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REVIEW

Circular Bio-economy—Paradigm for the Future: Systematic Review of Scientific Journal Publications from 2015 to 2021

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Abstract

While 'renewable' is the keyword in a bioeconomy and resource conservation is the motivation behind a circular economy, a circular bioeconomy is one in which waste streams from renewable bio-resources are looped back into the technosphere—open-loop or closed-loop recycling or conversion from matter to energy. This systematic review brings together 385 publications from 2015 to 2021, originating from 50 countries and appearing in 150 journals, into a coherent account of the status quo of published research on circular bioeconomy. The numbers bear testimony to the growing interest in this field of research. Germany is the leading contributor to the scientific literature base (10%), while the Journal of Cleaner Production (9%) tops the list of journals in the fray. The methodology adopted has been clearly explained, and the discussion has been segmented into sub-sections and sub-sub-sections to do justice to the diversity of the nature of the publications. A little flexibility in organisation of the flow of the text has been availed of, to improve readability. The circular bioeconomy can be visualised as a set of 'many through many to many' relationships, enabling both economies of scale and scope in the longer run. This calls for extensive collaboration and cooperation among the numerous stakeholders involved. Several barriers will have to be overcome. Technology impact assessments and sustainability risk appraisals need to be carried out in order to ensure and convince stakeholders that they are on the right path. But as one knows and will appreciate, challenges lurk where there exist opportunities to be availed of, to replace the take-make-use-dispose paradigm of a linear economy to the grow-make-use-restore alternative.

Keywords Bioeconomy/bio-economy · Bioenergy · Bio-products · Circular bioeconomy/bio-economy · Circular economy

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Introduction

A circular economy (referred to as CE at some junctures in the text) is ‘an economic system aimed at eliminating waste and ensuring the continual use of resources, through reuse, sharing, repair, refurbishment, remanufacturing and recycling to create a closed-loop system, minimising the use of resource inputs and reducing the creation of waste, pollution and carbon emissions’ [1]. The concept or idea of circularity in an economy was first propounded by Kenneth Boulding [2] way back in 1966. Circular economy has strong links to the Sustainable Development Goal no. 12 of the UN 2030 Agenda for Sustainable Development—namely, Sustainable Production and Consumption [3].

A bioeconomy (bio-based economy), as defined by [4], is ‘the production of renewable biological resources on land and water, and the conversion of these resources and waste streams into value-added products , such as food, feed, bio-based products and bioenergy’.

While ‘renewable’ is the keyword in a bioeconomy (what resources are used), and resource conservation is the motivation behind a circular economy (how resources are used), a circular bioeconomy is one in which side streams from renewable bio-resources are looped back into the technosphere—open or closed recycling or conversion from matter to energy [5]. While a circular economy, in general, includes both renewable and non-renewable resources, a full-fledged circular bioeconomy focusing only on renewable resources is attractive for the attainment of several sustainable development goals. A non-linear bioeconomy, emphasising on innovation to find ways and means for the utilisation of waste streams and end-of-life products in the technosphere, is thus a subset of a circular economy. ‘Circular economy’ and ‘bio-economy’ may be considered to be subsets or parts of a ‘green economy’, a term that was coined in 2012, and included social equity and well-being in addition to economic growth and environmental sustainability [6]. The gamut of recommended behaviours in ‘the era of R’s’ [7] in a circular bioeconomy (not limited to waste management) has increased over the years, and, as noted in [8], now includes ‘reclaim, remediate, reuse, recycle, renovate, refuse, replenish, rainwater-harvest, resilience and reverence for nature’.

These concepts/paradigms have now become increasingly popular in academic, research, industrial and governance circles, coincident with the UN Sustainable Development Goals (SDGs) launched in 2015. It is hoped that the social, technological and organisational innovations which are necessary for, and encouraged by, a transition to a restorative and regenerative circular bio-economy will herald a renewal in competitiveness in the global economy, environmental sustainability, positive economic development and employment generation in the years to come.

The primary, overarching goal of this paper is a general broad-based understanding of the interest garnered by the aspects of a ‘circular bioeconomy’, evidenced by peer-reviewed scientific journal publications. The sub-goals include, firstly, the identification and categorisation of the different sectors of economic activity, which are being brought into the fold of a circular bio-economy and the presentation of the novel findings of the publications concerned, which may be tested or replicated in other parts of the world, and secondly, the summarisation of key recommendations given, and useful insights about the threats and opportunities obtained and shared, to guide future research in this burgeoning field. Essentially, this serves the purpose of dissemination of knowledge to enable the propagation and popularisation of successful initiatives, be they on lab, pilot or commercial scales.

It must be clearly mentioned here that this review circumscribes itself to journal publications which have explicitly used the term ‘circular bioeconomy/bio-economy’ as a single compound word or as separate terms (circular economy, bioeconomy (bio economy)/bio-economy)), in the title and/or abstract and/or keywords. Having said that, readers must be aware of the fact that the defining aspect of a circular bio-economy—use of renewable biological resources and conversion of the waste streams generated from such use, into value-added products—has been a well-entrenched research area for a much longer time. This would mean that, what in principle would be publications implicitly dealing with a circular bio-economy may not be extracted from literature, by the search conducted.

A brief bibliometric analysis follows in the Methodology section, and is in turn followed by a systematically organised coherent review (Discussion) of the corpus of publications. The organisation is in keeping with the two sub-goals referred to earlier—sectoral categorisation for case studies, and useful insights and recommendations which will benefit future research in this field. The Conclusion presents a comprehensive summary of the contents of the paper, and highlights some of the key points, to guide researchers looking for topics to focus on, in their research on 'circular bioeconomy'.

Methodology and Results of the Bibliographic Search

Approach Adopted in Brief

It was decided to limit the search to the Scopus database, which, to date, is known to be the largest multidisciplinary citation and abstract database available, encompassing most of the major and minor publishers. The search was conducted on the 10th of November 2020, and thereby publications added to Scopus after that date would fall out of this review. Two search terms were used—'Circular bioeconomy' and 'Circular bio-economy'—knowing well that even if these two words did not appear one after the other as a single compound word, in the title and/or abstract and/or keywords, such publications would also show up in the search results. The requirement obviously is that the word 'bioeconomy/bio-economy' must appear in at least one of the three parts of the publication, with or without the adjective 'circular' before it. In cases where the adjective 'circular' does not appear before 'bioeconomy/bio-economy', the term 'circular economy' or the word 'circularity' or the adjective 'circular' followed by terms like 'business models', 'processing chains', 'approach(es)' and 'principle' must be found in at least one of the three parts of the publication. The scope was widened to include peer-reviewed articles, conference papers, reviews, short surveys, book chapters and editorials. The publications were split into two broad categories—case studies and theory/reflection/review (refer to A1 in the Appendix).

The abstracts were first screened to confirm relevance, before including the publication for review, the winnowing-out being done wherever needed. Where access to the full publication was available through the library of Karlstad University (Sweden), the author made it a point to read through the entire paper. Else, it was just the abstract which had to be relied upon. The practice of using cited references in the publications unearthed, as a secondary source of literature analysis, was not adopted.

Results of the Database Search

Figure 1 shows the occurrence of search phrases (11 possibilities considered for each of the three parts) in the publications. The term 'circular bioeconomy/bio-economy' occurs 168 times in the abstracts (44% of the total), 68 times among keywords (18%) and 71 times in the titles (19%). In 14 publications, it appears in all three. There are 26 instances of the adjective ‘circular’ followed by some related term other than ‘economy’ or ‘bioeconomy/bio-economy’, in title, abstract and keywords taken together. These related terms include ‘agriculture’, ‘approach’, ‘approaches’, ‘aquaculture’, ‘business models’, ‘cascading design’, (circularity), ‘economic approaches’, ‘food system’, ‘model’, ‘principles’, ‘processes’, ‘process chains’ and ‘system’, in alphabetical order. Interestingly, there are 2 instances where both ‘circular bioeconomy’ and ‘bioeconomy’ appear among the keywords. The hyphenated form of bio-economy appears 71 times in all, either by itself, or preceded by the adjective ‘circular’.

Figure 2 depicts the spread of the typologies of the publications unearthed, over the 7-year period. It is seen that there is almost an exponential rise in the number of articles till 2020, with 2021 likely to maintain the trend. The absence of conference publications in 2020 is obviously due to the pandemic. The first three publications—from 2015—originated in Germany (2) and Italy (1) and were published in the German Journal of Agricultural Economics, Bio-based and Applied Economics, and Current Opinion in Chemical Biology, while on countries of origin, Figure 3 shows the continental split, with Europe contributing 72%, followed by Asia (16%). Figure 4 shows the leading 10 countries in the list, with Germany and Italy (countries from where the publications in 2015 originated), leading the pack, followed by Spain and Finland. India is the first developing country to figure in the list, at number five. Brazil comes in at number six, and China at number eight. These ten countries together account for 63% of the publications. From just Germany and Italy in 2015, the number of countries in the fray has gone up to close to 50 now.

From just 3 journals in 2015, one can count close to 150 journals at the time of writing, with publications related to circular bioeconomy. The top five journals in this long list, which account for a little under 28% of the total number of publications, are as follows:

1. Journal of Cleaner Production (33)
2. Bioresource Technology (31)

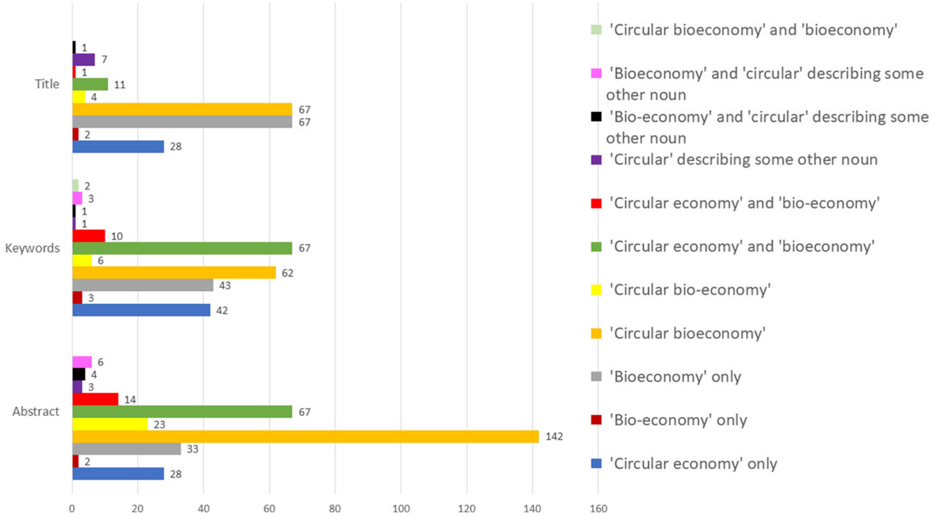

Figure 1 The occurrence of search phrases in title, abstract and keywords (also refer Figure A1 in the Appendix for the data)

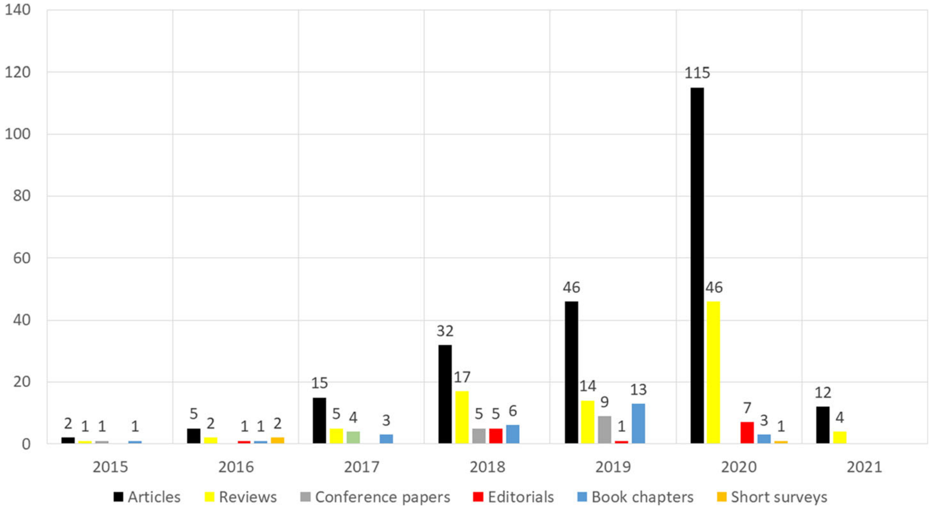

Figure 2 The typologies of the publications

3. Sustainability (Switzerland) (18)
4. Forest Policy and Economics (12)
5. New Biotechnology (11)

Structure Adopted for the Discussion

What follows is a systematic review, which has been organised into two main sub-sections—'Case Studies—Source Sectors in the Bio-economy' and 'Theoretical Publications, Overviews and Reviews'. The former is further split up into the source sectors 'Agriculture/Agro-food', 'Forestry (Silviculture)', 'Fisheries and Aquaculture', 'Municipal and Industrial Solid Waste and Sewage Management' and 'Bioenergy and Others' (sub-goal no. 1). The latter, which unearths key messages and findings to guide future research (sub-goal no. 2), is split into two sub-sub-sections—'Focussed' and 'General'. Table 1 in the Appendix categorises the literature on the basis of their types (case studies or otherwise), sub-types (focussed or general

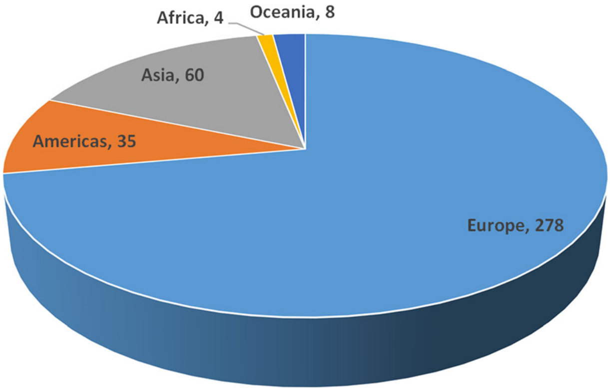

Figure 3 The continental shares of the publications

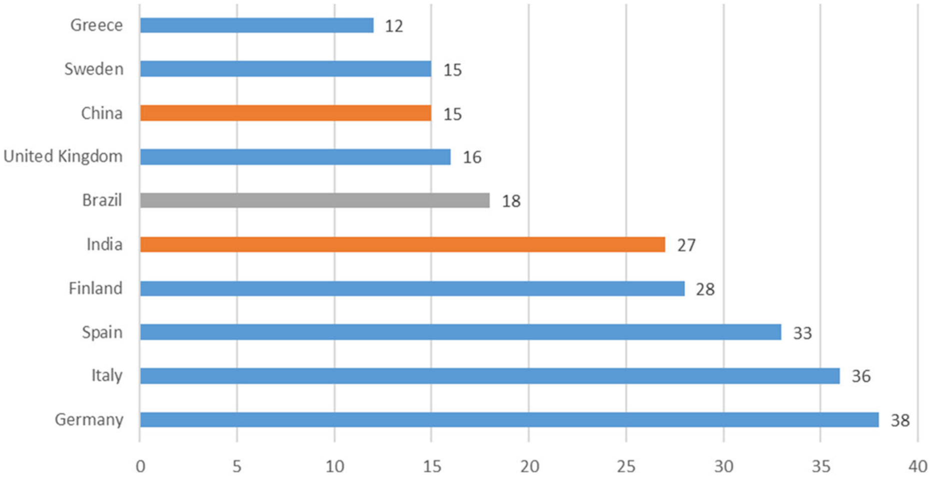

Figure 4 The top ten countries in the list, Germany to Greece

theoretical overviews or reviews) and focus/foci (source sector/s of the bio-wastes and the end-use sector/s of the valorised bio-products).

The typification has been done at the author's discretion and it is possible that some papers which have been categorised as theoretical overviews may be considered case studies by other researchers. It is also likely that publications which have been identified as theoretical/reviews/overviews in Table 1 may be called out to (also in, or even only in) in a case-study sub-section, and vice versa, where the context presents an opportunity for the same. In other words, the author has avoided a rigidity of approach, in order to do justice to the multi-faceted nature of publications, by adopting a more open approach to understanding the content. The systematic review is then followed by a consolidated conclusion which adopts an eagle's eye-view of the past (2015 till 2021), which is useful knowledge for the steering of the future circular bioeconomies in the world.

Discussion—Systematic Review

Case Studies—Source Sectors in the Bio-economy

Agriculture/Agro-food

Agricultural wastes have been studied globally since the 1950s, and since 1998, they have become more relevant [167]. Some papers focusing on agro-industrial wastes have been included in this sub-section rather than in the one dealing with municipal and industrial solid waste and sewage management.

A paper originating in Spain [17], describes an experiment carried out on chestnut shells to extract hemicellulosic oligosaccharides and phenolic compounds (the main focus in [264]) for use in nutraceuticals for their prebiotic and antioxidative properties. As far as prebiotics are concerned, the proprietary technologies of the Swiss firm Embion Technologies SA, to valorise low-value food and agro-industrial by-products and wastes, are worth referring to, at this juncture [44]. Upcycling wastes in this manner is also possible by combining anaerobic digestion and thermochemical gasification, and fermenting the gaseous mixture consisting of hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO) and ammonia (NH_3) to protein-rich single-cell microbial biomass. Matassa et al. (2020) [45] have estimated that over 600 million tonnes of microbial protein can be produced annually, if all the food wastes generated in the world are collected and valorised in this fashion. Well, practically, this cannot be achieved, but it is always good to have a lofty target to pursue. Soybean protein meal (Glycine max) has been found to yield antimicrobial and antitumoral peptides [121], while antioxidative anthraquinones can be extracted from the roots of *Morinda citrifolia*, a plant belonging to the coffee family [168], and waste peels of the Juçara fruit have been found to be rich in phenolic compounds [29]. Hydrothermal treatment which is known to enhance enzymatic cellulose degradation [344] has been carried out on several other undervalued waste streams like olive prunes and peanut shells, indicating a swathe of potential side streams to be harnessed in a circular bio-economy knitting the agro-food sector with the chemical-pharma-food sector.

The nitrogen-fixing fern *Azolla pinnata* has the potential to yield bio-hydrogen, volatile fatty acids and nutritious animal feed, when subjected to a series of unit processes—acidogenesis, hydrolysis and pyrolysis—in a biorefinery [153], while the fruiting bodies of the mushroom *Agaricus blazei* which do not conform to market requirements are good sources for the production of ergosterol used as a fortifying agent in yoghurts [18]. Non-conformity to market requirements thus may not be something to worry about, after all! Lavender and lavandin straws yield terpene derivatives, lactones and phenolic compounds when subjected to solvent extraction, and are able to induce the secretion of enzymes finding use in breaking down lignocellulosic biomass, from the white-rot model fungus *Pycnoporus cinnabarinus* [19], while camelina and crambe straws are shown to hold potential for being sources for the production of second-generation liquid biofuels, in addition to being combustible for heat energy [46]. Wang et al. (2021) [345] recommend renewable, eco-friendly, 'green' eutectic solvents in biorefineries, to lower the environmental footprint associated with valorisation processes. After all, the environment friendliness of a product depends not only on the nature of the raw materials, but also on the processes they are subjected to.

Engineering cellulolytic/hemicellulolytic lactic acid bacteria (LAB) strains to effectively valorise lignocellulosic biomass from fields and forests to bio-chemicals and bio-energy is the focus of [261]. These LAB strains will drive full-fledged lignocellulosic biorefineries of the future, which can have a truly sizable bio-product portfolio including *inter alia,* a range of cosmeceuticals and pharmaceuticals, activated carbon, carbon nanotubes, carbon nanohorns, cellulose fibres and bacterial cellulose [212]. Researchers in Brazil discovered that the high nitrogen and ash content and low mechanical durability of agro wastes, in general, are hindrances, when it comes to replacing wood for production of pellets [47].

Microwave processes, in combination with autohydrolysis, can economically convert walnut shells to xylose first and ultimately to lactic acid [30], which, among other things, is used to culture lactobacilli (a probiotic in healthcare), as a precursor to the bioplastic polylactic acid (PLA—laevorotatory or L-optical isomer), which is gradually gaining currency as a packaging bio-material [154], and also for the production of mulch films, disposable cutleries, framing materials and fibres [305]. Delbecq et al. (2018A, 2018B) [20, 145] have focused on the extraction of furfural which finds use in the chemical industry, for the production of resins, from sugars and polysaccharide feedstocks. Guillard et al. (2018) [259] remind readers that PLA can be biodegraded only in industrial composting installations in high temperature and high humidity conditions. When such facilities are not available, PLA can neither be composted nor recycled, but will have to be either incinerated or landfilled; and this at once makes one question its sustainability and aptness in a circular bioeconomy [306]. Chen et al. (2019) [31] in their Greek case study are in favour of utilising rice bran and rice husk as bio-compost and not as animal feed, and Greco et al. (2019) [32] are of the view of that true circularity would imply a proper soil-to-soil recycling—a view also echoed as support for availing of the multiple benefits of on-farm composting of horticultural wastes, in De Corato (2020) [169]. En route from soil to soil, a bio-product can also be made to serve an additional purpose—biochar from agro-wastes is used as an adsorbent in wastewater treatment before being sent back for soil amendment to fields [21]. On the other hand, Overturf et al. (2020) [48], reporting on the progress of the RiceRes EU project, have shown that straw, husk and bran from the fields can also be valorised into building insulations, bio-fillers for polymer-based composites and food industry supplements, respectively. Defatted rice bran, the by-product which remains after the production of rice bran oil, can be further valorised to bioethanol, biobutanol and lactic acid [22].

The interesting questions which arise here are as follows: Can these processes be integrated into existing agro-food industrial setups, to widen their product portfolios? Or if the compositions of such wastes are more or less the same, and the purpose is to extract hemicellulosic compounds, can co-treatment of a mixture be done in a dedicated setup importing the bio-wastes as input raw materials? Technological innovations are fine, but without the presence of strong symbiotic relationships among players in a circular bio-economy, they would not be able to deliver the goods. The reference here is to bottom-up initiatives which resulted in the success of the agro-industrial complex in the Almeira region of Spain which is making good use of the opportunity to become an integral part of a sustainable circular bioeconomy, by recognising the resource potential of the horticultural residues generated [33, 49, 170, 379]. On the other hand, in a historical analysis of the complex nexus among landscape, livestock, farming population and land uses in the agrarian metabolism in Barcelona, researchers have concluded that there has been a conspicuous decrease in circularity over time [146], which needs to be restored. French researchers tried to simulate the re-designing of the farming system in a small region of France, by imagining near-complete local circularity through crop and livestock symbiosis (feed-manure cycle), fewer livestock and avoidance of external inputs (chemical fertilisers for instance) [171], and arrived at the conclusion that while mitigating greenhouse gas (GHG) emissions, the farming community would have to be content with a drop in both food and bioenergy production. The British case study in Velenturf (2017) [11] documents how some existing symbiotic relationships came into being in the UK, to utilise agricultural feedstock (as well as wood-waste and bio-refuse derived fuel), in the service of the energy sector, and emphasises the importance of government-planned, facilitated and self-organised industrial symbiotic partnerships in circular bio-economies.

The food supply chain is a rich source of biomass feedstock for biomethane production. Hoo et al. (2020) [50], in a Malaysian study of the economic feasibility of providing feed-in-tariff for injecting biomethane into the natural gas grid, advocate a rationalisation of the price of natural gas, along with the levy of a carbon tax to make investments in food waste–derived biomethane generation, upgrading and injection attractive. Investing in biomethane generation from domestically sourced renewable feedstock reduces import dependency, guarantees energy security and helps to effectively tackle geopolitical uncertainties. Crude palm oil biomass also has other applications, as pointed out in Sadhukhan et al. (2018) [307]—pellets, long fibre and bio-fertiliser, which enhance the profitability of the biorefinery. Palm oil mill wastes like palm kernel shells, when combined with the fat-hydrolysing enzyme *Fusarium heterosporum* lipase, effectively trans-esterify palm oil mill effluents to biodiesel [51]. Adopting a novel approach, Chinese researchers [52] have been able to produce both biogas (by anaerobically digesting chicken manure and rapeseed straw pre-treated with the liquid fraction of the digestate) and biodiesel (from black soldier fly larvae grown on the solid fraction of the digestate). The larvae can alternately be supplied to fish farms as protein-rich feed [53].

The potential for extracting H_2 from organic solid wastes and wastewaters is huge [54], and this may very well be the fuel for the future. Righetti et al. (2020) [380], in an Italian case study, focus on the dark fermentation and anaerobic digestion of cattle manure and grass silage to yield a H_2–CH_4 mixture (called bio-hythane) and volatile fatty acids as precursors of bio-plastics, thus augmenting the value added in the bioeconomy. In two papers from Italy [34, 118], the authors have worked with whey (dairy wastes) and molasses (sugar factory wastes) to yield biohydrogen and bio-plastics—polyhydroxybutyrate or PHB to be specific—through dark fermentation and photo-fermentation, in that order. The focus of Melendez-Rodriguez et al. (2020) [122] is another bio-polymer—poly(3-hydroxybutyrate-co-3-hydroxyvalerate) or PHBV—used to make packaging 'bio-paper' with superior mechanical and barrier properties. Once studies to confirm the durability and shelf-life of naturally biodegradable bio-plastics like PHB used for packaging are published, they would act as verifiers for their entrenchment as substitutes for petroleum-based plastics [154]. Non-wood-based paper (made from elephant dung for instance) is a specialty product, which does not have a big market. Spanish researchers [55] have tested with agro-food wastes and have arrived at the conclusion that these may well be able to replace wood, when the brightness requirement of the paper product is not high.

Hydrophobicity and antioxidant effects are necessary properties of packaging films, and while Missio et al. (2020) [213] have found out that co-ground wood fibres and tannins in aqueous media fit the bill perfectly well, nanotechnologists from Spain have advocated biowaste-based nanomaterials for the purpose [172]. Meanwhile, tannins and cellulose nanocrystals are known to improve the bonding properties of synthetic adhesives [173]. Both increasing shelf life of the packaged food and thereby reducing food waste, and shifting to sustainable bio-packaging options are essential components of a circular bioeconomy [259]. The three key characteristics of sustainable packaging, according to Korhonen et al. (2020) [214] are compatibility with the circular production-consumption system, ability to satisfy heterogeneous consumer needs and potential to support sustainable lifestyles by extended material life cycles.

The potential for the maximisation of the environment friendliness of viticulture while enhancing its economic value by product diversification through valorisation of wastes is emphasised by [56], while the same approach has been advocated in other publications for sugar beet [35], lemon [174] and mango [57]. An alternative use for tomato pomace is as mulch to trap solar radiation and heat the soil to control nematodes, fungi, bacteria and crop-damaging pests [12], while biotically/abiotically stressed tomato plants are rich sources of rutin and solanesol, valued for their medicinal properties [58]. Open burning of agro-wastes, which is a common practice in India, accounts for a sizable fraction of India's GHG emissions, and what is conveniently being overlooked is the tremendous potential which these wastes hold for conversion to biogas [175]. If that would happen on a large scale, instead of open burning, fossil fuels can be replaced and a net reduction in GHG emissions from the energy sector can be achieved. Policy interventions and stronger collaboration between policymakers and potential biogas producers in the agricultural sector are needed to tide over technical, financial and regulatory barriers [59, 155, 175] and hasten the march towards a circular bio-economy.

Too much dependence on subsidies from policymakers, though, may dampen the entrepreneurial enthusiasm of players in the agricultural sector [13].

Bio-ethylene is the focus of Kuznecova et al. (2018) [23], who have compared corn, sugarcane, beet sugar, manioc, conifer and wheat, as potential sources, and arrived at the conclusion that sugarcane has the material productivity while sugar beet has the smallest GHG footprint. However, what stands in the way is unfavourable economics, with the unit life-cycle costs for the production of bio-ethylene higher than that for petroleum-derived ethylene, which it ought to replace in a circular bioeconomy. The sugarcane bagasse which is left behind after the production of sugar and/or ethanol may well be used as a fuel in-plant, and potato pulp from the starch industry may be used as animal feed, but researchers have discovered that the structural properties of bio-based composites with agro-industrial wastes, like sugarcane bagasse fibres/potato pulp/torrefied coffee husk flour/flaxseed flour + linseed–derived oils/bacterial cellulose nano-crystals/poultry feathers/hydrothermally carbonised cellulose in them as fillers, are enhanced, making them fit for structural, semi-structural and non-structural applications [60–62, 134–136, 176]. Potato residues, as carbon sources, can be used for the biological denitrification of wastewater from aquaculture, making it fit for recirculation and ensuring sustainable fish production [63]. The potential of modified lignocellulosic biomass—forestry wastes like pine/spruce wood and agricultural wastes like wheat/barley straw—to adsorb oil spills (diesel, crude oil), dyes and contaminant heavy metals from both wastewater and the hydrosphere (aiding effective remediation), has been explored by researchers who have uncovered synergies whereby the co-production of sugars which are raw materials for the biofuel industry will cover the expenses of the pre-treatment of the bio-based adsorbents [24].

Forestry (Silviculture)

Silveira et al. (2017) [14] have analysed the prospects of bioenergy in the Baltic sea region which encompasses Denmark, Sweden (the country which provides 10% of the globally traded sawn wood, pulp and paper, from just 1% of the world's commercial forest area—[215]), Finland (the country which has published over 32% of the total number of scientific forest-industry publications in the period 2003–2020 [216]), Belarus, Latvia, Poland, Lithuania and Estonia. They consider the possibility of bringing on stream more feedstock from fields, forests and seas, and also from the waste management sector, to augment the share of bioenergy in the respective national energy mixes. Bioenergy is verily a life-saver in Africa, where there is a reliance on using solid fossil fuel for cooking indoors. Sustainable management and future valorisation of biomass resources to food, feed, fibre, fuel and other bioproducts is indispensable for the struggling economies of Sub-Saharan Africa in particular [381]. Authors of a Kenyan case study [106] have compared the biogas stove, the biomass pellet–fired gasifier stove and the improved cookstove using wood logs, and concluded that the former has the smallest environmental footprint. This is good news as biogas produced from biowastes (manure, wastewater sludge etc.) is preferable to wood logs, the latter likely to lead in the longer run to deforestation.

While Costa Rica is known for its near-total green electricity (hydropower + wind + solar), it continues to rely heavily on fossil fuels for transportation and heat energy requirements in its economy. Valverde et al. (2020) [86] think that there exists good potential for forestry biomass to become vital inputs to the energy mix of Costa Rica's developing circular bioeconomy. Italy too is mulling over a sustainable forest-based bioeconomy [87], and the strategies which have been identified include, *inter alia*, the promotion of investment in forest infrastructure, and the enhancement of innovative forest-based value chains. Quite obviously, the way forward for any country is not merely to focus on technological knowledge creation and diffusion via pilot and demonstration projects, but also to give importance to the non-technological (socio-cultural, political, economic) issues affecting the development of a fledgeling circular forestry-bioeconomy [88].

Fractionating hardwood into cellulose, hemicellulose and lignin in biorefineries, while maintaining their potential for valorisation to not just biofuels but also other bio-products, is the focus of Olsson et al. (2019) [79]. Gschwend et al. (2020) [80] managed to also extract heavy metals from contaminated wood using a protic ionic liquid. A circular bioeconomy may sound like going back to basics, but it can very well utilise all the postmodern technological advances. Watanabe et al. (2019) [81] have presented the case of a collaboration between the Finnish forestry major UPM with Amazon which transformed the forestry-based bioeconomy into a digital platform industry, a co-evolutionary coupling which will be a hallmark of the burgeoning circular bioeconomy in the future [82]. Markstedt et al. (2019) [83] write about utilising cellulosic bio-wastes, sourced from forestry, to 'grow wood' by 3D-printing and produce a range of objects—from food packaging to pharmaceuticals to construction, and thereby reduce the rate at which trees for harvested. Prolonging the use of wooden products is tantamount to trapping the carbon in it for a longer time; here is where reuse, refurbishing and modular ('circular') design of wooden products (bio-based products, in general) become one of the defining characteristics of a circular bioeconomy [77, 84, 346]. Prolongation of use can be accomplished by creating a demand for recyclable wood-plastic composites, which has been posited as an environmentally attractive initiative which can be undertaken in circular economies of the future [78]. Talking of plastics, while bio-resources from which biopolymers can be produced are aplenty, some wood-based ones pose challenges when it comes to polymerisation. However, research seeks and often finds ways out of impasses such as these, and that is exactly what has been discovered by Stamm et al. (2019) [85].

Fisheries and Aquaculture

Gruduls et al. (2018) [91], in a Latvian case study dealing with round-goby fish wastes from the Baltic sea, have conducted lab-scale experiments to test the biochemical methane potential of said wastes when co-digested efficiently and sustainably with sewage sludge. Indeed, what applies to goby fish wastes, as the authors point out, will also apply to other species around the world. Wastes from different species of fish can be combined together for co-digestion with sewage sludge if lab experiments prove that benefits could be optimised by such an approach. When fishery wastes are hydrothermally treated, protein-rich peptones are obtained [93]. When these peptones were used as nitrogen sources to culture lactic acid bacteria (LAB) and marine probiotic bacteria (MPB), both of which find use in the food industry, researchers found that the production costs could be decreased by up to 75% and 98% respectively [94]. Bio-calcite—crab shells [92], oyster shells and gastropod shells—have been experimented with phosphorus adsorbents in wastewater treatment and for other value-added bio-products.

Microalgae and macroalgae (seaweeds in other words)—bio-extractors of nitrogen, phosphorus, CO_2 and toxic heavy metals from wastewater [9, 234, 235], sources for third-generation biofuels and good solutions to the food-fuel-fibre-feed impasse [64, 305], space constraints and land-use change issues in circular bio-economies—will hopefully be key environment-friendly contributors in what some researchers have termed as a blue bio-economy bolstered by advances in marine biotechnology [236–238]. The environment friendliness of algal-biodiesel can be augmented by replacing conventional solvents with greener alternatives [95], also advocated by Wang et al. (2021) [345]. Algae have other uses too, besides being energy sources—production of omega-3 fatty acids, natural food colorants, dyes, fertilisers, bioplastics [15, 156, 239], protein-rich fish feed for aquaculture [9] and pharmaceuticals [291], in a Cascading Algal Biomethane Biorefinery System or CABBS, a term introduced in [382]. As Venkata Mohan et al. (2016A) [90] recommend, with afforestation having its limits as a CO_2-sequestration strategy, harnessing the ability of diverse microbial taxa to take in CO_2, metabolise complex organic biowastes and yield valuable bio-products [265], is a strategy one must latch onto for, and in a circular bioeconomy.

Aquaponics refers to the breeding of fish and the cultivation of food plants (vegetables for instance) in an integrated system. Recycling the wastewater from the aquaculture sub-system to the hydroponics sub-system can be most efficiently done by using bio-trickling filters as reported by Pous et al. (2021) [96]. When eutrophic lakes need to be cleaned up, the excess algal biomass can be used as a substrate in microbial fuel cells to generate electricity. Experiments conducted by Ali et al. (2020) [97] with *Microcystis aeruginosa* have demonstrated improved electrochemical performance vis-à-vis conventional substrates. A nexus between algaculture via waste valorisation, and aquaculture, has been demonstrated in Bongiorno et al. (2020) [65]—microalgae cultivated on digestates from pig farms being fed to Siberian sturgeon.

Municipal and Industrial Solid Waste and Sewage Management

Simha et al. (2016) [25], adopting a technological approach, have experimented with urine diversion from toilets, using granular activated carbon produced from coconut wastes for the extraction of urea, to be recirculated back to the agricultural sector. This is an interesting give-and-take in a bioeconomy, with agriculture providing a waste-derived product to aid in the recovery of urea from human (bio-) waste to be sold back to the agricultural sector. They conclude that it is very much possible to ideally supply at least 20% of the total nitrogen demand for food production globally with urea recovery from urine. In a pilot study done in Finland, Simha et al. (2020) [66] have shown that source-separated urine can be subjected to alkaline dehydration and converted to a dry, nitrogen-rich fertiliser. Such separation to recover nitrogen from human wastes upstream, instead of recovering just a part of it as ammonium sulphate at wastewater treatment plants [36], can lead to greater biomethane production when the relatively nitrogen-poor stream of human excreta is anaerobically digested. This is due to a reduction in the inhibitory effect of ammonia on bacterial activity. Theoretically, if all the human wastes in China could be anaerobically digested for the maximum attainable biomethane production to generate electricity to substitute coal power, a reduction in emissions of 142 kt of CO_2-eq per day could be achieved, while substituting gasoline in transportation would yield a reduction of about 55 kt of CO_2-eq per day [107]. Recovery of phosphorus from the digestate is also a must in the years to come [36, 102, 157], with the phosphate reserves likely to dwindle rapidly, and is doubtlessly preferable to directly using the nutrient-bearing conditioned sewage sludge with some non-desirable organics and toxic heavy-metal content [26]. However, phosphorus extraction can also happen via gasification of the sewage sludge (or co-gasification with other types of bio-residues) which Werle et al. (2019) [102] advocate as the best option, and report that the phosphorus pentoxide content in the recovered by-product is close to that of naturally occurring phosphate rock. Agro-industrial wastewaters [125] are excellent sources for the recovery of struvite which, in addition to providing magnesium, nitrogen and phosphorus, also supplies potassium and calcium (macronutrients) and iron, sodium, copper, manganese, cobalt and zinc (micronutrients), making it a wholesome organic fertiliser option.

Restricting their focus to limiting zinc additions to soil through sewage sludge, Rigueiro-Rodríguez et al. (2018) [26] recommend the addition of smaller amounts of composted sludge as soil amendment, in combination with relatively larger quantities of anaerobically digested sludge or pelletised sludge, periodically replaced by synthetic (inorganic) fertilisers. Likewise, just blindly replacing synthetic phosphorus fertilisers with organic alternatives without testing if the agronomic efficiency of plant dry mass yield and plant phosphorus uptake is acceptable is not advisable [147]. After all, it is not just the presence of phosphorus in the soil but also its availability which determines the soil fertility. As far as the use of digestates and compost are concerned, there are health risks which need to be estimated. Longhurst et al. (2019) [131] have done exactly that in a UK case study and have concluded that these bio-fertilisers pose negligible risks to human, animal, environmental and crop receptors, when the appropriate stipulated risk management controls are adhered to.

Ferreira et al. (2018, 2019) [37, 38] experimented with the algal-bacterial treatment of different types of wastewater streams—swine, cattle, poultry, dairy, brewery and urban—to grow microalgae which was subsequently dark-fermented to yield bioproducts, while Wicker et al. (2020) [39] treated nutrient-rich liquid digestate with a microalgal-bacterial consortia to accomplish the triple objectives of wastewater treatment, nutrient recovery for reuse in agriculture and cultivation of biomass to be put to multiple uses [40]. Waste streams with higher nutrient concentrations resulted in a marked improvement in the microalgal productivity [37, 38, 41]. In a similar paper on the wastewater-microalgae-bioenergy theme, Belete et al. (2019) [42], in an Israelite case study, worked with the aqueous stream from hydrothermal carbonisation of activated sludge from wastewater treatment as a useful nutrient and carbon source for microalgae. While the algal biomass is an in-feed to the bioenergy sector, the treated effluent is diverted to irrigation of fields in water-scarce Israel, with optimised concentrations of nitrogen and phosphorus. Sutherland et al. (2020) [98] have shown that CO_2 augmentation of raceway ponds treating nutrient-rich wastewater streams with microalgae accomplishes a reduction in NH_3 volatilisation, greater biomass productivity courtesy a rise in nutrient uptake, and consequently, improved effluent quality to avoid downstream eutrophication. In case studies conducted on wastewater and lignocellulosic wastes in the UK [126], ion exchange was rated as the preferred technology for nitrogen and phosphorus removal from the former, while the integrated thermochemical and biochemical processes were recommended for the valorization of lignocellulosic bio-wastes to valuable bio-products.

Increase in biomethane potential is the focus of an experimental anaerobic digestion study carried out in China [108] with food waste, in which syngas produced by pyrolysing the substrate was reinjected into the digester to augment the biomethane output by 22% in the thermophilic reactor, vis-à-vis the mesophilic reactor, while biochar and bio-oil were also produced as valuable pyrolysis by-products. A resource-rich aqueous waste stream called the bio-oil aqueous phase results from the pyrolysis process. Borole et al. (2018) [271] have discussed a range of technologies like centrifugal separation, pH manipulation, capacitive deionisation, microbial electrolysis and electro-fermentation to generate electricity, and produce hydrogen and a host of bio-chemicals like alcohols, diols, medium-chain fatty acids and esters from the said bio-oil aqueous stream. High-yield extraction of carotenoids, tocopherols and flavonoids using supercritical fluid, pressurised liquid, microwave or ultrasound, from food wastes, is the focus of [273].

Chakraborty et al. (2019) [103] throw light on the hitherto-overlooked immense potential for generating biomethane and biohydrogen by co-digesting the huge quantities of food and vegetable wastes generated in India, all along the value chain, especially on the downstream, from restaurants and public eateries, while Sharma et al. (2019) [274] support vermicomposting (symbiosis between earthworms and microorganisms) as an effective, economical and environment-friendly approach when the purpose is simply to produce rich organic fertilisers. Vermicompost has been shown to be a better alternative than compost and digestate, as a replacement for peat, for the soilless cultivation of the perennial evergreen *Salvia officinalis* (sage, in common parlance) [67]. Dealing with wastes from tomato, orange, potato and olive processing units in Italy, the techno-economic analysis in Cristobal et al. (2018) [127] shows that it is usually economically more attractive to centralise the bio-refining by concentrating the production of the valorised bio-products and availing of economies of scale, albeit necessitating transportation of the feedstocks over longer distances. In a Canadian case study [132], interestingly, the authors have argued in favour of smaller and numerous biomass depots in a denser network. Decentralisation of biowaste management (valorisation) systems is the recommendation of [347]; the authors consider it to be 'a coherent supporting mechanism for achieving long-term climate goals in a circular bioeconomy'. These differences in viewpoints are testimony to the need for optimisation on a case-by-case basis, instead of generalising.

Replacing traditional anaerobic digestion feedstocks with food wastes has significant environmental benefits, not just with regard to reduction in GHGs, but also with regard to avoiding nutrient leakage to the hydrosphere, which would have occurred if the food wastes had been landfilled instead [128]. Interestingly, co-digesting livestock manure and mixed sewage sludge along with fruit, vegetable, coffee, fish-canning industry and crop wastes has been shown to enhance the biogas recovery substantially [68]. While most publications take food waste for granted and decide to focus on how it can be valorised in a circular bioeconomy [244], Oldfield et al. (2016) [10] adopt a different approach in an Irish case study. By differentiating between avoidable food waste and unavoidable residues (along the food chain), they evoke the first 'R' of the waste management hierarchy—reduce—and clearly show the immense environmental and economic benefits of minimising food waste as much as possible. This can be partly done by motivating changes in personal habits and consumer behaviour, in other words by entrenching sustainable consumption in a circular bioeconomy [43]. The other 'R'—recycle—comes into play in a social reverse logistics system called InnovOleum [133], within which households in Cyprus cooperate in the recycling of used cooking oil for subsequent catalytic transesterification to biodiesel and/or bio-lubricants, which now can be accomplished in different ways—acid/base, magnetic heterogeneous and biological [281]. InnovOleum's success is largely due to social acceptability followed by heightened awareness among the citizens who are willing to cooperate with the stakeholders, and understand very well the significance of the reverse logistics system [282] and the multi-functionality of the bio-waste in question [177]. Social acceptability goes hand in hand with top-down regulatory measures, as seen in Taiwan where the quantities of food wastes collected for recycling in anaerobic digesters and aerobic composting facilities quintupled over a 9-year period [283].

Co-digestion of diverse bio-waste streams like harvested water hyacinth and dairy wastewater, tested by [69], also yielded a wide range of bio-products, quite like in [108]. Even the leachate from the organic fraction of municipal solid wastes (MSW)—be it from collection trucks or landfills—which is looked upon as nothing other than an environmental menace, can be the source of medium-chain fatty acids [109]. Kwan et al. (2018) [101] and Zhang et al.

(2020) [123], by experimenting with saccharification of food and beverage sector wastes, using different combinations of enzymes, could establish the possibility of extraction of glucose and fructose therefrom. Techno-economic feasibility studies are awaited; nevertheless, this would be a small but significant step in the direction of reducing the stress on agricultural land as a source of sugar sources, while also being able to generate nutrition for insects (for entomoculture) [158, 266], proposed substitutes for animal protein in the medium term [159].

Pyrolysis has been the technology of choice, for olive mill solid wastes (OMSWs) in [70] and [27] and for eucalyptus wood fines in [89], to yield bio-oil and biochar, the former thereafter being valorised to a whole range of platform chemicals. Alternately, by subjecting OMSWs to thermal pre-treatment followed by anaerobic digestion, phenol and biomethane can be obtained [124]. The emphasis on ascending the so-called bioeconomy value pyramid is maintained in [148], with animal feed from OMSW being prioritised over compost and bioenergy. Environmental life-cycle analysis (E-LCA) of two olive agro-biorefinery systems, one producing biodiesel, triacetin, phosphate salts and an antioxidant for biodiesel, and the other producing animal feed and pomace bio-oil, showed that the environmental impact per ton of primary product (olive oil) could be considerably reduced by availing of the latter alternative [71]. Further support for use as animal feed comes from [137], in which E-LCA and life-cycle costing applied to different valorisation alternatives for food waste showed that use as animal feed is environmentally and economically more attractive than the conversion to organic acids. Using agro-industrial by-products as animal feed, to replace a part of the cereals fed to beef cattle, did not affect the quality of the meat in any way, as shown by Diaz et al. (2020) [72]. Part of the animal feed manifests as manure which again is a biorefinery input. It yields biogas when the solid fraction is digested anaerobically, and bio-oil, when the liquid portion is subjected to hydrothermal liquefaction [138]. While scenarios with bioenergy production were shown to rank higher on a scale of environmental sustainability in [110], the profitability, intuitively, will be greater if the wastes are valorised to bio-chemicals and bio-polymers [284]. An E-LCA of an anaerobic digester and a combined heat and power (CHP) plant handling biowastes done in [111] established the environment friendliness of this combination when compared to composting biowastes and sourcing power from the Italian electricity grid. From an energetic, economic and environmental perspective, Yaashikaa et al. (2020) [285] have recommended the anaerobic processing of MSW over all other available treatment alternatives. It is, for that matter, a well-entrenched process in biorefineries valorising agricultural residues and livestock wastes, and finds favour with many other researchers too [178, 179]. While OMSWs have been the foci of a handful of publications referred to above, Zabaniotou et al. (2018) [129] have focused on sunflower meal, a by-product of sunflower oil production, which can be cascade-refined to antioxidants, protein isolate, biochar, pyro-oil, pyro-gas, poly(3-hydroxybutyrate) and microbial oil. Sustainability assessment performed for biorefineries in two different countries in Africa—Egypt, using cassava peel, and Ghana using corn stover [73]—showed that the former was more sustainable from both donor and user perspectives.

Positioned at the confluence of waste management and agriculture, Sayadi-Gmada et al. (2020) [74] are of the opinion, that reduction in the generation of inorganic wastes originating from the agro-sector must not be deprioritised in a circular bio-economy which tends to focus a lot more on the recovery and valorisation of the bio-wastes. For that matter, even if bioplastics replace petroleum-based plastics in the technosphere, they need not necessarily be considered bio-energy sources at the end of their lifetimes. The circularity pertaining to material recycling can very well be repeated [275], provided the design-for-recycling concept is strictly followed when products are fabricated from biopolymers, and it is ensured that appropriate recycling infrastructure is in place [252]. Panagiotou et al. (2018) [117] have proven that waste eggshells (from anywhere along the egg supply chain, right down to the consumers and MSW management) are effective adsorbents for phosphorus in effluent wastewater from anaerobic digesters, prior to being potential bio-fertilisers in the form of brushite—hydrated calcium biphosphate. The adsorptive capacity of eggshells also makes them excellent bio-flocculating media to gather microalgal cells for harvesting (as proven for *T. obliquus* algal cells in [99]).

However, one must not generalise the supposed environmental benefits of waste valorisation, as shown by [112], in a UK case study—environmental impacts due to biodiesel production from spent coffee grounds (SCGs), which would rank higher on the biomass value cascade in a circular economy than energy recovery, are greater than those due to anaerobic digestion, landfilling and incineration (all three with energy recovery), composting and direct application on land, for a host of impact categories. The authors have suggested that decarbonization of the UK electricity mix and 'greening' of the solvent used in the transesterification process for biodiesel production from SCG will serve to make it much more eco-friendly than it turns out to be in the paper. By blending the SCG oil methyl ester with Euro diesel, pentanol, octanol and butanol, Atabani et al. (2020) [113] have shown that the density and cold flow properties of this multi-fuel blend approach that of pure Euro diesel. Still on coffee, Del Pozo et al. (2019, 2020) [104, 114] have pyrolyzed coffee silverskin—by-product from coffee roasting which is usually discarded as industrial waste—to yield energy-rich oils, antioxidants and biochar. While Rajesh Banu et al. (2020) [245] believe that a positive net present value (NPV) can be achieved if the product portfolio of an SCG-biorefinery can be diversified, further research has however been recommended into the economic feasibility and environmental desirability of extracting valuable by-products from SCG [104, 253].

Bioenergy and Others In an interesting case study from Sweden [115], the authors have performed a techno-economic analysis of a state-of-the-art technology for the so-called carbon capture, utilisation and storage or CCU/S, in a circular bio-economy which knits together agriculture, MSW management and forestry on the one hand as sources of wastes, the bio-energy sector as an user of these wastes and the construction sector as the secondary user of the biogenic CO_2 emitted by the CHP plants. While agriculture and forestry are primary sources of bio-wastes, MSW management is a secondary source, and the bio-energy sector (which is one of the destinations of the bio-waste flows) can be looked upon as a tertiary sector of 'recyclables', in this case, biogenic CO_2. The CO_2 is sintered into high-quality concrete blocks, and thus carbon negativity is achieved. Carbon negativity is indispensable moving forward if climate change has to be effectively tackled. However, without political will and support with incentives, subsidies and tax rebates, the authors aver that such creatively destructive technologies may struggle to entrench themselves. Talking of concrete blocks as entrapments for biogenic CO_2, designing concrete constructions from a circular bioeconomy point of view is the focus of [295], with infrastructure taking over some of the responsibility of carbon sequestration from the forests of the world. CO_2 capture and conversion can also be done using chemolithoautotrophic microbial electrosynthesis (MES) [255], or methylotrophic yeasts [75], whereby atmospheric CO_2 is captured and reduced and useful bio-chemicals are synthesised [90]. Just as CO_2 can be captured in concrete blocks, it can also be sequestered in bio-polymers, using the photosynthetic machinery RuBisCO (ribulose-

1,5-bisphosphate carboxylase/oxygenase). Glycolate-based copolymers have been synthesised using this approach [105].

Another tertiary source output is glycerol from biodiesel production which, Giacombono et al. (2019) [383] look upon as a valuable starting material for the production of citric acid, a chemical which finds use ultimately in the food and pharmaceutical sectors. Biocarbon/biocoal—a product of biomass pyrolysis—has been touted as a substitute for non-renewable talc and glass fibre fillers for polypropylene automotive components [105, 384]. If a single output process chain is challenged by unfavourable economics, clever thinking to tide over this challenge is a vital aspect of a successful circular bioeconomy, as Etchegaray et al. (2017) [100] have shown with *Bacillus amyloliquefaciens* OG, which yields biosurfactants, biodiesel and p-xylene.

Theoretical Publications, Descriptive Accounts, Overviews and Reviews

Focussed

Mandegari et al. (2017) [142], in a publication originating from South Africa (known for its sugarcane plantations), have reviewed publications which have carried out techno-economic analyses of technologies available for the conversion of sugarcane bagasse, juice, trash and molasses in 'biorefineries' into a gamut of bio-products ranging from, in ascending order of created value, heat and electricity, biofuels, biochemicals and biopolymers. Lignocellulosic waste streams from sugar mills, being utilised to produce a plethora of value-added products, provide the perfect solution to the food-fuel-feed-fibre conflict (also raised in [14] and [327]) which has arisen courtesy the first-generation biofuels produced from corn, wheat, sugar beet etc., and significantly improve the NPV of sugar mills, which otherwise struggle to be economically feasible by relying solely on sugar production [16, 217, 328]. Biorefineries of the future ought to resort to technoeconomic and environmental analyses to find the right combination of 'green' technologies and processes to expand their product ranges, and do so, with a minimal social footprint [14, 180, 181, 246, 256, 348, 349]. When it comes to biorefineries utilising waste streams from sugar mills, Farzad et al. (2017) [16] have shown that thermochemical routes are more environment-friendly than biochemical ones. Silva et al. (2018) [200] have discussed the prospects of enzyme-based treatment of lignocellulosic wastes, which at the time of writing is a nascent technology likely to catch up in the years to come, while Cao et al. (2019) [206] have dwelt on the need for effective depolymerisation of lignin to valorise it into high-end 'green' chemicals. Speaking of technologies and waste streams, Zuin et al. (2018) [149] have discussed solvent, microwave, ultrasound and supercritical treatments, on a host of agro-industrial wastes associated with citrus products, coffee, corn and sugarcane, to yield valuable outputs like polyphenols, proteins and essential oils for the food/feed, bio-chemical and bio-pharmaceutical sectors. The potential is proven and huge and, with the right 'industry 4.0' technologies chosen after critical assessment, must entrench a robust national/regional/global circular bio-economy based on multidisciplinary collaboration, utilising agricultural and forestry wastes optimally, in the future (as exemplified in case studies identifying research priorities in a future Spanish bioeconomy, by [28]; in the economies in the Danube region by [308]; and in [182]). Some of these '4.0' technologies have been referred to, in a paper focusing on the agro-food sector—robotics, nanotechnology, synthetic protein, cellular agriculture, gene editing technology, artificial intelligence, blockchain and machine learning [183].

The adjective ‘optimally’ is implicitly evoked in [329], in which the authors refer to four levels of residual biomass potentials in decreasing order of magnitude—theoretical (determined by biophysical limits), technical, economic and sustainable (all three determined by practical considerations). The pulp and paper industry is associated with forestry and while one of its waste streams—lignin—which is conventionally looked upon as a source of heat energy in plant can potentially be refined to yield biochemicals, biopharmaceuticals and biopolymers [218], economic infeasibility and a weak market pull are hurdles to the large-scale commercialisation of lignin biorefineries, which have to be overcome [184].

While thermochemical liquefaction using green solvents is supported as an economical, effective and environment-friendly technology [119, 185], Song et al. (2020) [185] have pointed out that continuous availability of biomass [350] would be a prerequisite for the upscaling of advanced bio-refineries. Now what if the availability of bio-wastes from any of these sectors is constrained? Kallio et al. (2018) [201] have discussed the economic and (consequential) environmental impacts of constraining forestry harvests in the EU and Norway in order to sustain the capacity of the forests to be able to both fuel a circular bioeconomy [207, 208] and act as carbon sinks for a long time to come. This sustenance is indispensable in the light of the fact that wood biomass is the main source of bioenergy in the EU, and figures prominently in its post-2020 bioenergy policy [385]. One however must be aware of the pitfalls of a blind unilateral policy in this era of globalisation, which is sure to shift problems out of the EU and Norway and result in a rise in harvests in countries with improperly managed forests and thereby unintended environmental consequences [330], and a possible net decrease in the capacity of the world’s forests to be carbon sinks. Not just that; they also anticipate a drop in wood availability resulting in a rise in demand for GHG-adding substitutes like concrete and steel [201]. Forest areas are quite common in the Nordic region in and around urban conglomerations, but not so much in southern and eastern Europe, which, according to [209], will benefit holistically if afforestation projects can be planned in or on the outskirts of cities thereof.

In a paper which has challenged several established patterns of thought, van Zanten et al. (2019) [160] have questioned the relevance of the existing food-product-footprint approach and the generalised preferability of locally produced food over imported alternatives, to guide decision-making in moving towards circular food systems. As a stop-gap *en route* from a meat-based lifestyle to a totally vegan (or vegetarian) lifestyle, the prioritisation of bio-wastes from farms and fields (and aquatic habitats) as feed for animals has been advocated in [160] and [150]. This point of view is in direct contradiction to what is supported by [31] (referred to in an earlier sub-section).

Bolwig et al. (2019) [276], in a Danish study, have also argued in favour of looking beyond using brewer’s spent grain as animal feed, while recognising the potential of this industrial bio-waste to yield high-value bio-products for the chemical and pharmaceutical sectors. Chinese researchers [116] have estimated the potential of reducing the GHG footprint of whiskey production by producing biogas in-plant and netting in revenues from the sale of surplus electricity, through dark hydrogen fermentation and anaerobic digestion of the wastes generated. Still on alcohol, winery wastes—leaves, stems, pomace, marc and vinasse—can be subjected to advanced biorefinery processes to yield a variety of biochemicals [186, 187] and, in addition to providing economic and environmental benefits, will also contribute to preserving the aesthetic appeal of the rural landscapes in wine-producing regions [188]. In another instance of looking beyond animal feed, Herrmann et al. (2019, 2020) [189, 262] have written about the alternate uses the enzymes—phytases—can be put to—food processing and environmental resource management wherein it can be used to release organically bound phosphorus (bound as phytate) and improve plant availability and uptake. In an analysis of the Norwegian food industry's role in a circular bioeconomy [272], the authors emphasise the importance of innovative thinking, and recommend the use of second-grade vegetables for the production of smoothies and the use of potato peels as inputs for bioplastics. Proteins as biomacromolecules have been touted as super-absorbent polymers which could soon replace non-renewable materials in the production of healthcare and personal care products like sanitary napkins and diapers for instance [254].

Industries using bio-based raw materials are surely key players in a circular bio-economy, but so are MSW-management utilities. The waste-to-bioenergy (high-calorific value bio-hythane from food processing wastes in [246]) route can very well play a role in mitigating the negative environmental impacts associated with the bioenergy sector in general—loss of biodiversity, abiotic depletion, eutrophication and land-use change [242]. An advanced circular bio-economy of the future can very well move up the value chain (or more appropriately 'value circle', according to [330] in this context), and in doing so generate 10 euros of added value in the EU, for every euro invested, if adequate public consensus can be sought and attained, and both supply-side and market-uptake policies could be simultaneously strengthened [143]. It is also important to resolve any transportation issues that may exist when bio-waste from one value circle in one region has to be connected to another value circle in another region for transformation and re-induction into the economy [330]. It is here that one can refer to the bioresource-mapping model developed by Attard et al. (2020) [351], with Ireland and Andalusia (Spain) as examples. This is a useful decision-making aid for entrepreneurs interested in investing in greenfield biorefineries. They have also written that while animal manure is the dominant bio-resource in Ireland, olive residues figure at the top of the list for the Spanish region. In India, for that matter, the potential of the waste-derived 'circularised' bio-economy is yet to be tapped fully, with absence of proper source segregation and the lack of awareness about bio-wastes as high-value resources, being key hurdles [161, 202]. Open dumping and burning of bio-wastes are founts of concern for human health and the environment in South Asia [180].

Croatia, an EU country where marine littering is a problem, also has to overcome a host of hurdles *en route* to a possible circular bio-economy in the future [286]—non-existent landfill tax which provides no incentive for biomethane capture, poor market for recycled materials, the lack of financial support from the government, absence of separate collection of bio-waste, the urgent need for awareness generation among the citizens and education in schools and universities and, as observed in [208], the want of circularity in the country's wood-based sector. It is imperative to valorise the organic waste fraction of MSW and the vast quantities of food supply chain wastes generated around the world [130, 144, 260, 263, 277]. In the EU, for one, the degree of composting has risen at an annual average rate of 5.4% over a 20-year period from 1995 to 2015 [143], while the share of disposal in landfills has shrunk conspicuously. Chia et al. (2020) [190] have pointed out that compost can also be used as a fuel source for the generation of electricity. Teigiserova et al. (2019, 2020) [278, 287], by differentiating between avoidable and unavoidable food waste, define a category inedible and unavoidable food wastes (IUFWs) collected upstream of the end-consumer, which they consider the feedstock for valorising into high-end products like acids, colorants, enzymes, proteins and bioplastics, with oily fatty-acid wastes in particular being candidates for microbially assisted conversion to polyhydroxyalkanoates (PHA, biopolymers in other words) [120, 257, 258]. Microbial proteins are released during the PHA production process which can be captured and utilised as animal feed and for the production of bio-adhesives [267].

Food-waste valorising refineries in bioeconomies are advised to match the technology of choice to the market price and demand of the bio-products—fermentation for instance being chosen for lower-priced products like acids (citric acid etc.), and energy-intensive options availed of, for higher-value ones like colorants (anthocyanin, lycopene etc.) [278]. Ojha et al. [191] have linked entomoculture with food waste management, with the edible insects doubling up as both protein sources and bioconversion agents, to work on food waste and valorise it to fertilisers and animal feed.

Paes et al. (2019) [279], in their SWOT analysis of organic waste management, have however emphasised on doing more to eliminate the threats that exist and the weaknesses that prevail, *en route* to a full integration of organic waste management in a global circular bio-economy. The theoretical convertibility of these huge masses of diverse organic waste streams, thanks to different hydrolytic enzymes [352], justifies investments in a range of advanced and innovative thermochemical and biochemical approaches in integrated phase III biorefineries [180], with the backing of 'green' venture capital [143, 144, 202]. Kircher (2015) [240] had observed that bioeconomic policies tended to favour biofuels and bioenergy, at the expense of other higher-value bio-products, but that seems to have changed since then, with bioenergy increasingly being integrated with the cascade biorefinery models [151, 243]. Yet, this does not in any way mean that bioenergy must be deprioritised, as observed by Theuerl et al. (2019) [162] in their 'visionary' review of future automated, flexible and adaptable, modular, information-driven and highly efficient agricultural biogas plants handling a wide variety of feedstocks, in Germany. They claim that biogas plants will continue to be the keystones for residue management in agriculture, enabling in part a true soil-to-soil circular flow in the form of the digestate used as a substitute for inorganic fertilisers, a view also held by [329]. Germany may well become the benchmark for Ukraine, which, as Havrysh et al. (2020) [247] write, has not fully harnessed the energy potential of its agricultural and industrial bio-wastes. While a soil-to-soil circularity is indeed desirable, ensuring that there is satisfactory nutrient transfer from the biofertilizer to the roots is extremely necessary, and this can be done by inoculating the soil with beneficial microorganisms like rhizobia and mycorrhizal fungi [163].

If Chen et al. (2019) [31] have considered the bio-waste-to-bio-fertiliser route to be more suitable for a circular economy, and van Zanten et al. (2019) [160] have prioritised bio-waste-to-animal-feed to circularise the food sector, Ren et al. (2019) [164] in a vein similar to the one adopted by [175] have favoured the abolition of straw-burning in Chinese fields, and the gravitation towards a 100% circularising of the straw waste generated in the country, to produce biofuels and building materials. This, the authors believe, is possible only when subsidies and tax rebates work together with penalties and fines inter-regional collaboration improves, and storage-transport infrastructures are beefed up, to trigger incentives for change and substitution, quite similar to what has been recommended for the competitiveness of biomethane vis-à-vis natural gas in Malaysia [50]. The economic viability of biorefineries utilising soyabean, palm, rapeseed, sunflower, jatropha, microalgae, yeast and activated sludge to produce biodiesel is a key factor, and public policy initiatives and concerted research and development (R&D) will most likely enable biodiesel to compete with petroleum-sourced diesel in the years to come [165]. While the fatty-acid-fraction of yeast is valorised to biodiesel, the non-fatty part is used to extract carotenoids, as reported by Passarinho et al. (2020) [76], in their study with *Rhodosporidium toruloides* NCYC 921.

While forestry wastes can be effective aids in the adsorption of oil spills and heavy metals from wastewater and aquatic ecosystems [24], inexpensive bioremediation of wastewater and the pedosphere with bacteria, fungi, yeast, algae and plants to remove pharmaceutical and personal care products (PPCPs) has been propounded as an essential ingredient of a bioeconomy [248, 249]. Activated carbon produced from yeast residues [139] and nanoporous carbon from mango wastes [192] have been shown to remove compounds like dipyrone and atrazine respectively from synthetic aqueous effluents. The microalgae and the macro-phytoremediation agents subsequently can be used as sources of bio-energy (where there is a bioaccumulation of the PPCPs) or as food/feed and bio-fertiliser where the PPCP has been degraded/metabolised after bio-absorption. The microalgal ponds used to treat wastewater also build up a wonderfully symbiotic relationship between aerobic bacteria utilising oxygen produced by the photo-autotrophic microalgae (which can also be looked upon as CO_2-sequestering agents in a circular bio-economy), to degrade the organics in the wastewater and improve the effluent water quality, while providing nutrient-rich algal biomass for valorisation downstream [193, 232, 238, 248, 250, 280]. Focusing on a specific type of microalgal biomass in their study—*Arthrospira* spp.—Mitra et al. (2019) [233] have recommended the extraction of both high-value and low-value bioproducts, in order to move as close as possible to ‘zero waste’ and maximise the returns from the investment, by adopting what has been referred to as ‘integrated hydrothermal and biological techniques’ by [353]. As far as wastewater treatment is concerned, a promising addition in a future circular bioeconomy could be the so-called bio-electrochemical systems [251], which directly transform wastewater to electricity and chemicals.

General

In an interesting much-cited analysis of the paradigm ‘green economy’, Loiseau et al. (2016) [6] have discussed the relationships among different theories, concepts, approaches and tools. The authors have concluded that bioeconomy, typically, has a link to weak sustainability and advocates a high substitutability of natural capital (natural resources) to anthropogenic capital (read technological advances in resource recovery). In other words, in a bioeconomy, there is not so much pressure on humans to alter their lifestyles. Birner (2017) [296] advocates a shift in the bioeconomy from a mere resource substitution perspective to a biotechnological innovation perspective. The term ‘ecotechnology’ fascinates Haddaway et al. (2018) [309] who have traced the coinage back to the 1970s—technology for a circular bioeconomy when viewed from an ecological perspective. However, the agro-ecological and biotechnological perspectives have not attracted as much attention from researchers, as the resource-management perspective of a bioeconomy [386].

Bioeconomy preaches techno-optimism, while a circular economy advocates techno-realism, and a bioeconomy, by itself, cannot be deemed to be sustainable [297]. It is for this very reason that De Oliveira et al. (2018) [310] have considered bioeconomy, circular economy and sustainability to be three different but overlapping 'trends' in mitigating environmental impacts. But when we consider a 'circular bioeconomy', we at once make that giant leap from weak to strong sustainability [311]. The nascence or 'emergentness' of a bio-economy [331] makes it an interesting field of learning, research and industry for the years to come. It continues to evolve as new and existing technologies [292], inputs and ways of interworking and bridge-building between biotechnology and economy, as well as between science, industry and economy, are experimented with [387]. This makes a watertight definition impossible and inadvisable at the time of writing [312, 331], with the 'bioeconomy' being looked upon as a 'chameleon of notions' and a 'master narrative' attracting rival visions [332], and a harmoniser of circular economy, climate protection and the growth philosophy [313].

In Muizniece et al. (2018) [314], the authors have identified nexuses of importance in a circular economy, green economy and what they term a 'biotechonomy' (an economy bolstered by biotechnologies), and have identified 22 impacting/impacted and enabling/enabled factors which come into play in decision-making. Every one of these 22 factors has a nexus/link to every other, in our wheels-within-wheels postmodern existence, necessitating the implementation of a circular bioeconomy as an integrated system [354]. Buchmann-Duck et al. (2020) [355] are concerned that biodiversity protection is rarely mentioned in theory or policy related to circular bioeconomy and caution against relegating it to the background. Greater reliance on bio-resources in the name of holding back the rate of abiotic depletion and controlling a handful of other environmental impacts may just create a new set of problems in the biosphere—associated with a loss of biodiversity. However, harking back to an earlier reference [242], the waste-to-energy component of a circular bioeconomy may well turn out to be a biodiversity-conserving strategy.

Writing after [6], D'Amato et al. (2017) [298] and Gregorio et al. (2018) [315] reviewed literature for 'circular economy', 'bioeconomy/bio-economy' and 'green economy' separately, while D'Amato et al. (2019A) [333] did a survey to identify shared or divergent opinions among researchers. They advocated a reciprocally integrative approach like [316] before them, based on an understanding of their overlaps, synergies, divergences and limits, instead of mistaking these terms for being mutually substitutable ones, an exercise which was also undertaken later by Carus et al. (2018) [317]. Green economy, which is a broader 'umbrella' concept, factors in social sustainability as well [6, 298, 356, 388], implying that the scope of the adjective 'green' has to be expanded beyond just environmental concerns [293, 357]. Circular bioeconomy (the synergistic combination of CE and BE in other words) is represented by a small sliver which is associated with techno-knowledge fixes to enable economic growth with a relative decoupling from environmental impacts [298], while Giampietro (2019) [334] describes it as a combination of a desirable 'what' (circular economy) with a viable, feasible and desirable 'how' (bioeconomy).

The concept of 'cascade utilisation' (CU) has been around for quite some time, and can be traced back to literature from the early 1990s. It is defined in Bezama (2016) [270] as the 'qualitative and quantitative measurement of the temporary material stocks associated with characteristic individual products in a system during their use phase, and used to estimate the potential types and quantities of materials that are available for the recycling infrastructures at a certain time'. Introduced and popularised by the Europeans

(Germans especially) as a policy matter, it has been, by default, applied to bio-based materials, especially wood from the forestry sector [203, 204, 318, 332], with the primary goal being the creation of profitable business opportunities from the versatility of wood-based resources [210, 289]. However, the large-scale cascading of wood from forests can only be enabled by the sustained presence of inducements, legislative obligations or demand from end-use sectors [205, 219]. Construction is evidently one of the end-use sectors for wood, and the Finns have pioneered the wood-frame multi-storey construction which is gradually entrenching itself in Finland and also some other cities of Europe [220], and attracting attention in North America as well [221]. As Mair et al. (2017) [199], in their attempt to find similarities and differences between the ways the concepts CU and CE are interpreted and used by researchers, advise, CU can be considered a concept that forms a bridge between CE and a bioeconomy, in effect giving birth to what we are dealing with in the present paper—a circular bio-economy as a vision for the years to come. It follows that the default association with wood can very well be extended to encompass all other bio-resources which lend themselves to utilisation in a cascade and thereby prolongation of lifetime, before being combusted for energy recovery. If value addition of the waste streams can happen via new bio-based products, smaller economies can develop their export markets, and narrow their trade deficits (or augment their trade surpluses) [335]. Cultivated biomass itself can be exported for conversion in refineries to biomaterials and biochemicals, to optimise the eco-efficiency of national bioeconomies, as Ngammuangtueng et al. (2020) [194] have recommended for cassava grown in Thailand. Instead of operating in silos [319], the primary sectors of the bio-economy and their associated downstream process sectors can very well seek inspiration from each other's innovations, and uncover synergies to establish industrial-symbiotic partnerships that may not yet have been identified and be flexible enough to respond to fast-changing external factors [11, 195, 270, 336]. Wreford et al. (2019) [337] concur with [319] and [358] when they state that the largest barrier to the strategic development of a bioeconomy is the inertia caused by the lack of a cross-sectoral top-down strategy with clearly defined goals, indicators and incentives. The EU has chalked out its key strategic orientations for the support of research and innovation towards the first strategic plan for Horizon Europe 2021–2027, and among them, figure nature-based solutions for sustainable and circular use of bio-resources [338, 359], an imperative for post-Covid rebuilding. With tourism likely to be resuscitated from year 2021 onwards, Maugeri et al. (2017) [299], in their Sicilian case study, has advocated a closer look at the role the tourism sector can play in supporting and sustaining a circular bioeconomy on the Mediterranean island.

Mengal et al. (2018) [319] have written about the Bio-based Industries Joint Undertaking in the EU, which proposes to remove obstacles to private investment, and facilitate the delivery of bio-based products made from domestic renewable raw materials in advanced biorefineries adopting innovative technologies, superior, or at least comparable, to non-bio-based products in terms of price, performance, availability and sustainability, and in the process, create several employment opportunities. Duan et al. (2020) [196], while chalking out a similar agenda for the future of the Chinese circular bio-economy, which is also being bolstered in the country's universities by way of new post-graduate courses in bio-based circular economy [339], have used informative and attractive graphics, and references to numerous case studies, and, similar to [294], have listed a range of conversion technologies in an advanced biorefinery—continuous and semi-continuous fermentation, anaerobic digestion, transesterification, gasification, pyrolysis, enzymatic hydrolysis, enzymatic saccharification, composting etc., to yield a host of high-value bio-products in order to facilitate an attractive return on investment in the said technologies [320]. Ferreira et al. (2019) [389] point out that an integrated waste biorefinery model incurs lower capital investment costs and with the selection of appropriate technologies, and a widening of both the feedstock diversity and thereby the bio-product range results in higher revenues and is poised to become an indispensable part of a circular bioeconomy [14, 180, 246].

While understanding the perceptions and perspectives of consumers, and their possible reluctance to behaviour change, cannot be overlooked [211, 290, 360], cooperation and collaboration among stakeholders—both local and international—is key in a sustainable and durable circular bio-economy [11, 350, 361]. Limited consumer interest and acceptance may be a major stumbling block to the progress of a circular bio-economy [300, 332]. Generating awareness among, disseminating information to, seeking consent and acceptance from and respecting the opinions of all the stakeholders, social groups and competent authorities involved, is of paramount importance, as Kokkinos et al. (2020) [361] have emphasised while introducing their Fuzzy Cognitive Map Decision Support System for the smooth and successful transition to a circular bio-economy for the Thessaly region of Greece; Devaney et al. (2018) [321] have advocated for Ireland; DuPont-Inglis et al. (2018) [322] for the EU as a whole; Wozniak et al. (2021) [362] for Poland; Holmgren et al. (2020) [222], Lukina (2020) [223] and Temmes et al. (2020) [224] for the forestry sector—in general, in Russia and Sweden-Finland respectively.

After all, a circular bio-economy is a political (inter-governmental), industrial and societal initiative, necessitating, inter alia:

- instillation of a flexible and encouraging organisational change culture in the value chains [211, 225]
- stronger private-public partnerships [323]
- innovative approaches in addition to ‘technology-push’ traditional R&D or a piecemeal approach to different technologies [323]
- willingness to establish bio-based industries to attain self-sufficiency in essential commodities (as exemplified for bio-nutraceuticals in Italy [268])
- collaborations

  between ‘conventional and non-conventional entities’ in the economy [322]
  among various disciplines in academic and industrial research [288]

- rural recapitalisation and integration of marginalised communities [226]
- robust institutional structures at local and regional levels [363]
- systems thinking at all levels [364, 365]
- strong governance, an effective policy mix, appropriate legal framework conditions and innovative approaches [227, 340, 366]
- a revamp of quality standards to accommodate recycled bio-products [166]
- changes in entire systems through the joint efforts of researchers, technology centres, industries, the primary sector, new entrepreneurs, consumers, civil society and governments [140, 291, 324, 325, 330]

- reimagination of cities which house over 50% of the global population, are centres of direct and indirect consumption of resources and are often vilified as exporters of ecological ‘bads’, as sites of bioeconomic value [367]

It is here that post-modern technologies like cloud computing, social networks and big data promise to be useful enablers [301], while bioinformatics [368] and econometric models [241] are effective decision-making aids for firms to develop a clear future-oriented vision of the goals they wish to pursue [369], to be able to adopt a triple-bottom-line approach and make the most of novel business opportunities [228, 229].

The importance and relevance of so-called bio-economy indicators for the EU (complementary to those of the Sustainable Development Goals of the United Nations), which, post-weighting, could be aggregated to a ‘single-score’ bioeconomy index, have been emphasised by researchers [228, 229, 362, 370, 371, 390]. The effectiveness of the ‘single-score’ also applies to communicating the results of E-LCA which is a prominent decision-making tool in a circular bio-economy [302, 336].

Conclusions

The focus in this systematic review was on articles, reviews, book chapters, short surveys, editorials and conference publications, focusing on aspects of a circular bioeconomy/bio-economy. Only Scopus which is known to be the largest database of peer-reviewed journal publications was mined and 385 publications downloaded and reviewed enabled the author to fulfil the primary goal of this paper. The categorisation into different sectors of the economy and the presentation of key results to disseminate information about successful initiatives on a range of scales, to inspire similar efforts in different parts of the world, satisfactorily fulfilled sub-goal no. 1. The presentation of recommendations for future research and identification of threats as well as opportunities, in the latter sub-sections of the Discussion section, fulfilled sub-goal no. 2. There surely are numerous publications focusing on various aspects of a circular bioeconomy, which may not have used that term explicitly in the title, abstract or keywords, giving some solidity to the viewpoint that this is just a trendy new expression for something which has been inadvertently practised in some parts of the world, for several years now [214].

A sustainable bioeconomy is only feasible if, and only if, all three pillars of sustainability [372] are accounted for, from the very beginning. Though complete circularity is utopia, an idealised concept [330], and is obviously not realistic or feasible, not trying to improve the degree of circularity in the economies around the world, will make the prevailing situation even more dystopic than it is, as the scarcity of resources will keep looming larger and larger with time [141]. The need of the decade/century/millennium is to focus more on value creation in order to cover costs (positive and constructive thinking) instead of conservatively thinking more on the lines of traditional cost reduction.

Eco-innovation is driven by a combination of regulatory push, technology push/pull, market pull and firm strategies [140, 303, 324], and the circularity principle needs to be incorporated in co-design and co-innovation too, making it an iterative, ‘outbound and inbound' process [152]. Innovations for a circular bioeconomy are fourfold, according to Bröring et al. (2020) [373]—product substitution, new bio-based processes, new bio-based products and, last but not the least, new behaviour. Gregg et al. (2020) [197], in their review of the dairy, brewery, slaughterhouse and forestry industries, have discovered that while the former avails of a strong and guaranteed market pull to invest in bio-waste valorisation, the other three are hampered by the lack of the same and thereby are, by and large, fence-sitters in many parts of the world. Establishing a market pull is necessary for the entrenchment of a circular bio-economy, which can contribute to the attainment of 53 targets in 12 of the 17 SDGs [371, 391] by year 2030, at which time, its value will be equal to USD 8 trillion [374].

Draft versions of bioeconomy strategies have been approved in many countries, while some others have, reportedly so far, prepared feasibility study reports/policy papers, identifying their priorities and strategies for the transition to a circular bioeconomy [304, 341]. A qualitative assessment of national and regional strategies, carried out in Finland, Spain, Slovakia, Greece, Romania and France, revealed that bio-based circular economy was hardly ever included as a term [342]. Academic researchers have to take up the responsibility of educating the unaware and sceptical sections of the population, about the long-term benefits of the transition to a circular bio-economy, while collaborating more actively with the so-called bio-entrepreneurs in the industry [140, 343]. More empirical research on company-level implementation of circular bioeconomy business models is likely to happen in the future [230], setting examples for the laggards. Circular bioeconomy will increasingly be a topic of research in universities in the years to come, courtesy investments committed by the EU for R&D [326], resulting in a rapid rise in the number of publications in peer-reviewed journals. This has to be supplemented by popular-science articles to bust jargon and widen outreach to non-experts, who outnumber by a considerable extent, the experts at whom scientific journal publications are targeted.

As pointed out in [305], multiple criteria decision analysis (MCDA) for sustainability is valuable but not without its limitations when applied to immensely complex systems. Harmonisation of E-LCA methodologies is called for [375] and the tendency to prioritise climate change over other impact categories is to be avoided [231], and the system boundary for the evaluation of socio-economic benefits must be widened [269]..

To summarise and conclude, the circular bioeconomy can be visualised as a set of 'many (multi- feedstock – [392]) through many (processes and technologies and pathways – [292]) to many (end-use value-added bio-products or end-use sectors in the global economy)' relationships, enabling both economies of scale and scope in the longer run. This is what makes it at once interesting and confusing, as decision-making becomes a wee bit complicated, entailing triple-bottom-line thinking if the circular bioeconomy one intends to entrench is also to be sustainable. Numerous barriers will have to be overcome [376]. Stakeholders have to be convinced that they are on the right path [377]. But as one knows and will appreciate, challenges lurk where there exist opportunities to be availed of. The take-make-use-dispose paradigm of a linear economy will hopefully be replaced by the grow-make-use-restore alternative as extensively and as soon as possible [198], as technical constraints are gradually resolved and the challenges to the upscaling of biowaste valorisation are surmounted [378].

Appendix

Table 1 The spread of the published literature

Case studies and quantitative analyses

Sectoral focus/foci*	**2015**	**2016**	**2017**	**2018**	**2019**	**2020–2021**
Agriculture		[9, 10]	[11–16]	[17–28]	[29–43]	[39, 44–76]
Forestry			[11, 14, 77, 78]	[24, 28]	[79–85]	[55, 80, 86–89]
Fisheries and aquaculture		[9, 90]	[15]	[28, 91]	[92]	[53, 63, 65, 93–99]
(Bio)Energy		[9, 10]	[11, 14, 100]	[37, 91, 101]	[34, 36, 38, 42, 102–105]	[40, 46, 47, 50–54, 56, 59, 64, 68–70, 73, 76, 86, 89, 95, 97, 106–116]
(Bio)chemicals and (bio)-polymers		[100]	[23, 27, 117]	[29, 30, 34, 35, 85, 102, 104, 105]	[40, 54, 56, 64, 73, 89, 109, 110, 114, 118–120]	
Food and pharmaceuticals		[9, 10]		[17, 28, 101]	[32, 34, 35, 121]	[44, 45, 48, 50, 56–58, 73, 76, 93, 94, 108, 114, 122, 123]
Municipal and industrial solid waste and sewage management		[10]	[11, 14, 124]	[21, 25, 26, 37, 117, 125–130]	[32, 34, 36, 38, 42, 102–104, 131–133]	[39–41, 44, 45, 47, 50, 55, 63, 66–69, 89, 98, 107, 108, 111, 116, 118–120, 122, 123, 134–139, 182, 186–188]
Others		[90]	[105]	[24]	[83, 102]	[48, 55, 60–62, 70, 115, 122, 134–136]

Theory, descriptive accounts, reflections and reviews

Main focus/foci*	**2015**	**2016**	**2017**	**2018**	**2019**	**2020–2021**
Agriculture	[140,	141]		[142–144]	[90, 130, 145–152]	[153–166]
[14, 22, 90, 138, 167–198]						
Forestry		[199]	[145, 151,	200–205]	[154, 206–211]	[14, 173, 176, 180, 184, 185, 197, 212–231]
Fisheries and aquaculture		[156, 232, 233]	[90,	234–239]		
(Bio)Energy	[240]		[142, 143, 241]	[151, 202, 242, 243]	[69, 213, 228, 266, 270 [232, 233]	[22, 54, 90, 139, 175–181, 184, 185, 190, 192, 193, 196, 198, 244–251]
(Bio)chemicals and (bio)-polymers	[240]		[142–144, 252]	[130, 151, 202]	[154, 156, 206, 232, 233, 253, 254]	[22, 75, 90, 173, 176, 178, 180, 181, 184, 185, 196, 212, 213, 239, 248, 251, 255–258]
Food and pharmaceuticals		[142–144]		[160, 232, 233, 261–263]		

Table 1 (continued)

			[130, 202, 259, 260]		[22, 90, 120, 168, 172, 180, 183, 191, 196, 212, 237, 244, 246, 248, 257, 258, 264–269]	
Municipal and industrial solid waste and sewage management		[270]	[143, 144]	[130, 151, 202, 260, 271, 272]	[38, 157, 253, 273–276], [277–280]	[54, 90, 120, 139, 172, 177, 180, 190–193, 196, 197, 234, 235, 244, 245, 248–251, 258, 264–267, 269, 281–288]
General/policy/overarching [81, 228, 231, 316, 327–343]	[289, [82,	290] 249, 340,	[5, 6, 8,	291–294] 344–378]	[7, 199, 295–304]	[305–326]

*Publications may straddle multiple sectors of the economy, as when the waste streams from one or more source sectors of the bio-economy are utilised in another/others. The numerical references correspond to the order in which the publications are referred to in the Discussion section

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