CIRCULAR BIO-ECONOMY – REVIEW OF SCIENTIFIC JOURNAL PUBLICATIONS WITH FOCUS ON WASTE-WATER TREATMENT

CIRCULAR BIOEKONOMI – RECENSION AV VETENSKAPLIGA ARTIKLAR MED FOKUS PÅ AVLOPPSVATTENRENING

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Abstract:
A circular bioeconomy is one in which waste streams from the processing of 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 a small set of 46 publications from the period 2016–2021, sourced from 28 journals and originating in 22 countries (decided solely on the basis of the first author's affiliation) into a concise and structured account of published research pertaining to water and wastewater in a circular bioeconomy. The publications deal with either bio-products from other sectors which find use in wastewater treatment, or bio-products valorised from municipal and agro-industrial wastewater streams. Some publications (15 in all) which do not focus on water or wastewater per se have been included, in order to provide a good introduction, and take-home messages for the readers. The simple methodology has been clearly outlined, and the discussion has been organized in sub-sections and sub-sub-sections to facilitate improved readability. The take-make-use-dispose paradigm of a linear economy has to be replaced by the grow-make-use-restore alternative.

Sammanfattning
I en cirkulär bioekonomi, recirkuleras avfallsströmmar från bearbetning av förnybara bioresurser tillbaka in i teknosfären – via öppen eller sluten återvinning eller omvandling från materia till energi. Den systematiska granskningen samlar en liten uppsättning av 46 publikationer från perioden 2016–2021 och 28 tidskrifter, med ursprung i 22 länder (enligt den första författarens formella anknytning) till en kortfattad och strukturerad redogörelse för publicerad forskning om vatten och avloppsvatten i en cirkulär bioekonomi. Publikationerna behandlar antingen bioprodukter från andra sektorer som använts i avloppsvattenrening eller bioprodukter som är producerad från kommunala och jordbruksindustriella avloppsströmmar. Vissa publikationer (15 totalt) som inte fokuserar på vatten eller avloppsvatten i sig har inkluderats, för att ge en bra introduktion och 'ta-hem' meddelanden för läsarna. Den enkla metoden har tydligt beskrivits, och diskussionen har organiserats i underavsnitt för att underlätta förbättrad läsbarhet. Linjär-ekonomi paradigmet måste gradvis ersättas av det cirkulära. Mera samarbete behövs bland samhällen, industrier, regeringar och forskningsinstitutioner. Vatten vill fortsätta att spela en viktig roll i processer i en växande cirkulär bioekonomi.

Keywords: Anaerobic digestion, Biogas, Bioproducts, Circular bioeconomy, Wastewater, Sewage sludge

Introduction

A circular bioeconomy is one in which waste streams (or side-streams) from the processing of renewable bio-resources are looped back into the technosphere – open or closed recycling or conversion from matter to energy (Sheridan, 2016). The gamut of recommended behaviours in 'the era of R's' (Stahel, 2017) in a circular bioeconomy (not limited to wastewater management) has increased over the years and as noted in Prasad (2016), now includes reclaim, remediate, reuse, recycle, renovate, refuse, replenish, rainwater-harvest, resilience and reverence for Nature.

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. Further, among those publications satisfying this criterion, only those with a focus (primary or secondary) on bio-products unearthed from other sectors finding use in wastewater treatment and bio-products valorised from wastewater streams, are considered for this article. 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 wastewater streams generated from such use, into value-added products – has been a well-entrenched research area in industrial ecology and water/wastewater engineering for a much longer time.

Methodology and results of the bibliographic search

Method in brief

Only the Scopus database was availed of, as it is known to be the largest multidisciplinary citation and abstract database available, encompassing a swathe of publishers – old and new, major and minor. The search was conducted on the 10th of November 2020, and thereby publications which may have been added on to this database subsequently, would not be covered by 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)', 'principle' etc., 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. Every abstract was screened to determine if the main focus or one of the foci of the publication was water supply or wastewater treatment or resource recovery from wastewater.

From the long list of 385 publications (originating from close to 50 countries) and published in 150 journals, satisfying the primary criteria, 46 publications from 28 journals were shortlisted. Table 1 lists the journals in the fray along with the number of publications in each of them. Of the 46 publications, 3 are book chapters and do not thereby figure in Table 1. Bioresource Technology (6) and Journal of Cleaner Production (5) are the top two, followed by 6 journals with 2 publications each, and 20 journals with one publication each. Twenty-six of 46 publications are from year-2020.

The countries of origin (decided solely on the basis of the first author's affiliation) are, in alphabetical order, Australia, Brazil, Canada, China, Colombia, Cyprus, Denmark, Finland, Greece, Hungary, India, Israel, Italy, Poland, Portugal., Romania, Russia, Slovenia, South Korea, Spain, Sweden and the United Kingdom. Australia leads the pack with 5 publications, while the UK and Spain follow with 4 each.

Table 1: *The journals in the fray (alphabetical order) and the number of publications.*

Name of the journal	Number of publications
Applied Sciences	1
Biofuels	1
Biofuels, Bioproducts and Biorefining	1
Chemical Engineering Journal	1
Computer-Aided Chemical Engineering	1
Current Opinion in Green and Sustainable Chemistry	1
Engineering in Life Sciences	1
Environment International	1
Environmental Research	1
Frontiers in Bioengineering and Biotechnology	1
Frontiers in Marine Science	1
Journal of Colloid and Interface Science	1
Journal of Environmental Quality	1
Journal of Food Process Engineering	1
Land Use Policy	1
New Zealand Journal of Botany	1
Proceedings of the World Congress on Mechanical., Chemical and Material Engineering	1
Sustainability	1
Trends in Biotechnology	1
Trends in Plant Science	1
ACS Sustainable Chemicals and Energy	2
Algal Research	2
Energies	2
Environmental Science and Pollution Research	2
Frontiers in Environmental Science	2
Journal of Environmental Management	2
Journal of Cleaner Production	5
Bioresource Technology	6

Discussion – systematic review

Case studies – source /end-use sectors in the bio-economy

Agriculture / Agro-food

While being circularised from soil to soil, biochar which is the solid product obtained by pyrolyzing agro-wastes, can 'stop over' as an adsorbent for wastewater treatment, before being sent back for soil amendment to fields. As an adsorbent, it may also be able to withdraw some nutrients from the wastewater and enhance its own fertiliser value in the process (Dahal et al., 2018). While potato pulp from the starch industry can find use in composites, potato residues which may perhaps be used as animal feed, can be put to use as carbon sources for the biological denitrification of wastewater from aquaculture (instead of using methanol or ethanol), making the treated wastewater fit for recirculation and ensuring sustainable fish production (Kiani et al., 2020).

Forestry (silviculture)

Bioenergy is verily a life-saver in Africa. However, the use of charcoal for cooking indoors in poorly-ventilated kitchens is hazardous. Authors of a Kenyan case study (Carvalho et al., 2020) 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 (sewage sludge being an important feed to the digesters) is preferable to wood logs, the latter likely to lead in the longer run to deforestation.

Fisheries and aquaculture

Quite like biochar (referred to in the previous section) bio-calcite – the calcium compound found in crab shells (Nekvapil et al., 2019), oyster shells and gastropod shells - has been experimented with, hitherto, as phosphorus adsorbents in wastewater treatment and for other value-added bio-products; to be then used as bio-fertiliser. In this case, it is a circulation from the hydrosphere to the pedosphere, while being availed of, briefly in the wastewater treatment plants.

Microalgae and macroalgae (seaweeds in other words) - bio-extractors of nitrogen, phosphorus, carbon dioxide (CO_2) and toxic heavy metals from wastewater (Seghetta et al., 2016; Solovchenko et al., 2020; Nagarajan et al., 2020), sources for third-generation biofuels and good solutions to the food-fuel-fibre-feed impasse (Wood et al., 2020; Lokesh et al., 2018), 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 (Vieira et al., 2020; Rotter et al., 2020; Venkata Mohan et al., 2020).

Aquaponics – the term referring to the combination of aquaculture + hydroponics – 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). 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.

Municipal and industrial sewage management

Quite like biochar from agro-wastes, granular activated carbon from coconut wastes is the agent used in Simha et al. (2018), to extract urea from diverted urine, 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 it. They conclude that it is very much possible to ideally supply at least 20% of the total nitrogen demand for food production globally in this manner. In a pilot study done in Finland, Simha et al. (2020) 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 (Szymanska et al., 2019), can lead to greater biomethane production when the relatively nitrogen-poor stream of human excreta is anaerobically digested, thanks to a reduction in the inhibitory effect of ammonia on bacterial activity. If all the human wastes in China could be anaerobically digested for the maximum attainable biomethane production to generate electricity, and if this electricity would replace an equivalent amount of coal-derived power, reduction in GHG emissions of 142 kt of CO_2-eq per day could be achieved, while substituting gasoline in transportation with the same amount of biomethane, would yield a reduction of about 55 kt of CO_2-eq per day (Duan et al., 2020). Recovery of phosphorus from the digestate is also a must in the years to come (Szymanska et al., 2019; Werle et al., 2019; Jarvie et al., 2020), with the phosphate reserves likely to dwindle rapidly. This is undoubtedly preferable to directly using the nutrient-bearing conditioned sewage sludge with some non-desirable organics and toxic heavy-metal content (Rigueiro-Rodríguez et al., 2018). 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) advocate as the best option. They also report that the percentage of phosphorus pentoxide in the recovered by-product is very close to that in naturally-occurring phosphate rock. Agro-industrial wastewaters (Taddeo et al., 2018) are excellent sources for the recovery of struvite which is a wholesome fertiliser option. In addition to providing magnesium, nitrogen and phosphorus, it also supplies potassium and calcium (macronutrients) and iron, sodium, copper, manganese, cobalt and zinc (micronutrients). In the opinion of Longhurst et al. (2019), bio-fertilisers derived from sewage sludge pose negligible risks to human, animal, environmental and crop receptors, as long as the stipulated risk management controls are adhered to.

Ferreira et al. (2018, 2019) experimented with the algal-bacterial treatment of different types of wastewater streams – agricultural (swine, cattle, poultry), industrial (dairy, brewery) and municipal – to cultivate microalgae. It was subsequently subjected to dark fermentation to yield bio-chemicals, bio-fertilisers and bio-hydrogen. Wicker et al.

(2020) 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 for several end-uses (Arashiro et al., 2020). Researchers have shown that waste streams with higher nutrient concentrations resulted in a marked improvement in the microalgal productivity (Ferreira et al., 2018; Ferreira et al., 2019; Sutherland et al., 2020A). In a similar paper on the wastewater-microalgae-bioenergy nexus, Belete et al. (2019), 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. The algal biomass is supplied to the bio-energy sector, while the treated effluent with optimised concentrations of nitrogen and phosphorus, is diverted to irrigation of fields in water-scarce Israel. Sutherland et al. (2021) have shown that supplying carbon dioxide to raceway ponds treating nutrient-rich wastewater streams with microalgae, reduces ammonia volatilisation and results in greater biomass productivity, thanks to a rise in the uptake of nutrients. Additionally, as a consequence, the effluent quality is improved, in order to avoid eutrophication downstream. In case studies conducted on wastewater in the UK (Guo et al., 2018), ion exchange was rated as the preferred technology for nitrogen and phosphorus removal.

Co-digestion of diverse bio-waste streams like harvested water hyacinth and dairy wastewater, tested by Arutselvy et al. (2020), also yielded a wide range of bio-products. While Dahal et al. (2018) have demonstrated the dual benefits of biochar from agro-wastes as adsorbent in wastewater treatment and soil amendment in that order, Panagiotou et al. (2018) have proven that waste eggshells (from anywhere along the egg supply chain, from poultry right down to the consumers), are also effective adsorbents for phosphorus in effluent wastewater from anaerobic digesters. Quite like the bio-calcite referred to earlier in this article, the egg-shells in combination with the adsorbate, are potential bio-fertilisers in the form of brushite – hydrated calcium biphosphate. This property of eggshells also makes them excellent bio-flocculating media to gather microalgal cells for harvesting, as proven for T. obliquus algal cells in Roy et al. (2020).

Theoretical publications, descriptive accounts, overviews and reviews

Focussed

While forestry wastes can be effective aids in the adsorption of oil spills and heavy metals from wastewater and aquatic ecosystems (Sidiras, 2018), inexpensive bioremediation of wastewater and soil 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 (Molina et al., 2020; Francocci et al., 2020). Activated carbon produced from yeast residues, and nanoporous carbon from mango wastes have been shown to remove dipyrone and atrazine respectively from synthetic aqueous effluents (Modesto et al., 2020; Amezquita-Marroquin et al., 2020). 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 PPCPs have been degraded/metabolised after bio-absorption. The microalgal ponds used to treat wastewater 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, improve the effluent water quality and thereby that of the aquatic ecosystems, while providing nutrient-rich algal biomass for valorisation downstream (Venkata Mohan et al., 2020; Molina et al., 2020; Sutherland et al., 2020B; Sutherland et al., 2020C; Wollmann et al., 2019; Yarnold et al., 2019). As far as wastewater treatment is concerned, bio-electrochemical systems (Jung et al., 2020), which directly transform wastewater to electricity and chemicals, may be promising additions to a circular bioeconomy.

General

In order to entrench a circular economy, structural changes have to be wrought in society, to be able to meet sustainability challenges, as this concept does not agree that natural capital can be completely substituted by manmade capital. Bioeconomy preaches techno-optimism, while a circular economy advocates techno-realism, and a bioeconomy, by itself cannot be deemed to be sustainable (Székács, 2017). But when we consider a 'circular bioeconomy', we at once make that giant leap from weak to strong sustainability (Leal Filho, 2018). The nascence or 'emergentness' of a bio-economy (Iversen et al., 2019) makes it an interesting field of learning, research and industry for the years to come. It continues to evolve as new and existing technologies (Mohan et al., 2016), inputs and ways of interworking are experimented with, and promises to build bridges between biotechnology and economy, and knit together science, industry and society (Aguilar et al., 2019).

In Muizniece et al. (2018), the authors have identified nexuses of importance in a circular economy, green economy and what they term a 'biotechonomy' (an economy bolstered by biotechnologies). The 22 impacting/impacted and enabling/enabled factors which come into play in decision-making include land, waste, welfare, climate change, bioresources, fossil resources, human resources, research and innovation, energy, education/know-ledge, policy, health, behaviour, technologies, **water,** natural environment, consumption, financial resources, economic growth, food, production and pollution. Every one of these 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.

In D'Amato et al. (2017), 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, while Giampietro (2019) describes it as a combination of a desirable 'what' (circular economy) with a viable, feasible and desirable 'how' (bioeconomy).

Conclusions

The focus in this brief review was on articles, reviews, book chapters, short surveys, editorials and conference publications, focusing on aspects of a circular bioeconomy/ bio-economy in general, and having water/wastewater as a sub-focus. The total number of such publications mined from Scopus was 46, found in 28 journals and originating in 22 countries.

In the years to come, academic researchers have a key role to play in educating the sceptical and the unaware, the cynical and the non-cooperative, 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 economy (Viaggi 2015; Bikse et al., 2019), and thus give up living in their 'ivory towers' (Bezama, 2018). 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 (Bell et al., 2018), 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.

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