B. K. Sharama, T. A. McKeon, in *The Lipid Handbook with CD-ROM*, ed. F. D. Gunstone, J. L. Harwood and A. J. Dijkstra, CRC Press, 3rd edn, 2007, ch. 9, pp. 591–635; (*b*) L. A. Quinchia, M. A. Delgado, C. Valencia, J. M. Franco and C. Gallegos, *Ind. Crops Prod.*, 2010, **32**, 607–612.

209 A. Bono, O. P. Pin and C. P. Jiun, *J. Appl. Sci.*, 2010, **10**, 2508–2515.

210 S. Arumugam and G. Sriram, *Tribol. Trans.*, 2012, **55**, 438–445.

211 (*a*) V. Dossat, D. Combes and A. Marty, *J. Biotechnol.*, 2002, **97**, 117–124; (*b*) R. N. M. Kamil, S. Yusup and U. Rashid, *Fuel*, 2011, **90**, 2343–2345.

212 T. A. Isbell, *Grasas Aceites*, 2011, **62**, 8–20.

213 G. Booth, D. E. Delatte and S. F. Thames, *Ind. Crops Prod.*, 2007, **25**, 257–265.

214 E. Milchert and A. Smagowicz, *J. Am. Oil Chem. Soc.*, 2009, **86**, 1227–1233.

215 Y. Xia and R. C. Larock, *Green Chem.*, 2010, **12**, 1893–1909.

216 Bigeast, 2010, http://www.big-east.eu/index_gre.html, accessed 12 July 2012.

217 R. H. Wang, M. S. Shaarani, L. C. Godoy, M. Melikoglu, C. S. Vergara, A. Koutinas and C. Webb, *Enzyme Microb. Technol.*, 2010, **47**, 77–83.

218 M. P. Dorado, S. K. C. Lin, A. Koutinas, C. Du, R. Wang and C. Webb, *J. Biotechnol.*, 2009, **143**, 51–59.

219 R. L. Greasham, in *Biotechnology – Bioprocessing*, ed. H. J. Rehm, G. Reed, A. Puhler, P. Stadler and G. Stephanopoulos, VCH, New York, 2nd edn 1993, vol. 3, ch. 7.

220 W. Russ and R. Meyer-Pittroff, *Crit. Rev. Food Sci. Nutr.*, 2004, **44**, 57–62.

221 K. Waldron, C. Faulds and A. Smith, *Total Food: Exploiting Co-Products – Minimizing Waste, Total Food Proceedings*, Institute of Food Research, Norwich Research Park, 2004.

222 S. Bhushan, K. Kalia, M. Sharma, B. Singh and P. S. Ahuja, *Crit. Rev. Biotechnol.*, 2008, **28**, 285–296.

223 A. U. Mahmood, J. Greenman and A. H. Scragg, *Enzyme Microb. Technol.*, 1998, **22**, 130–137.

224 K. Sriroth, R. Chollakup, S. Chotineeranat, K. Piyachomkwan and C. G. Oates, *Bioresour. Technol.*, 2000, **71**, 63–69.

225 C. C. J. Leung, A. S. Y. Cheung, A. Y. Z. Zhang, K. F. Lam and C. S. K. Lin, *Biochem. Eng. J.*, 2012, **65**, 10–15.

226 C. Du, S. K. C. Lin, A. A. Koutinas, R. Wang, P. Dorado and C. Webb, *Bioresour. Technol.*, 2008, **99**, 8310–8315.

227 R. L. El Kossori, C. Villaume, E. El Boustani, Y. Sauvaire and L. Mejean, *Plant Foods Hum. Nutr.*, 1998, **52**, 263–270.

228 M. Del Valle, M. Camara and M. E. Torija, *J. Sci. Food Agric.*, 2006, **86**, 1232–1236.

229 M. S. Saunders, F. Takeda, R. P. Bates and F. Regulski, *Proc. Fla. State Hortic. Soc.*, 1982, **95**, 107–109.

230 M. E. Gomez, J. M. Igartuburu, E. Pando, F. R. Luis and G. Mourente, *J. Agric. Food Chem.*, 2004, **52**, 4791–4794.

231 D. Arapoglou, T. H. Varzakas, A. Vlyssides and C. Israilides, *Waste Management*, 2010, **30**, 1898–1902.

232 USDA, 2008.

233 A. J. Garcıa, M. B. Esteban, M. C. Marquez and P. Ramos, *Waste Management*, 2005, **25**, 780–787.

234 W. H. Kampen, in *Fermentation and Biochemical Engineering Handbook-Principles, Process Design and Equipment*, ed. H. C. Vogel and C. L. Todaro, Noyes Publications, New Jersey, USA, 2nd edn 1997, ch. 3, pp. 122–160.

235 Hong Kong: The Facts, Information Service Department, HKSAR, 2011.

236 Update on the Progress of the Key Initiatives in the "Policy Framework for the Management of Municipal Solid Waste (2005 – 2014)", Advisory Council on the Environment, 2011.

237 A. Park, *Waste Not. Time Magazine*, US edn, 10 September 2012.

238 CityU first invites the bioconversion of food waste into succinic acid, Apple Daily, Hong Kong, 6 September 2012, http://hk.apple.nextmedia.com/news/art/20120906/18009277?ref=fb.

239 Update on the Progress of the Key Initiatives in the "Policy Framework for the Management of Municipal Solid Waste (2005–2014)", Advisory Council on the Environment, 2011.

240 http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_ARTICLEMAIN&node_id=222&content_id=CNBP_030537&use_sec=true&sec_url_var=region1&__uuid=b65e7203-48ba-4527-8764-3fa6c6748b92.

241 L. Pfaltzgraff and J. Clark, in *Green Chemistry Newsletter*, Green Chemistry Network, York, UK, 2012, vol. 39.

242 S. K. C. Lin, C. Du, A. C. Blaga, M. Camarut, C. Webb, C. V. Stevens and W. Soetaert, *Green Chem.*, 2010, **12**, 666–671.

243 F. Cherubini, G. Jungmeier, M. Wellisch, T. Willke, I. Skiadas and R. Van Ree, *Biofuels, Bioprod. Biorefin.*, 2009, **3**, 534–546.

244 U.S. Food and Drug Administration Online Resource, http://www.fda.gov/Food/ScienceResearch/ResearchAreas/SafePracticesforFoodProcesses/ucm100250.htm, accessed 12 July 2012.

245 H. Peker, M. P. Srinivasan, J. M. Smith and B. J. McCoy, *AIChE J.*, 1992, **38**, 761–771.

246 B. Antizar-Ladislao and J. L. Turrion-Gomez, *Energies*, 2010, **3**, 194–205.
247 T. I. Georgieva and B. K. Ahring, *Biotechnol. J.*, 2007, **2**, 1547–1555.
248 W. Widmer, K. Grohmann, Ethanol from orange processing waste. National Meeting of Institute of Food Technologists/Food Expo. Presentation No. 140–09, 2007, Agricultural Research Service, http://www.ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=207114, accessed 12 July 2012.
249 G. A. Pinto, R. L. C. Giordano and R. C. Giordano, *Bioprocess Biosyst. Eng.*, 2009, **32**, 69–78.
250 G. Pollard, Catalysis in renewable feedstocks – A technology roadmap, The Department of Trade and Industry, Report number CR7656, BHR Solutions Project No 180 2421, 2005.
251 M. A. R. Meier, *Macromol. Chem. Phys.*, 2009, **210**, 1073–1079.
252 A. S. Carlsson, *Biochimie*, 2009, **91**, 665–670.
253 A. Wisniewski, V. R. Wiggers, E. L. Simionatto, H. F. Meier, A. A. C. Barros and L. A. S. Madureira, *Fuel*, 2010, **89**, 563–568.
254 F. Franek, O. Hohenwarter and H. Katinger, *Biotechnol. Prog.*, 2000, **16**, 688–692.
255 J. J. Fitzpatrick and U. O'Keeffe, *Process Biochem.*, 2001, **37**, 183–186.
256 M. S. Kwon, T. Dojima and E. Y. Park, *Biotechnol. Appl. Biochem.*, 2005, **42**, 1–7.
257 S. Ghorbel, N. Souissi, Y. Triki-Ellouz, L. Dufosse, F. Guerard and M. Nasri, *World J. Microbiol. Biotechnol.*, 2005, **21**, 33–38.
258 M. Koller, R. Bona, G. Braunegg, C. Hermann, P. Horvat, M. Kroutil, J. Martinz, J. Neto, L. Pereira and P. Varila, *Biomacromolecules*, 2005, **6**, 561–565.
259 B. Farges-Haddani, B. Tessier, S. Chenu, I. Chevalot, C. Harscoat, I. Marc, J. L. Goergen and A. Marc, *Process Biochem.*, 2006, **41**, 2297–2304.
260 J. A. Vazquez and M. A. Murado, *Enzyme Microb. Technol.*, 2008, **43**, 66–72.
261 M. Patel, M. Crank, V. Dornburg, B. Hermann, L. Roes, B. Husing, L. Overbeek, F. Terragni and E. Recchia, *The BREW project report: Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources*, European Commission's GROWTH Program (DG Research), Utrecht, 2006, http://www.chem.uu.nl/brew/BREW_Final_Report_September_2006.pdf, accessed 16 July 2012.
262 A. A. Koutinas, R. H. Wang and C. Webb, *Biofuels, Bioprod. Biorefin.*, 2007, **1**, 24–38.
263 A. A. Koutinas, C. Du, R. H. Wang and C. Webb, in *Production of Chemicals from Biomass, Introduction to Chemicals from Biomass*, ed. J. H. Clark and F. Deswarte, Wiley-VCH, 1st edn 2008, pp. 77–101.
264 K. I. Kim, W. K. Kim, D. K. Seo, I. S. Yoo, E. K. Kim and H. H. Yoon, *Appl. Biochem. Biotechnol.*, 2003, **107**, 637–647.
265 (*a*) G. Du, L. X. L. Chen and J. Yu, *J. Polym. Environ.*, 2004, **12**, 89–94; (*b*) O. Wolf, M. Crank, M. Patel, F. Marscheider-Weidemann, J. Schleich, B. Husing and G. Angerer, *Techno-economic Feasibility of Largescale Production of Bio-based Polymers in Europe*, Institute for Prospective Technological Studies, Technical Report Series, EUR 22103 EN, 2005.
266 D. K. Y. Solaiman, R. D. Ashby, T. A. Foglia and W. N. Marmer, *Appl. Microbiol. Biotechnol.*, 2006, **71**, 783–789.
267 R. Datta and M. Henry, *J. Chem. Technol. Biotechnol.*, 2006, **81**, 1119–1129.
268 R. A. J. Verlinden, D. J. Hill, M. A. Kenward, C. D. Williams and I. Radecka, *J. Appl. Microbiol.*, 2007, **102**, 1437–1449.
269 A. A. Koutinas, F. Malbranque, R. H. Wang, G. M. Campbell and C. Webb, *J. Agric. Food Chem.*, 2007, **55**, 1755–1761.
270 L. Y. Zhu, M. H. Zong and H. Wu, *Bioresour. Technol.*, 2008, **99**, 7881–7885.
271 Y. Y. Liu, Q. H. Wang, L. W. Chen, X. Q. Wang and J. Wang, *Adv. Mater. Res.*, 2010, **113–114**, 1080–1083.
272 X. Meng, J. Yang, X. Xu, L. Zhang, Q. Nie and M. Xian, *Renewable Energy*, 2009, **34**, 1–5.
273 A. A. Koutinas and S. Papanikolaou, in *Handbook of BioFuels Production – Processes and technologies*, ed. R. Luque, J. Campelo and J. H. Clark, Woodhead Publishing Limited, 2011, pp. 177–198.
274 A. S. Carlsson, *Biochimie*, 2009, **91**, 665–670.
275 M. G. Kulkarni and A. K. Dalai, *Ind. Eng. Chem. Res.*, 2006, **45**, 2901–2913.
276 C. C. J. Leung, A. S. Y. Cheung, A. Y. Z. Zhang, K. F. Lam and C. S. K. Lin, *Biochem. Eng. J.*, 2012, **65**, 10–15.
277 S. Chanprateep, *J. Biosci. Bioeng.*, 2010, **110**, 621–632.
278 E. Lakovou, A. Karagiannidis, D. Vlachos, A. Toka and A. Malamakis, *Waste Management*, 2010, **30**, 1860–1870.
279 Future supply chain 2016, Global Commerce Initiative, 2008, http://www.capgemini.com/insights-and-resources/by-publication/future_supply_chain_2016/, accessed 16 July 2012.
280 *Understanding Food Waste – Research Summary*, WR1204 Household Waste Evidence Review, WRAP, 2007.
281 J. Thøgersen and F. Ölander, *J. Econ. Psychol.*, 2002, **23**, 605–630.