Article:

Sherwood, James orcid.org/0000-0001-5431-2032 (2020) The significance of biomass in a circular economy. BIORESOURCE TECHNOLOGY. 122755. ISSN 0960-8524

https://doi.org/10.1016/j.biortech.2020.122755

Review

The significance of biomass in a circular economy

James Sherwood

PII: S0960-8524(20)30024-9
DOI: https://doi.org/10.1016/j.biortech.2020.122755
Reference: BITE 122755

To appear in: *Bioresource Technology*

Received Date: 21 November 2019
Revised Date: 2 January 2020
Accepted Date: 3 January 2020

Please cite this article as: Sherwood, J., The significance of biomass in a circular economy, *Bioresource Technology* (2020), doi: https://doi.org/10.1016/j.biortech.2020.122755

The significance of biomass in a circular economy

James Sherwood[a]

[a]Green Chemistry Centre of Excellence, Department of Chemistry, University of York, Heslington, UK, YO10 5DD. Email: james.sherwood@york.ac.uk

Abstract

A circular economy relies on the value of resources being maximised indefinitely, requiring that virtually no unrecoverable waste occurs. Biomass is highly significant in a circular economy in terms of material products and the provision of energy. To establish a circular bioeconomy, the practical implications of biomass use need to be appreciated by stakeholders throughout the value chain, from product design to waste management. This review addresses sustainable biomass production and its function as a feedstock from a European perspective. Anaerobic digestion of food waste is used as a case study to represent appropriate waste treatments. Crucial challenges are (1) Uncoupling the petrochemical industry and biomass production with renewable fertilisers; (2) Providing plentiful biomass for bio-based products by prioritising other renewable sources of energy; (3) Waste arising from food and agriculture must be minimised and returned to the economy; (4) Enhancing stakeholder cooperation across value chains.

Keywords

Circular economy; bioeconomy; biomass; food waste; anaerobic digestion.

1. Introduction

A circular economy is defined by two governing principles: maximise the service provided by the materials embedded in products; and minimise the loss of service with time (Clark et al., 2016). Unsustainable resource consumption, product redundancy, waste and pollution need to be avoided. Policies promoting renewable energy and bio-based products have elevated the importance of biomass feedstocks in the European Union (EU). This helps create the conditions that enable a circular economy through the use of renewable materials. China also has strong circular economy ambitions (albeit via different policies). The incentivisation of “eco-parks” exemplifies the Chinese emphasis on industrial development (Matthews and Tan, 2016). This is a form of industrial symbiosis, where the waste of one operation (material or energy) is the input of another.

It is crucial to consider all material flows within an entire value chain to successfully implement a circular economy. One fundamental principle is that the materials from which a product is made has an impact on suitable end-of-life waste management options. The Ellen MacArthur Foundation represented this by introducing twin cycles of technology and biology in their iconic “butterfly” infographic that illustrates recirculating material flows in a circular economy (adapted as Figure 1a). Although many end-of-life practices are shared between the two, it is for the most part helpful to emphasise salvaging rare metals on one hand and composting and anaerobic digestion on the other. The latter constitute the restoration cycle considered unique to biomass; whereby waste biomass contributes to the formation of new biomass. This can be thought of in mass-balance terms when carbon dioxide is the start and end of the biomass lifecycle, but also compost and the digestate of anaerobic digestion can be used as soil conditioners to improve biomass production. It can be argued that there are other restorative material flows that return a resource to nature. The global nitrogen cycle operates on a comparable timespan to biomass restoration, while some minerals (e.g. limestone and dolomite) are also reformed but at a much slower rate. The smaller cycles on Figure 1a (e.g. repair, recycling) retain more value and circumvent production, transport, and other time and energy consuming activities. The circular material flows differentiates Figure 1a from the waste hierarchy that influenced it (Figure 1b).

The term “circular bioeconomy” has been adopted to describe the integration of bioeconomy initiatives into the newer policy emphasis on circularity. An OECD paper highlights some confusion in policies that need to be resolved to fully integrate the two philosophies (Philp and Winickoff, 2018). For instance, the presumption that only low value waste is fit for biorefineries is impeding the development of a bio-based economy and unnecessarily restricting the potential for retrieving maximum value from wastes.

Fundamentally it is not disputed that a circular economy is an international cooperation of all stakeholders committed to eliminating waste without value. Aspiring to, and proactively working towards, a highly productive society without waste is undoubtedly beneficial. Yet the idealised concept of a circular economy has been criticised by likening it to a perpetual motion machine, an unattainable utopian idea (Cullen, 2017). Whether or not a truly circular economy is realised, if this objective helps reduce waste and limit the consumption of finite resources it must be accepted as a useful tool to promote positive action. The same argument can be made about sustainability as a concept. Practices described as “more sustainable” are not sustainable in themselves but represent an improvement that can be measured against agreed criteria. The underlying aim of any circular economy action is to reduce waste, making the ultimate goal less ambiguous than for a ‘sustainable’ practice, but the means of achieving circularity are more open to interpretation than sustainability actions. This is reflected by European policies. For example, the revised Renewable Energy Directive of 2018 precisely defines sustainability requirements but avoids the ambiguity of what sustainable actually means (EU, 2018a). Meanwhile, amendments to the Waste Directive represent the primary circular economy initiative published by the EU, defining acceptable upper limits of waste (EU, 2018b, 2018c), but is not prescriptive in the approaches needed.

1.1 Feedstocks

The choice of appropriate feedstocks is a particular concern if resources are small compared to demand. Perceived resource shortages (Supanchaiyamat and Hunt, 2019), are debated for many elements and minerals, including cobalt and indium. Often a product can be made from different materials and scarce resources avoided. Furniture can be made from wood, metal (steel or aluminium), natural or synthetic textiles, partially from glass, or a combination of these abundant materials. There are more acute concerns for the basis of electronics and electrical equipment. Successful disruptive technologies render their predecessor redundant with time, fixing demand for specific resources. The substitution of one metal for another is surprisingly difficult given electronics have developed to a point where complex combinations of many materials are required to provide the service required (Graedel et al., 2015). Only a major re-evaluation and restructuring of the infrastructure surrounding the electronics industry (and many other sectors) will prevent the complete depletion of the economically viable reserves of many elements. Examples might include carbon-based replacements for the transparent and conductive indium-tin oxide thin films used in touchscreen electronics (Wassei and Kaner, 2010). Sodium ion batteries do not require cobalt or lithium-based anodes and the cathode can be made of biomass derived carbons (Dou et al., 2017). As these technologies mature, more effective recycling operations will be required to adapt to new materials in waste streams (Velázquez-Martínez et al., 2019).

The EU critical raw materials list prioritises concerns over the longevity of essential resources. As represented in Figure 2, the resources with the greatest supply risk are metals (EU, 2017). The only biomass included is rubber, with specific uses in elastomers. Phosphate demand is linked to biomass production due to its major market as a fertiliser (see Section 2.1). Rubber and phosphate are amongst the lowest concern within the critical raw materials, yet the fact they are on this list indicates proactive measures to protect and preserve these resources are needed.

In addition to metals and other minerals, crude oil and natural gas are vitally important resources at present. Approximately 90% of petroleum stock is used as fuel, and the remainder is separated and processed into base chemicals, and materials like bitumen (asphalt) for construction (Morrison and Golden, 2015). The large market commodities produced by oil refining are the foundation of the chemical sector. Base chemicals (syngas, olefinic and aromatic hydrocarbons) are needed to make the majority of the organic products that consumers and businesses demand. Within a relatively short time period our dependence on fossil fuels must be phased out for environmental protection reasons. Thus, the substitution of petroleum must happen earlier than if it were only decided by its finite quantity. However, it is this non-renewable nature of coal, crude oil and natural gas that demands once utilised it remains in use virtually indefinitely to fulfil a circular economy. This is certainly not the case at present, especially for fuels. Despite this, countries such as the UK, Germany, and France persist in subsidies for fossil fuels, although more money does go towards the provision of renewable energy (EC, 2019). Petrochemicals at least have the possibility of being reused and recycled, given product design and waste management infrastructure are adequate. Levi and Cullen (2018) have analysed the global chemical production from fossil derived sources for the year 2013. Figure 3 shows the quantity of feedstocks (left) and what products they are converted into (right), with the height of each section representative of the relative mass of each substance. Nitrogen fertiliser (275 million tonnes, MT) and plastics (222 MT) are the largest outputs. Accordingly, these markets require the greatest attention in a circular economy, not necessarily just for the risk of exhausting the feedstock but because of the scale of waste created.

Biomass is the alternative organic feedstock to crude oil and natural gas. Biomass is a general term applicable to all plant and animal derived materials. Plant-based biomass is cultivated to make food and animal feed, bio-based products, and burnt for renewable energy. The United Nations Food and Agriculture Organization recorded over 9 billion tonnes of crops produced in 2017, and over 5 billion cubic metres of forestry products (timber and boards, excluding paper and pulp) (FAOSTAT, 2019). The composition of domestic biomass production in the EU is 12% wood for timber, 4% wood for fuel, 40% food crops, 12% crop residues and 32% fodder (animal feed) (Eurostat, 2018).

The major structural components of terrestrial biomass are cellulose, hemicellulose, and lignin. These are the inedible polymers that form wood and straw for example. Edible portions of plants can include starch, free sugars, protein, and vegetable oils (triglycerides). Some crops also provide a source of essential oils and other secondary metabolites of high value. The processes of separating and valorising biomass are the function of a biorefinery (analogous to an oil refinery). A waste-free biorefinery utilises all the available biomass components to make products and energy, consistent with the fundamental objective of a circular economy.

It is inconceivable that biomass will be capable of replacing crude oil and natural gas for the production of like-for-like chemicals and materials at the current scale and cost. Instead, different substances become accessible from biomass at more attractive prices because they incorporate the chemical functionality already present in biomass. There is no reason to reduce oxygenated biomass to hydrocarbons only to reintroduce oxygen atoms just to re-join the existing chemical industry infrastructure (Farmer and Mascal, 2015). It is foreseeable that a greater degree of petrochemical displacement by bio-based products will introduce different types of plastics, such as polyethylene furanoate to replace polyethylene terephthalate (PET) (Zhang and Deng, 2015). Similarly, *d*-limonene (Ciriminna et al., 2014) and Cyrene™ (Camp, 2018) are bio-privileged alternatives to petrochemical solvents. Other chemical sectors have a longer tradition of incorporating natural products, such as cosmetic and home care formulations, lubricants, and surfactants. Demand for biomass feedstocks, like any other, can be managed by implementing efficient reuse and recycling strategies for the products made from them. This is how a circular bioeconomy paves the way for the substitution of unsustainable feedstocks with biomass. Without extending the longevity of biomass thorough cascaded uses, it will be impossible to satisfy demand for both materials and energy in a sustainable way.

2. Sustainable biomass

A circular bioeconomy requires sustainable biomass as a guarantee that the restoration cycle is completed and can be completed indefinitely. Certification schemes are used to validate the sustainability of biomass, a requirement of the revised EU renewable energy directive (EU, 2018a), but which represents a small proportion of all biomass crops (i.e. 4% of all sugarcane cropland) (Bonsucro, 2019). There are wide ranging considerations when determining whether biomass is sustainable across social, economic, and environmental domains. The major certification agencies all give environmental sustainability the most significant weighting if measured in terms of the number of principles that must be adhered to. Nevertheless, all aspects of sustainability must be followed in these schemes to verify any negative impact on food production, biodiversity, human/worker rights, pollution, etc. is limited and stable.

To enact a circular bioeconomy, sustainable biomass feedstocks must be produced in the necessary quantities for the foreseeable future, yet certification schemes do not demand enough of operators to ensure longevity to their biomass production. It is true that certification can be revoked if unsustainable practices are discovered, but accreditation is mostly based on current practices and not long terms goals. The duration of a sustainable biomass production certificate can be just 1 year (ISCC, 2019), up to 5 years for forestry (FSC, 2019). A stronger obligation for biomass producers to sustainably manage their land use for a much longer period of time is important in a circular bioeconomy. A business model that maintains sustainable production is ultimately profitable for a longer time in the face of new legislative actions and the preservation of the environment necessary to continue producing high yielding biomass. However, this responsibility should be recognised formally and be aligned with policies for a circular bioeconomy, which at present are not distinct in themselves but are found in the overlap of circular economy and bioeconomy strategies. The actions stated in the EU bioeconomy strategy (updated in 2018) are more concerned with promoting, supporting and monitoring a bioeconomy than establishing the conditions to sustain it (EC, 2018). There is no legislated limit to the amount of biomass that can be considered sustainable but it is clear that in the future more intensive farming and less food waste must go hand-in-hand with greater utilisation of whole biomass for additional non-food purposes (Philp and Winickoff, 2018). The quality of soil is a major concern, as is the competing energy market. These considerations are now discussed in more detail.

2.1 Fertiliser

Producing biomass incurs energy and material costs. Fertilisers based on nitrogen, phosphorus and potassium, and the energy needed to make them, are very important considerations in a circular economy because of the magnitude of this industry, and its vital importance to the bioeconomy in order to produce high yielding biomass crops. A significant 1% of global energy demand is consumed making nitrogen fertilisers (Dawson and Hilton, 2011). The huge scale of nitrogen fertiliser production is clear from Figure 3, and far greater than that required to only satisfy market growth. The current situation indicates net consumption and insufficient nutrient recirculation achieved by manure spreading, ploughing straw back into soil, and reclamation from sewage sludge. Insufficient closed loop recycling opportunities and significant loses to the environment hampers fertiliser recovery and creates environmental pollution. Fertiliser demand increases at a greater rate than crop productivity which will accelerate resource depletion in the context of an increasing world population (Sattari et al., 2016).

The abundance of potassium mined from mineral reserves means it causes the least concern over the supply security of the three primary fertiliser nutrients. Current annual extraction is 0.7% of reserves and an estimated 0.02% of the estimated total potash on Earth (USGS, 2019). Regarding nitrogen and phosphorus, the situation is much more severe. Anthropogenic “interference with the nitrogen and phosphorus cycles” has exceeded sustainable levels (Rockström et al., 2009). There is also an inescapable link between fertiliser and fossil fuels that means the bioeconomy is dependent on the petrochemical industry. Even if we set energy arguments aside, nitrogen fertiliser production requires methane, used as a source of hydrogen. This methane is near-exclusively sourced from natural gas. The isolation of phosphorus from mineral ores requires sulphuric acid, made by oxidation of the sulphur isolated from natural gas exploration. Thus, natural gas is vital to the fertiliser industry and therefore biomass production. For biogas to be used to any meaningful extent to make nitrogen fertilisers the annual volumes will need to be huge: 120 MT for ammonia production (Levi and Cullen, 2018), 200 MT to serve the whole petrochemical market (Figure 3), and 2800 MT including energy uses (BP, 2019). Current biogas production is 26 MT in natural gas energy equivalents by comparison (Scarlat et al., 2018).

Clearly a reduction in fertiliser production by current means is important but alternative sources of nitrogen and phosphorus are inadequate. The quantities of mineral nitrogen reserves are too small, and viable phosphorus reserves are geographically constrained to mostly China, Morocco and the USA (Dawson and Hilton, 2011) and estimated to be depleted within 100 years (Cordell et al., 2009, Supanchaiyamat and Hunt, 2019). In the context of substantial projected increases in biomass production (for food, energy, and bio-based products), nutrient recycling rates must be improved. Denitrification (the process of bioavailable nitrogen being converted to N_2) occurs naturally and is promoted in water treatments to nullify pollution. In both instances the nitrogen recirculation is at its longest and least efficient pathway, having to re-enter the Haber-Bosch process or biological nitrogen fixation as N_2. Simplified annual global nitrogen fluxes (not total quantities) are represented as a Sankey diagram in Figure 4 (Canfield et al., 2010). This representation shows mass flows proportionally by the size of the arrows. The nitrogen flows occur between land, ocean, and atmospheric domains, as represented by boxes. Land losses of nitrogen to air and water nearly cancel out anthropogenic efforts to replenish it. One solution being explored by synthetic biologists is to engineer cereals to fix nitrogen through the expression of nitrogenases (Rogers and Oldroyd, 2014).

Optimistic projections calculate that 60% of mineral phosphate demand could be eliminated by phosphorus recovered from wastewater, preventing food waste, and changing agricultural practices to eliminate overuse where there is no return for the fertiliser applied (Koppelaar and Weikard, 2013). Sources of annual lost phosphorus are indicated in a Sankey diagram as Figure 5 (Cordell et al., 2009). Resource depletion is shown when the material flow arrows leave one of the value chain domains (processing, farm, consumption). The majority of phosphorus is lost due to erosion, underutilised manure, and the non-edible parts of crops (recirculation of the phosphorus in manure and straw is relatively minor and not shown in Figure 5 for simplicity).

There are a number of strategies to keep phosphorus in use. Precipitation of struvite ($MgNH_4PO_4 \cdot 6H_2O$) recovers ≥80% of soluble phosphates and ≥20% of ammonium salts from wastewater rich in nutrients (Le Corre et al., 2009). A cost-effective technology for struvite production could make a meaningful contribution to fertiliser recirculation (Li et al., 2019). Research continues into a host of other materials as well as biological and chemical methods to improve nutrient removal from wastewater, but normally without demonstrating its application as a fertiliser. An alternative approach is to remove elements from wastewater that are uncomplimentary to fertiliser applications (e.g. metal salts) and then use the water (still containing bioavailable nitrogen and phosphorus) in agriculture. Yuan *et al.* (2020) showed that hydrogels can remove copper and chromium from wastewater and that the nutrient-containing water is an adequate fertiliser. This approach is helpful to recirculate nitrogen and phosphorus but also capture water for biomass production. The availability of water has been described as a "significant constraint" on supplying biomass for energy purposes (Séférian et al., 2018). Concerns about water use will only increase with growing demand for bio-based products and energy. Unfortunately, wastewater is a dilute source of minerals and so as a source of nutrients it is unlikely to become economically competitive with virgin minerals until reserves are all but depleted. Agricultural run-off could provide a small contribution to the fertiliser market (Razon, 2018), being richer in compounds than the wastewater it contributes to.

Phosphorus recovery from manure is seen as more viable than from wastewater but the cost, energy and global warming potential of both these recycling approaches are greater than mining phosphate rock (Golroudbary et al., 2019, Grames et al., 2019). Sewage sludge is the downstream destination of un-reclaimed, untreated nitrogen and phosphorus before it is either repurposed directly as a form of fertiliser, processed in an anaerobic digester, or even burnt where there is no market for it. Incineration of sewage sludge does permit the recovery of minerals as ash, especially phosphorus (Fang et al., 2018). There are a number of techniques to further improve the bioavailability of nutrients in sewage sludge, such as gasification (Müller-Stöver et al., 2018). Ultimately a combination of different approaches will be needed to wean biomass production from its dependence on fertilisers derived from mineral reserves and natural gas.

2.2 Energy

The energy market is changing fast. The phasing out of pollution sources, notably coal for electricity generation and petroleum transport fuels, is dictated by policies to promote renewable energy. The BP Energy Outlook (BP, 2019) projects a rapidly increasing energy share from renewable sources. Annual bioethanol fuel production exceeded 70 billion litres in 2018 (Gavahian et al., 2019, Statista, 2019a), and more than 30 million tonnes of wood pellets, overwhelmingly for the

European market, are produced annually as a solid fuel (FAOSTAT, 2019, Statista, 2019b). The EU has an overall target for renewable energy to provide 20% of energy demand by 2020. Overall 17.5% of EU energy consumption in 2017 was from renewable sources (Eurostat, 2017). Sweden and Finland now obtain more than 50% and 40%, respectively, of their energy from renewable sources. The electricity energy mix in the UK for the second quarter of 2019 included about one third renewable energy. At 16%, wind power contributed the largest share of renewable electricity. Another 12% was biomass derived, 6% solar, and small contributions by hydroelectric power and tidal energy (Department for Business, Energy and Industrial Strategy, 2019). UK liquid biofuels (biodiesel and bioethanol) consumption was almost 600 million litres in the same time period, representing 3.8% of liquid transport fuel demand.

Biomass is somewhat different to other renewable energy sources because it is a material combusted to produce heat (before it can be converted into electrical or mechanical power) or indeed used as the precursor to products as well. In that sense, it is more like coal, crude oil or natural gas than it is wind or solar energy. Biomass is increasingly being used as an energy source for power stations. The Drax power station is the largest in the UK based on its power output and has converted four of its six power generators to use wood pellets as a feedstock (Drax, 2018). The use of biomass to meet such a large demand for energy can create issues with sustainable land use, water supply (Schyns and Vanham, 2019), and the protection of biodiversity (Fingerman et al., 2019, Hansson et al., 2019). The direct and indirect implications of land and crop management such as the carbon stock that is maintained in the soil must be considered and acted upon appropriately over relevant time periods, which can take decades to replenish for forestry products (Searchinger et al., 2018). The fossil fuel supply chain uses orders of magnitude less land space than renewable energy provision (van Zalk and Behrens, 2018). Biomass is the worst performing option in this regard, but it does reduce greenhouse gas emissions more than other renewable energy sources (Baležentis et al., 2019).

The scale of biomass production needed to reach political renewable energy targets is achievable (Oliver and Khanna, 2017), but we cannot be confident biomass will get anywhere near to completely replacing the total demand for electricity and liquid transport fuels because of the aforementioned reasons. Contrary to plans to increase the contribution of biomass towards energy demand (Scarlat et al., 2015), wind, hydro, and solar power sources must make up the majority of the electricity market in the absence of fossil fuels. Biomass can then primarily be converted into chemicals and materials once food and feed markets are satisfied (Service, 2019). Waste biomass however remains an appropriate option for solid and liquid fuels. The use of waste cooking oil triglycerides to make renewable diesel is a commercial enterprise operated by Neste for road transportation (Ondrey, 2014). British company Bio-Bean (Bio-Bean, 2019) produce solid fuel pellets from coffee grounds sourced from airports (London Stansted Airport, 2019) and other centralised waste locations. The calorific value of coffee pellets is actually greater than wood pellets but attention to their preparation is necessary (e.g. creating sufficiently high density) to meet the requirements of renewable energy accreditation schemes (Park et al., 2020). Should a combination of waste sources be needed to make an impact on the pellet energy market, then the careful selection of the fuel composition will be needed to ensure a stable power output.

It is not a straight-forward decision in designing a circular economy to simply say all our electricity will be provided by non-combustive means, because a high demand for certain scarce elements used in renewable energy production and storage technologies is created. Solar cells require critical elements such as tellurium, gallium, and indium (Grandell and Höök, 2015). Ironically, petrochemicals are vital too as a source of carbon fibre for wind turbines for example. Thus, it turns out that renewable energy is not limitless, but still restricted by resource availability just as fossil fuels are. The variable output of wind and solar energy makes efficient battery technology vital. Electric vehicles also require energy storing batteries to ease demand for liquid fuels, and this has strained cobalt reserves (Sun et al., 2019). Heavy freight (aircraft, ships) will need liquid fuel for the foreseeable future, which of course can be bio-based. Research into bio-based hydrocarbon aviation fuels is exploring the conversion of C5 (Jing et al., 2018) and C6 (Han et al., 2017) sugar derivatives by hydrodeoxygenation.

3. Recovery of value from waste

The primary area of concern regarding end-of-life biomass is food waste (which can be expanded to all organic waste), due to its volume and emotional significance for consumers (Mak et al., 2020, Nizami et al., 2017). The Waste and Resources Action Programme (WRAP) recorded 10.2 MT of post-farm food waste in the UK (2018 data), of which 7.1 MT is created by households (5 MT is edible food waste), and the remaining 3.1 MT is lost earlier in the supply chain (Gillick and Quested, 2018). Worldwide food waste equals a third of food production (1300 MT) (Matharu et al., 2016), with agricultural practices creating 570 MT of waste annually (Morrison and Golden, 2015). To tackle this issue, food suppliers need to understand more comprehensively the scale of food waste (Cicatiello and Franco, 2020), and employ more sophisticated analytical methods to understand the reasons for the creation of food waste (Filimonau and Gherbin, 2017, Broekmeulen and van Donselaar, 2019). A large step towards eliminating unnecessary food waste also needs to be made by consumers. Purchasing and household habits have a significant influence on the quantity of food that is wasted (Cicatiello et al., 2019, Ghinea and Ghiuta, 2019, Schanes et al., 2018). One type of initiative that allocates a balanced burden on both food supplier and consumer are take-back schemes for food waste (Eriksson et al., 2017). Upstream in the value chain, the environmental impact of food production was thoroughly examined by Notarnicola (2017) who concluded “agriculture is the most impacting life cycle stage for almost all the products” that were evaluated. Some of this impact is due to oversupply in anticipation of waste. By minimising unnecessary food waste, the problems arising from fertiliser use, pesticides and irrigation would be diminished even before re-evaluating agricultural practices.

Unavoidable food waste intercepted in the supply chain is a potential source of chemicals and materials that could contribute to a circular bioeconomy as the feedstocks for high value products. Inedible food waste (husks, peels, cobs, etc.) can be subjected to extraction, digestion, fermentation, chemical modification and pyrolysis (Nayak and Bhushan, 2019). Many of the bio-based intermediates produced by these technologies are the same regardless of whether they are produced from food waste or raw biomass because they are the thermodynamic products of carbohydrate pyrolysis and dehydration (e.g. 5-hydroxymethylfurfural), or the consequence of defined biological processes (e.g. ethanol) (Jing et al., 2019, Mika et al., 2018). The chemicals market needs to adjust to the availability of these compounds from (waste) biomass and not continue to rely solely on derivatising hydrocarbons to maximise the potential of bio-based chemicals.

3.1 Anaerobic digestion

Anaerobic digestion is a valued approach to dealing with organic waste, historically sewage sludge and manure but increasingly other organic matter too (Xu et al., 2018a). The variable operation scale, from household to industrial, makes it versatile (Vasco-Correa et al., 2018), and an efficient anaerobic digestion plant offers a significant reduction in global warming potential compared to composting and incineration (Edwards et al., 2018, Mayer et al., 2019). A valuable product is obtained in the form of methane, which can be used as a fuel on a local or national scale with the correct infrastructure. At a simplistic level, anaerobic digestion takes mixed, low value waste streams and converts the carbohydrate within them into methane with a theoretical maximum carbon efficiency of 50%. That is because the theoretical carbon balance of microbial acetogenesis then methanogenesis produces an equimolar amount of carbon dioxide which then need to be separated along with other gaseous products (Solarte-Toro et al., 2018). Membranes are being developed to improve the energy balance of this separation (Kertik et al., 2017). In reality, the anaerobic digestion feedstock will contain a variety of substances (some inhibitory), not just carbohydrate. Methane yield optimisation studies have produced yields from food waste of up to 0.70 L per gram of volatile solids after inoculation with lignocellulose hydrolysing bacteria (Li et al., 2018a), and 0.43 L/g of methane has been obtained from the co-digestion of paper and pulp sludge with food waste (higher than paper and pulp waste alone) (Veluchamy and Kalamdhad, 2017). Alternatively, different bioprocesses can be utilised to tailor the product composition (Liguori and Faraco, 2016, Venkata Mohan et al., 2016).

Many challenges will be faced along the trajectory anaerobic digestion needs to follow to contribute to its full potential in a circular bioeconomy (Sawatdeenarunata et al., 2016). Although anaerobic digestion is an established technology, research shows there are many options by which to pursue improved efficiency (Braguglia et al., 2018, Di Maria et al., 2018). Pre-processing (Paritosh et al., 2018, Ren et al., 2018, Tabatabaei et al., 2020), optimal design of tank reactors (Kariyama et al., 2018), process design, monitoring, and control (Depelo and Bridgeman, 2018, Panigrahi and Dubey, 2019, Xiao et al., 2018) are all active research areas. The productivity of an anaerobic digestion plant is subject to the quality of biomass waste that it processes. Co-digestion of different waste streams is seen as a method of enhancing methane production and permitting the processing of food waste and crop residues, improving economic viability and life cycle impacts (Edwards et al., 2017, Ingrao et al., 2018, Li et al., 2018b, Xu et al., 2018b). Prioritising local unavoidable food supply chain waste is preferable but only achievable with greater stakeholder cooperation (Gontard et al., 2018). Furthermore, the proportion of rejected material must be consistently low for the plant to be economically viable (Abad et al., 2019).

The important change in mindset that comes with a circular economy is that waste management becomes a process of returning resources to use, not just nullifying waste. Thus, the purpose of anaerobic digestion needs to be the provision of value-saving products, made from carefully selected feedstocks, not just a method of eliminating undesirable wastes. Methane is considered as the primary product, but using the digestate as a fertiliser is also an important consideration. There lies a risk regarding the distribution of pathogens and metals, especially if the traceability of mixed waste is poor (Nag et al., 2019, Sharma et al., 2019). Alternatively, the technology to recover nitrogen and phosphorus in mineral form is also available, rather than treating nutrient-rich effluent before discharge (Ma et al., 2018). The necessary removal of carbon dioxide from raw biogas to purify the methane for downstream applications is an obvious opportunity to capture this carbon dioxide and utilise it, yet there is no economic incentive to do so until the necessary technology is lower in cost than the penalty for carbon dioxide emissions.

Gasification by pyrolysis is a burgeoning waste management technology (You et al., 2018), converting organic waste to syngas (CO and H_2) directly rather than to methane. This performs the same function as methane production then steam reforming but in a single step, and also removes the cap on the theoretical maximum efficiency imposed by anaerobic digestion. In practice, organic municipal waste gasification technologies have varying productivity, syngas purity and CO:H_2 ratios (Watson et al., 2018). Anaerobic digestion can be integrated with gasification to provide further benefits (Pecchi and Baratieri, 2019). For example, digestates from anaerobic digestion can be used as the feedstock for gasification, or, the biochar co-produced in gasification can be used to stabilise anaerobic digestion and improve nutrient retention in the digestate for fertilising applications. Integrated waste management technologies create higher value from mixed wastes by processing a greater proportion of the feedstock, and as such are an essential innovation for a circular economy (Hidalgo et al., 2019).

4. Conclusion

A circular economy is a vision of a sustainable society, demanding greater responsibility for sustainable biomass production and the recovery of material value from products at end-of-life. To do this, fertiliser production must be uncoupled from mineral and fossil feedstocks, and a diverse renewable energy market established that utilises waste biomass. Integrated waste management technologies will be essential to extract the maximum value from mixed wastes.

References

1. Abad, V., et al., 2019. Promoting circular economy in the surroundings of an organic fraction of municipal solid waste anaerobic digestion treatment plant: biogas production impact and economic factors. Bioresour. Technol. 283, 10-17.
2. Baležentis, T., et al., 2019. The role of bioenergy in greenhouse gas emission reduction in EU countries: an environmental Kuznets curve modelling. Resour. Conserv. Recycl. 142, 225-231.
3. Bio-Bean, 2019. https://www.bio-bean.com/elements/pellets/ (accessed 28-10-2019).
4. Bonsucro, 2019. https://www.bonsucro.com/our-impacts/ (accessed 31-10-2019).
5. BP, 2019. https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html (accessed 01-11-2019).
6. Braguglia, C.M., et al., 2018. Anaerobic bioconversion of food waste into energy: a critical review. Bioresour. Technol. 248, 37-56.

7. Broekmeulen, R.A.C.M., van Donselaar, K.H., 2019. Quantifying the potential to improve on food waste, freshness and sales for perishables in supermarkets. Int. J. Prod. Econ. 209, 265-273.
8. Camp, J.E., 2018. Bio-available solvent Cyrene: synthesis, derivatization, and applications. ChemSusChem 11, 3048-3055.
9. Canfield, D.E., et al., 2010. The evolution and future of Earth's nitrogen cycle. Science 330, 192-196.
10. Ciriminna, R., et al., 2014. Limonene: a versatile chemical of the bioeconomy. Chem. Commun. 50, 15288-15296.
11. Cicatiello, C., et al., 2019. Investigating consumers' perception of discounted suboptimal products at retail stores. Resources 8, 129.
12. Cicatiello, C., Franco, S., 2020. Disclosure and assessment of unrecorded food waste at retail stores. J. Retail. Consum. Serv. 52, 101932.
13. Clark, J.H., et al., 2016. Circular economy design considerations for research and process development in the chemical sciences. Green Chem. 18, 3914-3934.
14. Cordell, D., et al., 2009. The story of phosphorus: global food security and food for thought. Global Environ. Chang. 19, 292-305.
15. Cullen, J.M., 2017. Circular economy: theoretical benchmark or perpetual motion machine? J. Ind. Ecol. 21, 483-486.

16. Dawson, C.J., Hilton, J., 2011. Fertiliser availability in a resource-limited world: production and recycling of nitrogen and phosphorus. Food Policy 36, S14-S22.
17. Department for Business, Energy and Industrial Strategy, 2019. https://www.gov.uk/government/statistics/energy-trends-section-6-renewables (accessed 05-11-2019).
18. Depelo, D., Bridgeman, J., 2018. Assessment of mixing quality in full-scale, biogas-mixed anaerobic digestion using CFD. Bioresour. Technol. 265, 480-489.
19. Di Maria, F., et al., 2018. Are EU waste-to-energy technologies effective for exploiting the energy in bio-waste? Appl. Energy 230, 1557-1572.
20. Dou, X., et al., 2017. Pectin, hemicellulose, or lignin? impact of the biowaste source on the performance of hard carbons for sodium-ion batteries. ChemSusChem 10, 2668-2676.
21. Drax, 2018. https://www.drax.com/press_release/drax-closer-coal-free-future-fourth-biomass-unit-conversion/ (accessed 05-11-2019).
22. EC, 2018. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment. European Commission, Brussels.

23. EC, 2019. Energy prices and costs in Europe. European Commission, Brussels.
24. Edwards, J., et al., 2017. Anaerobic co-digestion of municipal food waste and sewage sludge: a comparative life cycle assessment in the context of a waste service provision. Bioresour. Technol. 223, 237-249.
25. Edwards, J., et al., 2018. Life cycle assessment to compare the environmental impact of seven contemporary food waste management systems. Bioresour. Technol. 248, 156-173.
26. Eriksson, M., et al., 2017. Take-back agreements in the perspective of food waste generation at the supplier-retailer interface. Resour. Conserv. Recycl. 122, 83-93.
27. EU, 2017. Study on the Review of the List of Critical Raw Materials. Publications Office of the European Union, Luxembourg.
28. EU, 2018a. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the European Union, 61, 82-209.
29. EU, 2018b. Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste. Official Journal of the European Union, 61, 141-154.

30. EU, 2018c. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. Official Journal of the European Union, 61, 109-140.

31. Eurostat, 2017. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_ind_ren&lang=en (accessed 05-11-2019).

32. Eurostat, 2018. https://ec.europa.eu/eurostat/web/products-datasets/-/env_ac_mfa (accessed 07-11-2019).

33. Fang, L., et al., 2018. Recovery of phosphorus from incinerated sewage sludge ash by combined two-step extraction and selective precipitation. Chem. Eng. J. 348, 74-83.

34. FAOSTAT, 2019. http://www.fao.org/faostat/en/#data (accessed 31-10-2019).

35. Farmer, T.F., Mascal, M., 2015. Platform Molecules, in: Clark, J.H., Deswarte, F. (Eds.), Introduction to Chemicals from Biomass, second ed., John Wiley & Sons, Ltd, Chichester, pp. 89-155.

36. Filimonau, V., Gherbin, A., 2017. An exploratory study of food waste management practices in the UK grocery retail sector. J. Cleaner Prod. 167, 1184-1194.

37. Fingerman, K.R., et al., 2019. Opportunities and risks for sustainable biomass export from the south-eastern United States to Europe. Biofuels Bioprod. Biorefin. 13, 281-292.
38. FSC, 2019. https://info.fsc.org/certificate.php (accessed 04-11-19).
39. Gavahian, M., et al., 2019. Emerging techniques in bioethanol production: from distillation to waste valorization. Green Chem. 21, 1171-1185.
40. Ghinea, C, Ghiuta, O.-A., 2019. Household food waste generation: young consumers behaviour, habits and attitudes. Int. J. Environ. Sci. Technol. 16, 2185-2200.
41. Gillick, S., Quested, T., 2018. Household Food Waste: Restated Data for 2007-2015. WRAP, Banbury.
42. Golroudbary, S.R., et al., 2019. Environmental sustainability of phosphorus recycling from wastewater, manure and solid wastes. Sci. Total Environ. 672, 515-524.
43. Gontard, N., et al., 2018. A research challenge vision regarding management of agricultural waste in a circular bio-based economy. Crit. Rev. Environ. Sci. Technol. 48, 614-654.
44. Graedel, T.E., et al., 2015. On the materials basis of modern society. Proc. Natl. Acad. Sci. U.S.A. 112, 6295-6300.

45. Grames, J., et al., 2019. Understanding feedbacks between economic decisions and the phosphorus resource cycle: a general equilibrium model including material flows. Resour. Policy 61, 311-347.
46. Grandell, L., Höök, M., 2015. Assessing rare metal availability challenges for solar energy technologies. Sustainability 7, 11818-11837.
47. Han, P., et al., 2017. Synthesis of high-density biofuel with excellent low-temperature properties from lignocellulose-derived feedstock. Fuel Process. Technol.163, 45-50.
48. Hansson, J., et al., 2019. How is biodiversity protection influencing the potential for bioenergy feedstock production on grasslands? Global Change Biology Bioenergy 11, 517-538.
49. Hidalgo, D., et al., 2019. A multi-waste management concept as a basis towards a circular economy model. Renewable Sustainable Energy Rev. 111, 481-489.
50. Ingrao, C., et al., 2018. Food waste recovery into energy in a circular economy perspective: a comprehensive review of aspects related to plant operation and environmental assessment. J. Cleaner Prod. 184, 869-892.
51. ISCC, 2019. https://www.iscc-system.org/certificates/all-certificates/ (accessed 04-11-19).

52. Jing, Y., et al., 2018. Robinson annulation-directed synthesis of jet-fuel-ranged alkylcyclohexanes from biomass-derived chemicals. ACS Catal. 8, 3280-3285.
53. Jing, Y., et al., 2019. Catalytic production of value-added chemicals and liquid fuels from lignocellulosic biomass. Chem 5, 2520-2546.
54. Kariyama, I.D., et al., 2018. Influence of mixing on anaerobic digestion efficiency in stirred tank digesters: a review. Water Res. 143, 503-517.
55. Kertik, A., et al., 2017. Highly selective gas separation membrane using in situ amorphised metal–organic frameworks. Energy Environ. Sci. 10, 2342-2351.
56. Koppelaar, R.H.E.M., Weikard, H.P., 2013. Assessing phosphate rock depletion and phosphorus recycling options. Global Environ. Chang. 23, 1454-1466.
57. Le Corre, K.S., et al., 2009. Phosphorus recovery from wastewater by struvite crystallization: a review. Crit. Rev. Environ. Sci. Technol. 39, 433-477.
58. Levi, P.G., Cullen, J.M., 2018. Mapping global flows of chemicals: from fossil fuel feedstocks to chemical products. Environ. Sci. Technol. 52, 1725-1734.

59. Li, Y., et al., 2018a. Influence of feed/inoculum ratios and waste cooking oil content on the mesophilic anaerobic digestion of food waste. Waste Manage. 73, 156-164.
60. Li, Y., et al., 2018b. Reactor performance and economic evaluation of anaerobic co-digestion of dairy manure with corn stover and tomato residues under liquid, hemi-solid, and solid state conditions. Bioresour. Technol. 270, 103-112.
61. Li, B., et al., 2019. Phosphorous recovery through struvite crystallization: challenges for future design. Sci. Total Environ. 648, 1244-1256.
62. Liguori, R., Faraco, V., 2016. Biological processes for advancing lignocellulosic waste biorefinery by advocating circular economy. Bioresour. Technol. 215, 13-20.
63. London Stansted Airport, 2019. https://mediacentre.stanstedairport.com/london-stansted-to-become-first-airport-in-world-to-convert-all-its-coffee-waste-to-solid-biofuels-in-ground-breaking-partnership-with-bio-bean?amp=1 (accessed 28-10-2019).
64. Ma, H., et al., 2018. Nutrient recovery technologies integrated with energy recovery by waste biomass anaerobic digestion. Bioresour. Technol. 269, 520-531.

65. Mak, T.M.W., et al., 2020. Sustainable food waste management towards circular bioeconomy: policy review, limitations and opportunities. Bioresour. Technol. 297, 122497.
66. Matharu, A.S., et al., 2016. Opportunity for high value-added chemicals from food supply chain wastes. Bioresour. Technol. 215, 123-130.
67. Matthews, J.A., Tan, H., 2016. Circular economy: lessons from China. Nature 531, 440-442.
68. Mayer, F., et al., 2019. Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. Sci. Total Environ. 672, 708-721.
69. Mika, L.T., et al., 2018. Catalytic conversion of carbohydrates to initial platform chemicals: chemistry and sustainability. Chem. Rev. 118, 505-613.
70. Morrison, B., Golden, J.S., 2015. An empirical analysis of the industrial bioeconomy: implications for renewable resources and the environment. Bioresources 10, 4411-4440.
71. Müller-Stöver, D.S., et al., 2018. Phosphorus bioavailability in ash from straw and sewage sludge processed by low-temperature biomass gasification. Soil Use Manage. 34, 9-17.

72. Nag, R., et al., 2019. Anaerobic digestion of agricultural manure and biomass - critical indicators of risk and knowledge gaps. Sci. Total Environ. 690, 460-479.
73. Nayak, A., Bhushan, B., 2019. An overview of the recent trends on the waste valorization techniques for food wastes. J. Environ. Manage. 233, 352-370.
74. Nizami, A.S., et al., 2017. Waste biorefineries: enabling circular economies in developing countries. Bioresour. Technol. 241, 1101-1117.
75. Notarnicola, B., 2017. Environmental impacts of food consumption in Europe. J. Cleaner Prod. 140, 753-765.
76. Oliver, A., Khanna, M., 2017. Demand for biomass to meet renewable energy targets in the United States: implications for land use. Global Change Biology Bioenergy 9, 1476-1488.
77. Ondrey, G., 2014. Making renewable diesel and biopropane from vegetable oil. Chemical Engineering 121, 11.
78. Panigrahi, S., Dubey, B.K., 2019. A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste. Renew. Energ. 143, 779-797.
79. Paritosh, K., et al., 2018. Organic fraction of municipal solid waste: overview of treatment methodologies to enhance anaerobic biodegradability. Front. Energy Res. 6, 75.

80. Park, S., et al., 2020. Investigation of agro-byproduct pellet properties and improvement in pellet quality through mixing. Energy 190, 116380.
81. Pecchi, M., Baratieri, M., 2019. Coupling anaerobic digestion with gasification, pyrolysis or hydrothermal carbonization: a review. Renewable and Sustainable Energy Rev. 105, 462-475.
82. Philp, J., Winickoff, D.E., 2018. Realising the Circular Bioeconomy. OECD Publishing, Paris.
83. Razon, L.F., 2018. Reactive nitrogen: a perspective on its global impact and prospects for its sustainable production. Sustainable Production and Consumption 15, 35-48.
84. Ren, Y., et al., 2018. A comprehensive review on food waste anaerobic digestion: research updates and tendencies. Bioresour. Technol. 247, 1069-1076.
85. Rockström, J., et al., 2009. A safe operating space for humanity. Nature 461, 472-475.
86. Rogers, C, Oldroyd, G.E., 2014. Synthetic biology approaches to engineering the nitrogen symbiosis in cereals. J. Exp. Bot. 65, 1939-1946.
87. Sattari, S.Z., et al., 2016. Negative global phosphorus budgets challenge sustainable intensification of grasslands. Nat. Commun. 7, 10696.

88. Scarlat, N., et al., 2015. Renewable energy policy framework and bioenergy contribution in the European union – an overview from national renewable energy action plans and progress reports. Renewable Sustainable Energy Rev. 51, 969-985.
89. Scarlat, N., et al., 2018. Biogas: developments and perspectives in Europe. Renew. Energ. 129, 457-472.
90. Schanes, K., et al., 2018. Food waste matters - a systematic review of household food waste practices and their policy implications. J. Cleaner Prod. 182, 978-991.
91. Schyns, J.F., Vanham, D., 2019. The water footprint of wood for energy consumed in the European Union. Water 11, 206.
92. Searchinger, T.D., et al., 2018. Europe's renewable energy directive poised to harm global forests. Nat. Commun. 9, 3741.
93. Sawatdeenarunata, C., et al., 2016. Anaerobic biorefinery: current status, challenges, and opportunities. Bioresour. Technol. 215, 304-313.
94. Séférian, R., et al., 2018. Constraints on biomass energy deployment in mitigation pathways: the case of water scarcity. Environ. Res. Lett. 13, 054011.
95. Service, R.F., 2019. Renewable bonds. Science 365, 1236-1239.

96. Sharma, B, et al., 2019. Recycling of organic wastes in agriculture: an environmental perspective. Int. J. Environ. Res. 13, 409-429.
97. Solarte-Toro, J.C., et al., 2018. Evaluation of biogas and syngas as energy vectors for heat and power generation using lignocellulosic biomass as raw material. Electron. J. Biotechnol. 33, 52-62.
98. Statista, 2019a. https://www.statista.com/statistics/281606/ethanol-production-in-selected-countries/ (accessed 31-10-2019).
99. Statista, 2019b. https://www.statista.com/statistics/473246/worldwide-wood-pellet-consumption-by-major-region/ (accessed 31-10-2019).
100. Sun, X., et al., 2019. Tracing global cobalt flow: 1995-2015. Resour., Conserv. Recycl. 149, 45-55.
101. Supanchaiyamat, N., Hunt, A.J., 2019. Conservation of critical elements of the periodic table. ChemSusChem 12, 397-403.
102. Tabatabaei, M., et al., 2020. A comprehensive review on recent biological innovations to improve biogas production, part 1: upstream strategies. Renew. Energ. 146, 1204-1220.
103. USGS, 2019. https://www.usgs.gov/centers/nmic/potash-statistics-and-information (accessed 31-10-2019).

104. van Zalk, J., Behrens, P., 2018. The spatial extent of renewable and non-renewable power generation: a review and meta-analysis of power densities and their application in the U.S.. Energ. Policy 123, 83-91.

105. Vasco-Correa, J., et al., 2018. Anaerobic digestion for bioenergy production: global status, environmental and techno-economic implications, and government policies. Bioresour. Technol. 247, 1015-1026.

106. Velázquez-Martínez, O., et al., 2019. A critical review of lithium-ion battery recycling processes from a circular economy perspective. Batteries 5, 68.

107. Veluchamy, C., Kalamdhad, A.S., 2017. Influence of pretreatment techniques on anaerobic digestion of pulp and paper mill sludge: a review. Bioresour. Technol. 245, 1206-1219.

108. Venkata Mohan, S., et al., 2016. Waste biorefinery models towards sustainable circular bioeconomy: critical review and future perspectives. Bioresour. Technol. 215, 2-12.

109. Wassei, J.K., Kaner, R.B., 2010. Graphene, a promising transparent conductor. Mater. Today 13, 52-59.

110. Watson, J., et al., 2018. Gasification of biowaste: a critical review and outlooks. Renewable and Sustainable Energy Rev. 83, 1-17.

111. Xiao, B., et al., 2018. Temperature-phased anaerobic digestion of food waste: a comparison with single-stage digestions based on performance and energy balance. Bioresour. Technol. 249, 826-834.
112. Xu, F., et al., 2018a. Anaerobic digestion of food waste - challenges and opportunities. Bioresour. Technol. 247, 1047-1058.
113. Xu, R., et al., 2018b. A critical review on the interaction of substrate nutrient balance and microbial community structure and function in anaerobic co-digestion. Bioresour. Technol. 247, 1119-1127.
114. You, S., et al., 2018. Towards practical application of gasification: a critical review from syngas and biochar perspectives. Crit. Rev. Environ. Sci. Technol. 48, 1165-1213.
115. Yuan, J., et al., 2020. Simultaneous in situ nutrient recovery and sustainable wastewater purification based on metal anion- and cation-targeted selective adsorbents. J. Hazard. Mater. 382, 121039.
116. Zhang, Z., Deng, K., 2015. Recent advances in the catalytic synthesis of 2,5-furandicarboxylic acid and its derivatives. ACS Catal. 5, 6529-6544.

Captions

Figure 1. (a) Circular economy conceptual diagram. (b) The waste hierarchy.

Figure 2. EU critical raw materials on relative scales representing importance and risk. Data point radii represent logarithmic annual global production quantities. Phosphate and rubber data points are emphasised.

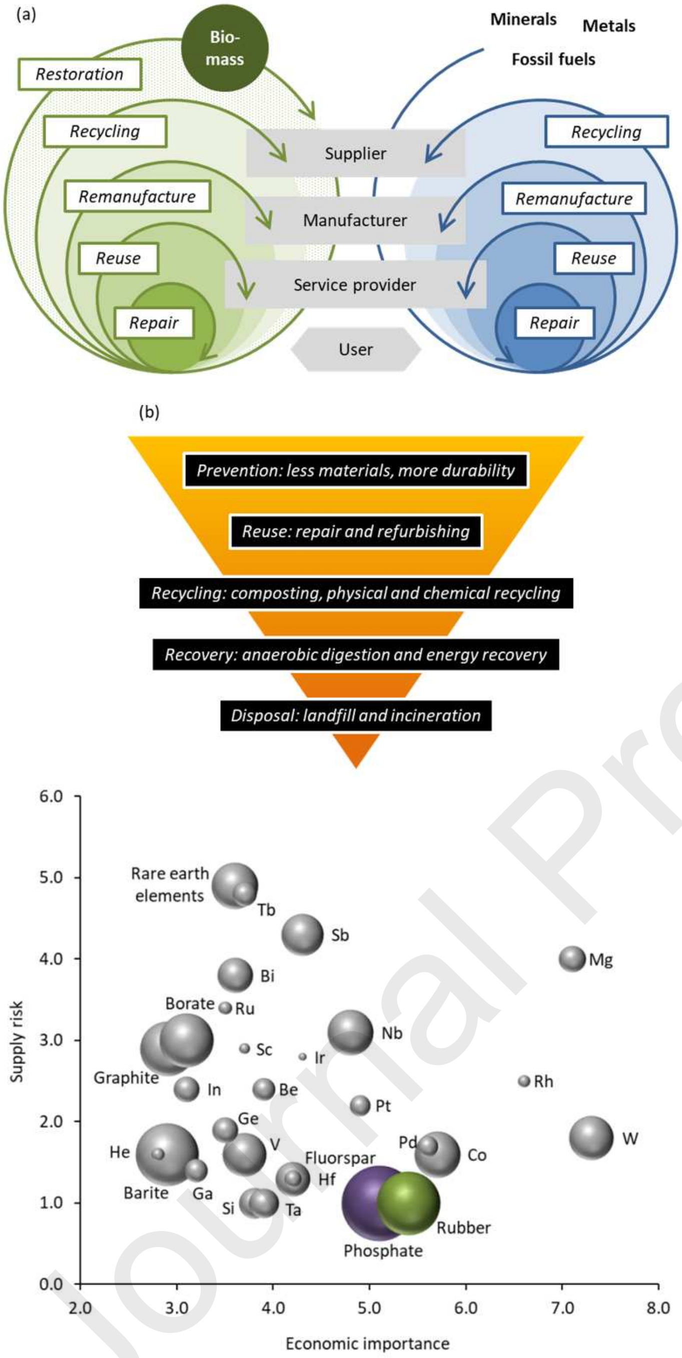
Figure 3. Proportional product streams in the petrochemical industry (globally 1640 million tonnes (MT) in 2013, excluding energy products) (Levi and Cullen, 2018).

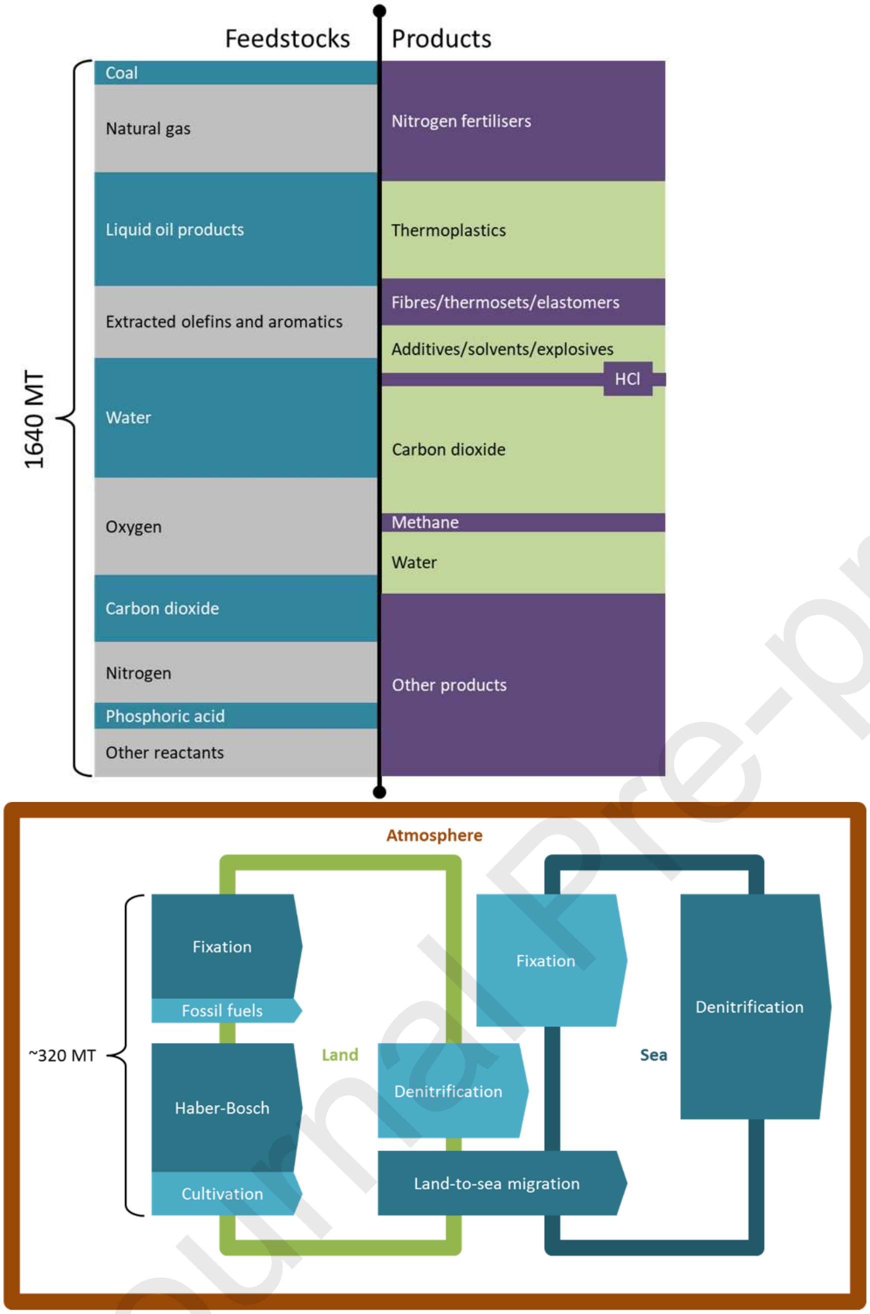
Figure 4. Annual nitrogen fluxes between atmospheric, land, and ocean domains (Canfield et al., 2010).

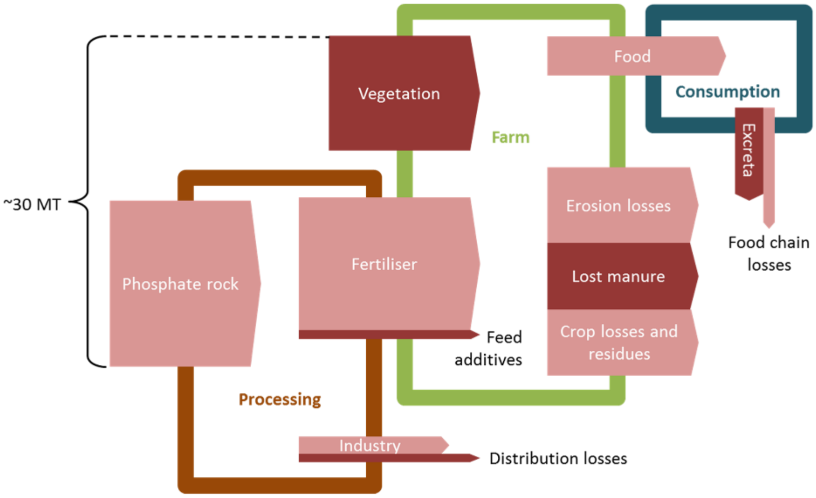
Figure 5. The material balance in the global phosphorus cycle (Cordell et al., 2009).

- Achieving a circular economy relies on plentiful and sustainable biomass
- Unlike fossil and mineral feedstocks, biomass is restored by organic recycling
- Minimising food waste is one of the major challenges for a circular economy

James Sherwood: Conceptualization, Formal analysis, Methodology, Resources, Validation, Visualization, Writing - original draft, Writing - review & editing.


(a)
Bio-mass
Restoration
Recycling
Remanufacture
Reuse
Repair
Minerals
Metals
Fossil fuels
Supplier
Manufacturer
Service provider
User
Recycling
Remanufacture
Reuse
Repair
(b)
Prevention: less materials, more durability
Reuse: repair and refurbishing
Recycling: composting, physical and chemical recycling
Recovery: anaerobic digestion and energy recovery
Disposal: landfill and incineration
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Supply risk
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Economic importance
Rare earth elements
Tb
Sb
Mg
Bi
Borate
Ru
Nb
Sc
Ir
Graphite
In
Be
Rh
Pt
Ge
Pd
W
He
V
Co
Fluorspar
Hf
Barite
Ga
Si
Ta
Rubber
Phosphate


Feedstocks
Products
1640 MT
Coal
Natural gas
Liquid oil products
Extracted olefins and aromatics
Water
Oxygen
Carbon dioxide
Nitrogen
Phosphoric acid
Other reactants
Nitrogen fertilisers
Thermoplastics
Fibres/thermosets/elastomers
Additives/solvents/explosives
HCl
Carbon dioxide
Methane
Water
Other products
Atmosphere
~320 MT
Fixation
Fossil fuels
Haber-Bosch
Cultivation
Land
Fixation
Denitrification
Land-to-sea migration
Sea
Denitrification


~30 MT
Vegetation
Farm
Food
Consumption
Excreta
Food chain losses
Erosion losses
Lost manure
Crop losses and residues
Phosphate rock
Fertiliser
Feed additives
Processing
Industry
Distribution losses

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: