Introduction

Human activity, at all stages and levels, relies on the use of natural resources as feedstock for technology and development. This gives rise to a highly symbiotic phenomenon involving the use of these common goods, which is often described as the three-point water–food–energy nexus (García and You, 2016). However, a more integrative definition for this phenomenon is suggested, i.e., the five-node water–energy–food–land–minerals resource nexus, which is discussed in Chapter 1. For simplicity, herein it is referred to as the resource nexus (RN). Although this concept is crucial for maintaining the demands and lifestyle of our society, the existing RN is unsustainable due to several interlinked global problems: increasing population, limited availability of food, natural resource depletion, increasing pollution and adverse climate change, social inequality, etc. Global population is expected to increase 40% by 2050, yet today, around 1 billion people struggle to have their daily sustenance and more than 1.2 billion still have no access to clean drinking water (García and You, 2016). Ironically, 1.3 billion tonnes of food is wasted every year (FAO, 2011a). With an increasing population, global food production will have to increase by at least 60% (OECD, 2013) while natural resources will become even more scarce. These facts illustrate the urgency in developing a well-distributed and sustainable RN management which allows the next generation to access water, energy and food accordingly to specific local needs.

A proximal quantitative distribution of specific resources (water, energy and food) within the nexus and supply network is illustrated in Figure 30.1. As per this diagram, our global food supply chain is highly water and energy intensive, consuming 30% of all produced energy and 70% of all distributed water. From the globally produced food directed for human and animal consumption, at least one-third (1.3 billion tonnes) is lost or wasted every year in the several stages of the food supply chain (production, transportation, processing, distribution and consumption) corresponding to a carbon footprint of 3.3 billion tonnes of CO$_2$ equivalent. The combination of food production and consumption by humans has been estimated to account for 20–30% of anthropogenic greenhouse gas (GHG) emissions, and food was found to account for 48–70% of a household’s impact on land and water consumption (Golden and Handfield, 2014). Food waste represents an economic loss of $750 billion (excluding fish and seafood) (FAO 2011a, 2013). In the UK alone, avoidable food waste (60% of total food waste) accounts for an annual economic loss of £11.8 billion (Bond et al., 2013).
While the traditional 3-point nexus is a good method for predicting the effect of actions within the increasingly complex area of water, food and energy, there is scope for it to be improved upon with the inclusion of minerals and land as discussed in Chapter 1. This change from a 3-point to a 5-point nexus allows for a much more complete and accurate depiction of the total effect actions taken on one part of the nexus will have on the whole nexus. Within the scope of food management and waste, mineral and land use are intrinsically important. The land used, not only in the growing of food crops, but also devoted to the processing and storage/treatment of the waste produced, influences the nexus as a whole. Plants uptake valuable minerals from the soil they are grown in, so accounting for these minerals throughout the supply chain is of paramount important to the continuation of good crop yield and quality from that plot of land. Commonly the inedible parts of the plant are left or tilled back in the soil they were grown in to allow for re-enrichment of the field with the minerals the plants absorbed for their growth.

Food waste can derive from all stages of the food supply chain. Although the contributions to food waste from developed and developing nations are very similar (630 and 670 million tonnes, respectively), their sources are very different. In developing countries food waste is mainly due to poor storage post-harvest. Moreover, economic and political issues and perfect environmental
conditions (warm and humid) for food spoilage contributes to the loss of edible food (FAO, 2013). On the other hand, in developed countries most of the wasted food comes from the post-consumer stage (considered avoidable and suitable for consumption), which reflects the consumerism culture present in these societies, along with the over restrictive food quality control and miscommunication between producers, retailers and consumers (FAO, 2013).

Where possible, policies and strategies for prevention and reduction of avoidable food waste should be encouraged coupled with redistribution of surplus food (FAO, 2013; Vandamme, Anthonis, and Dobbelaere, 2011). However, where unavoidable food waste is present as a result of primary and secondary processing (from farm to fork), then it should be considered as a rich source of biobased chemicals and materials in addition to bioenergy (composting, anaerobic digestion (AD), biomass burning and biofuels).

Utilisation of green chemistry practices and principles (also known as the 12 principles as listed below) as developed by Anastas and Warner (1998) coupled with the latest UN Sustainable Development Goals (United Nations, 2015) set in 2015 to protect the people and planet offers valorisation (value added) opportunities for unavoidable food supply waste other than landfill and/or composting/AD while sustaining the water–energy–food nexus (Figure 30.2). Green

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**Figure 30.2**  Linkage and contribution of food waste valorisation to the expanded nexus and Sustainable Development Goals (SDGs)
chemistry is an attitude that affords policy changes to improve chemical products and processes for the purpose of reducing their damage on human health as well as on the environment.

1. Waste prevention
2. Atom economy
3. Less hazardous chemical synthesis
4. Designing safer chemicals
5. Safer solvent and auxiliaries
6. Design for energy efficiency
7. Use of renewable feedstocks
8. Reduce Derivatives
9. Catalysis
10. Design for degradation
11. Real-time pollution prevention
12. Safer chemistry for accident prevention

According to principle 7, using unavoidable food waste as a renewable feedstock helps our society to move away from an oil-based to a bio-based economy, reducing environmental burden and turning what was once overlooked waste into an economically valuable renewable resource. Obviously, the complete success of a bioeconomy-driven chemical industry will also depend on the application of the other green chemistry principles.

Unavoidable food waste is widely distributed around the world in very high volumes (Figure 30.3), which gives it potential for exploitation at an industrial scale. In developed nations like in Europe and North America, the easier access to cutting-edge green technologies and high volumes of food waste (280–300 kg per capita yearly) (FAO, 2011a) opens up new opportunities for food waste valorisation. For instance, in the UK, where 15 million tonnes of avoidable food

![Figure 30.3 Potential global food waste volumes](Source: Matharu et al. (2016))

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Green chemistry

and drink waste is produced every year (Priestley, 2016), the outcome of biomass/biorefinery research centres allows for the development of new strategies and technologies for the use of food waste as a feedstock for biobased products. On the other hand, in developing nations like Brazil, India and South Africa, although the volume on unavoidable food waste is huge and diverse (see Figure 30.3), scientific research and development receives low support from the public sector and industry does not communicate with research institutions and universities, which then struggle to provide feasible technologies and opportunities to transform biomass into valuable products, instead of environment burden. It is estimated that 18% of anthropogenic CO₂ emissions come from the burning of biomass in the agricultural fields in developing countries (which are the main suppliers of food for the global market). The value of this burned biomass is equivalent to US$120 billion/ year if a valorisation approach was applied instead of open air burning (Internet, 2016b). Networking, collaboration and technology/knowledge transfer can have significant impact in helping biomass-rich countries to overcome political and economic barriers and engage academia and industry in the development of biorefineries and suitable technologies for production of bioenergy, biomaterials, and high-value chemicals from food waste.

Unavoidable food waste biorefineries

Like the concept of a traditional petroleum or oil refinery, the “biorefinery” concept is the fractionation of a natural resource into a variety of products including platform chemicals, energy and fuel, but using a renewable resource (biomass) instead of a non-renewable one (petroleum). It can be designed to be versatile regarding the variety or seasonality of the biomass used as input and to maximise outputs, not just in the procurement of product but also potential fuels. The following sections will illustrate three case studies of potential biorefineries for unavoidable food waste.

A case for bioenergy from food waste

The biorefinery concept can be applied to different sets of integrated technologies aiming to convert biomass into highly energetic molecules suitable for use as biogas or biofuels, i.e., bioenergy. As shown in Figure 30.1, 30% of all energy produced is directed to the production of food, hence from a circular bioeconomy point of view, it sounds reasonably sustainable that food waste can also be used to produce energy. Recently, new biotechnological approaches have applied renewable feedstock such as food waste to “feed” microorganisms used in the bioprocesses to produce bioenergy. For example:

Biohydrogen and biohythane

According to a review on biorefinery models using biotechnologies (Venkata Mohan et al., 2016), biogenic waste biomass (waste such as municipal solid waste or food waste that can produce “life”, i.e., microorganisms) could be used as feedstock for the production of a new generation of biogases, namely Biohydrogen (molecular hydrogen, H₂, produced by microorganisms) and Biohythane (a mixture of H₂ and CH₄). These biogases are produced during the acidogenesis stage within anaerobic digestion, whereby microorganisms “ferment” the biomass by means of various enzymatic reactions producing biohydrogen and/or biohythane, along with some minor volatiles compounds (such as fatty acids). In this process, minimal energy is lost usually as heat (only 3–5%). H₂ has a very high energy content (143 GJ/tonne), surpassing that of any other known fuel and is claimed to be 50% more efficient than gasoline (Waldron, 2007). Moreover,
hydrogen is considered the most environmentally friendly biofuel since it does not contain any carbon, hence, does not produce any greenhouse gases when burned.

To date, production of hydrogen has been heavily based on exploitation of non-renewable resources (natural gas, coal and oil), and electrolysis (which accounts for only 4% of total production due to the high costs involved). Besides being produced at low cost by cheap “bacterial cocktails”, biohydrogen produced by anaerobic digestion is probably the most cost-efficient method for production because of a high conversion rate, and waste biomass can be used as feedstock (Waldron, 2007). Currently, the EU has funded many research projects on developing green and economically feasible production of biohydrogen and, according to its market development, promising applications for novel hydrogen/hybrid vehicles and chemical storage of hydrogen (hydrogen fuel cells) have already started to appear (Internet, 2016a). Along with the EU, Japan, Taiwan and the US have already targeted biohydrogen as a high priority for providing hydrogen energy in the near future (Lai et al., 2011).

In our view, new biotechnological approaches that rely on the use of renewable biomass, such as the ones described in this case study, can potentially become a competitive alternative to the existing conventional methods of hydrogen production which are neither economically nor environmentally sustainable.

**Second generation bioethanol**

Although first generation bioethanol has been widely produced from maize and sugarcane (see Chapter 27 for more details), its production from food crops has been highly criticised due to ethical and socio-economic implications, for example, the food vs feed vs fuel debate. These are also influenced by other contemporary social phenomena, such as the increasing population, higher standards of living, changes in diet (higher consumption of animal derived-products requires more “food for feed”), fluctuant harvest yields and the dependence of agricultural systems on fossil energy (Vandamme, Anthonis, and Dobbelaere, 2011). As an alternative, second generation biorefineries that use residual lignocellulosic biomass as a feedstock (including unavoidable food waste), do not compete for food to produce biofuels. On the contrary, it complements the food supply chain by adding value to its co-products (Vandamme, Anthonis, and Dobbelaere, 2011).

The production of bioethanol from food waste biomass can take different forms and include different feedstocks. The “cascade” biorefinery approach (multiple process steps producing multiple products) has been applied to different types of food processing waste. For example, Tsukamoto et al. used orange peel waste (widely available in Brazil since it is a major producer of citrus waste, see Figure 30.3) as feedstock for the simultaneous production of nanocellulose and bioethanol (Tsukamoto, Durán, and Tasic, 2013) and cassava waste for producing bioethanol, biobutanol, and biogas, among other valuable chemicals (Zhang et al., 2016). Rice straw is a major unavoidable food waste in Asia, and Abraham et al. have reviewed the potential of rice straw-based biorefineries discussing the availability and feasibility of these models for the production of bioethanol in Asian countries (Abraham et al., 2016). Third generation biofuels are now being developed which use non-land feedstocks such as algae. (Ansari et al., 2015). It is expected that future biorefineries for biofuel production, especially bioethanol, will rely on the use of non-food grade biomass such as unavoidable food waste, making better use of the resource nexus.

**A case for vegetable proteins from food waste**

The increasing demand for non-animal, vegetable derived proteins within the food supply chain has seen a marked effect on the industry. This demand is not only caused by the growing
popularity of vegetarian/vegan diets, but also the general increase in global population. European legislation prohibits the use of animal protein in animal feed intended for human consumption, leading to an increased demand for vegetable protein in the meat/dairy industry as well. An increase of 50% with regard to the vegetable protein needed in animal feed has been observed within the last 10 years, and this value will continue to increase in future years (WRAP and French-Brooks, 2012).

Martin and Danielsson (2016) modelled the effect of reducing animal protein consumption from 51% (2010) to 25% by 2050 while replacing with proteins sourced from vegetables, on greenhouse gas emissions; a reduction of 42% in emissions by 2050 is predicted. Following the same protein-reduction plan an estimated 30% reduction in land usage and 20% in water usage by 2050 is proposed. Furthermore, Martin and Danielsson explored the effect of reduction in food waste on GHG emissions, land usage and water usage, modelling food waste reduction in retail and consumer sectors by 60% (2030) and 85% (2050) with a corresponding reduction in food production needed (as there would be less food going to waste) with a 12% and 16% reduction in 2030 and 2050, respectively. Their study assumed that all food waste at the retail and consumer sector was avoidable and on this basis estimated a 5% reduction in GHG emissions along with a 7% reduction in land use and a 10% reduction in water consumption would be achievable by 2050. However, their study did not consider the potential for reduction and re-utilisation of unavoidable food waste during industrial processing. This is, by far, the easiest stage at which to implement food waste valorisation methods as the waste is highly controlled, categorised, and homogeneous unlike household food waste. If the food waste stream was valorised into ingredients intended for re-use in food then this would aid reduction in GHG emissions, land, and water usage.

Potatoes are a source of protein which have attracted interest in recent years, partly because of their large global production (385 million tonnes in 2014) (FAO, 2014) as well as their relatively large percentage waste (across the entire supply chain roughly 53–55% for fresh potatoes and 41–46% for processed potatoes) (WRAP and French-Brooks, 2012). The reasons for the surprisingly high percentage waste for potatoes is a matter of several different factors including health and safety regulations as well as consumer demand for aesthetically acceptable products (Willersinn et al., 2015). For example, Table 30.1 shows broad ranging amounts of waste for agricultural production, wholesalers, retailers and household in Switzerland (Willersinn et al., 2015), while Table 30.2 focusses on food supply chain wastes from farm to fork (WRAP and French-Brooks, 2012).

Both Tables 30.1 and 30.2 do not consider over-production. Some years the amount of potatoes produced exceeds need. It has been stated that upwards of 9% of potatoes produced are fed to animals due to the production exceeding the needs of the county (Willersinn et al., 2015).

### Table 30.1 Potato wastage in Switzerland

<table>
<thead>
<tr>
<th>Agricultural production (%)</th>
<th>Wholesalers (%)</th>
<th>Retailers (%)</th>
<th>Household (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15–24</td>
<td>12–24</td>
<td>1–3</td>
<td>15</td>
</tr>
</tbody>
</table>

### Table 30.2 Potato wastage from farm to fork

<table>
<thead>
<tr>
<th>Agricultural production</th>
<th>Wholesalers</th>
<th>Retailers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field loss (%)</td>
<td>Grading loss (%)</td>
<td>Storage loss (%)</td>
</tr>
<tr>
<td>1–2</td>
<td>3–13</td>
<td>3–5</td>
</tr>
</tbody>
</table>

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Potatoes are a rich source of starch. Roughly 19% of the potato by weight is starch and starch is used for a variety of industrial purposes including, paper manufacture, as a food additive and in pet and animal food. Potato processing for starch is water intensive and while the starch-extraction methodology has been optimised, there is still potential for improvements. For example, the “waste” water produced during starch extraction is rich in proteins. Approximately, 2% by weight of potato tubers are protein and during the rasping/washing process 85% of that protein is extracted into the potato fruit juice (PFJ) meaning that protein extraction is being carried out incidentally within the starch refining process.

Potato protein can be relatively easily recovered using a range of precipitation methods depending on the desired properties of the final protein, these precipitation methods range from simple heat, through to acid-assisted and use of ammonium sulfate which is commonly used as a fertiliser allowing for the re-use of the water in irrigation of the fields used to grow potatoes. Potato protein is viewed to be of very high quality when compared to proteins sourced from other vegetable sources due to its relatively high concentration of the essential amino acid lysine which is usually in low concentration in other vegetable proteins (Waglay, Karbourne, and Alli, 2014).

The market for vegetable proteins is already well established and experiencing a rapid growth in recent years. Potato protein specifically is used in many areas of food production usually as an additive in products ranging from salad dressing, mayonnaise, ice cream, yogurt to high end uses such as a processing agent in wine manufacture. Potato protein has been estimated to have a market value of €0.8/kg if utilised for animal feed and €3/kg if used within the human food market, which is comparable if not above that for proteins sourced from other vegetables/cereals, and is approaching the price for animal-based proteins, as to be expected with the rapid growth in need of vegetable proteins within the last few years (Mulder et al., 2016).

A case for tropical fruit waste valorisation

The UK Foresight Project on Global Food and Farming Futures (Parfitt and Barthel, 2011) has stated that:

The four BRIC (Brazil, Russia, India, China) countries combined account for over a quarter of the world’s land area and more than 40% of the world’s population. The economic emergence of the BRICs will have unpredictable consequences on the global environment and patterns for food supply to 2050. Over recent years BRIC countries have been the major influence on changing food production and consumption patterns in the world economy.

Interestingly, foodstuffs from the four BRIC countries are becoming increasingly popular as exported crops as well as increasing in production due to the population growth within these areas. The three tropical countries from BRIC (Brazil, India and China) are major global producers of fresh and processed fruits (FAO, 2011b), and tropical fruits are experiencing a sharp increase in popularity in the western world, and a lot of the fruit is processed before reaching consumers, so along with the rise in exported exotic foods there is a corresponding increase in waste streams associated with these foods (van der Goot et al., 2016). Mango is a prime example, with production seeing a fourfold increase in the last 50 years to a global production of just under 44 million tonnes in 2013, assuming all mango production is processed, with a waste of 16–19% from peel only this would represent a potential waste of roughly 7–8 million tonnes yearly (Parfitt and Barthel, 2011).
Banana is the most consumed tropical fruit and the fourth most produced crop in the world (Ayala-Zavala et al., 2011). Production of bananas reached over 107 million tonnes in 2013 and has been experiencing a steady increase in production volumes over the last 50 years (FAO, 2014). Wastage as a result of processing exotic fruits can create as much as 60% waste by weight (Silva et al., 2014), representing a high volume resource of biobased chemicals and materials, for example, dietary fibres, pectin, colourants, pigments and anti-oxidants (Ayala-Zavala et al., 2011).

Dietary fibre, essentially a mixture of the polysaccharides present in the cell walls, is commonly used as a low-calorie bulking agent in foods, as a rheology (texture) modifier, a clouding agent as well as a binding agent. Dietary fibre is commonly found in relatively large amounts within fruit, but certain exotic fruit such as mango and guava, have bi-products (peel and seeds) that have a very high quantity of dietary fibre (78% and 61.4% respectively) (Ayala-Zavala et al., 2011).

Pectin is commonly used industrially as a thickener for preserves, and it is increasing in demand year by year. The global market for pectin reached US $ 850 million in 2013 and has an average price of roughly US $ 14/kg (Ciriminna et al., 2015). Many studies have shown that pectin can be extracted successfully from tropical fruit waste, with yields up to 20% being reported (Sirisakulwat et al., 2010). Given the large volumes of waste present in exotic fruit production and the relatively high-value bulk products that can be isolated from them, it is easy to see the attraction of valorising these waste streams into commercial products such as pectin and dietary fibres.

Betalains, carotenoids, anthocyanins and flavonoids are all present in abundance within tropical fruit waste streams (Parfitt and Barthel, 2011; Ayala-Zavala et al., 2011). Along with being natural pigments, these compounds also have anti-oxidant properties making them well suited for use in the food industry (Houlton, 2016), this, along with a growing trend of consumers demanding natural additive in their food, make flavour, fragrance and colour specific compounds from natural sources a rapidly expanding industrial endeavour.

Conclusions and perspectives
Intelligent resource recovery from unavoidable food supply chain wastes to yield biobased chemicals, materials and bioenergy is paramount and commensurate with the needs of a sustainable 21st century. As a global nation, we have unsustainable production and consumption patterns as exemplified by the 1.3 billion tonnes of food waste being generated annually, which have a negative impact on the water–energy–food nexus. Making better use of resources (doing more with less) destined for landfill and/or incineration mitigates climate change and improves efficiency of both land and water usage.

The adoption of a 5-point nexus approach comprising water, energy, food, minerals and land, is a positive step forward within sustainable food production and consumption, allowing for the exploration of how changing one part of the nexus will affect the rest as a whole. This is invaluable from a resource saving and waste reducing standpoint due to the fact that it takes into account the non-linearity of the problem as a whole. For example, re-utilisation of edible food back into the supply chain not only reduces waste, but also alleviates the pressure to produce as much food initially which will have a knock-on effect in the land, water and energy sectors.

Application of efficient, green and sustainable chemical technologies for the processing of unavoidable food supply chains into high-value molecules for (re)-nutrition (for example proteins, anti-oxidants, pectins, etc.) will maximise the inherent chemical potential, structure and
function provided by Nature. For example, modern green technologies such as pressurised fluid extraction, supercritical fluid extraction, ultrasound assisted extraction and microwave assisted extraction can be used to extract valuable chemicals from food waste.

Moreover, the concept of responsible and convergent innovation (which considers the environmental, economic and health impacts of technological innovation) is becoming a must for the industrial sector, especially for the foodstuff processing industry, which will inevitably have to adapt their processes to more efficient and intensive ones, as well as move from the production of global-driven pure and refined ingredients to more complex and specialised functional food fractions containing mixed composition with high bio-functional value (van der Goot et al., 2016).

Additionally, policy targets to reduce consumption of animal protein would decrease environmental burden of food waste, however, there might still not be enough to balance out greenhouse gases emissions, and land and water usage in Europe (Martin and Danielsson, 2016). Furthermore, the growing of agroecological production of food, which promotes the creation of short food supply chains, biodiversity care and local agriculture, has questioned the conventional food production model, considering it unsustainable and incapable of achieving the Sustainable Development Goals. Therefore, policymakers need to address food supply chains problems by acknowledging the lack of communication among food producers, retailers, and consumers as a political and economic challenge to be overcome.

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References


