Cardinal Stefan Wyszyński University in Warsaw
Institute of Philosophy
Center for Ecology and Ecophilosophy

# STUDIA ECOLOGIAE ET BIOETHICAE

22/3 (2024)

STUDIA ECOLOGIAE ET BIOETHICAE

**2024, 22, 3: 95-105**
p-ISSN 1733-1218; e-ISSN 2719-826X
DOI: http://doi.org/10.21697/seb.5813

# Optimisation of Water-Use in Pulp and Paper Mills: A Streamlined Review of Scientific Journal Publications

## Optymalizacja wykorzystania wody w celulozowniach i papierniach – usprawniony przegląd publikacji w czasopismach naukowych

**Felicia Ocklind, Kristin Liback, Lova Lundqvist, Wilma Harge, G Venkatesh***

Karlstad University, Sweden

ORCID FO https://orcid.org/0009-0006-3924-9462; KL https://orcid.org/0009-0005-7359-7543; LL https://orcid.org/0009-0008-5445-1225; WH https://orcid.org/0009-0008-7819-6767; GV https://orcid.org/0000-0003-3347-7262 • Venkatesh.govindarajan@kau.se

Received: 5 Feb, 2024; Revised: 8 Apr, 2024; Accepted: 10 Apr, 2024

**Abstract:** The water-, and energy footprints of the processes in the pulp and paper industry are sizable enough to warrant investment of money and commitment of time truncate the same. Besides, there is also a nexus between water and energy here, with optimisation of the use of one of these resoruces enabling that of the other too. This streamlined review focuses on journal publications (originating from different parts of the world, and targeted at researchers and decision-makers in the industry) which train the lens on the optimisation of water use in this particular sector of the (forestry) bioeconomy. The synergies and complementarities which exist among different sustainable development goals (SDGs) , promise positive ripple effects, caused by attending to the truncation of the water footprint. The articles, in general, recommend effective in-plant wastewater treatment in combinaton with recirculating the treated effluent, and looking upon the water streams as carriers or bearers of valorisable substances – organics which can yield a host of bio-products in bio-refineries, including bio-energy. Availing of water-pinch analysis as a tool to uncover possibilities of water use in a cascade (depending upon the requirements imposed on the water, by processes downstream in the cascade), has been shown to aid in the optimisation of both water use and energy demand within the plant. One case study, for example, showed that the demand for steam can be decreased by about 4 GJ per ton of output, by recovering the waste heat in the water streams.

**Keywords:** effluent treatment, pinch analysis, pulp and paper mills, recirculation, Sustainable Development Goals, water footprint, water use optimisation

**Streszczenie:** Ślad wodny i energetyczny procesów w przemyśle celulozowo-papierniczym jest wystarczająco duży, aby uzasadnić inwestycję pieniężną i poświęcenie czasu na jego zmniejszenie. Ponadto istnieje tu także związek pomiędzy wodą i energią, przy czym optymalizacja wykorzystania jednego z tych zasobów umożliwia również optymalizację drugiego. W tym uproszczonym przeglądzie skupiono się na publikacjach w czasopismach (pochodzących z różnych części świata i skierowanych do badaczy i decydentów zaangażowanych w tę branżę). Opracowanie to skupiają się na optymalizacji zużycia wody w sektorze biogospodarki (leśnej). Synergia i komplementarność pomiędzy różnymi celami zrównoważonego rozwoju (SDG) obiecują pozytywne skutki uboczne, spowodowane dążeniem do ograniczenia śladu wodnego. W analizowanych artykułach zasadniczo zaleca się efektywne oczyszczanie ścieków wewnątrzzakładowych w połączeniu z recyrkulacją oczyszczonych ścieków i traktowanie wody jako źródła substancji organicznych, z których można w biorafineriach wytwarzać szereg bioproduktów, w tym bioenergę. Wykazano, że wykorzystanie analizy „skurczu wody" jako narzę-

dzia umożliwiającego określenie możliwości wykorzystania wody w kaskadzie (w zależności od wymagań nałożonych na wodę w procesach znajdujących się poniżej kaskady) pomaga zoptymalizować w przedsiębiorstwie zarówno zużycia wody, jak i energii. Przykładowo przedstawiono studium przypadku, w którym wykazano, że zapotrzebowanie na parę można zmniejszyć o około 4 GJ na tonę produktu poprzez odzyskiwanie ciepła odpadowego ze strumieni wody.

**Słowa kluczowe:** oczyszczanie ścieków, analiza punktów zbliżenia, celulozownie i papiernie, recyrkulacja, Cele Zrównoważonego Rozwoju, ślad wodny, optymalizacja zużycia wody

## Introduction

As gathered from RI.SE (Research Institutes of Sweden n.d. A), the European industrial sector accounts for about 40% of the total water demand on the continent, while in Sweden, the corresponding value is 70% (RI.SE n.d.B). Within the industrial sector (both in Europe, in general, and in Sweden particularly), the pulp and paper industry accounts for a sizable share of the water-demand-pie. Owing to its conspicuousness in the said pie, attention has been, and will continue to be directed to using water efficienctly along the pulp-to-paper chain of processes – processing the logs of wood, debarking, pulping (if bleaching is called for, the water demand increases), papermaking (in which the pulp is considerably diluted with water to avoid flocculation).

While Sweden for one, may not really be plagued by water scarcity in the foreseeable future, and can harness the double-bounties of wood and water for a longer time to come, there are many countries around the world, which house pulp and paper mills, which have to gear themselves up for a water-scarce future. Even Sweden for that matter, got a wake-up call of sorts in the second half of the previous decade, as per RI.SE (n.d.B). This sector is is likely to grow in the years to come (in terms of resource usage, outputs generated, contribution to GDPs, and also employment generated), with bioeconomies entrenching themselves as solutions to a host of sustainability-related challenges. In 2015, the World Wildlife Fundhad forecast a doubling in the size of this sector (in terms of output), by 2045 (WWF 2015). The larger the sector, the higher is the consumption of water, and subsequently, gretaer will be the need to invest in water-use effiiency improvements.

Possibilities of using water in a cascade, before recirculating the treated wastewater, as many times as possible prior to the final discharge to the sink, can be uncovered if pinch analysis techniques can be availed of. The effuent which is handled in the in-plant treatment units has high concentrations of dissolved impurities and suspended particulate matter (Määtta 2019). It should be borne in mind that the stringent requirements, as far as process water quality is concerned, have to be met. This mandates a high degree of effluent treatment prior to recirculation. Optimisation of the treatment process thereby becomes imperative, to rein in the operational expenditure, which as shown by Zetterlund et al (2023) in an experimental case study conducted at Stora Enso's pulp and paper facility south of the city of Karlstad in Sweden, is very much possible with process modifications. Looking upon the (waste)water streams as carriers or bearers of valorisable substances – organics which can yield a host of bio-products in bio-refineries, including bio-energy, will be indispensable for a well-functioning circular bioeconomy in the years to come (Venkatesh 2018A; Pervaiz and Sain 2011; Perin-Levasseur et al. 2011).

This brief review aims to find out the status quo and the possibilities for the future, as far as optimisation of water usage in pulp and paper mills is concerned. The authors have grounded their discussion on sustainable development, and thereby the SDGs in question (see Figure 1):

- #6 – Clean water and sanitation
- #7 – Affordable and clean energy
- #9 – Industry, innovation and infrastructure
- #12 – Responsible consumption and production
- #13 – Climate change
- #14 – Life under water
- #17 – Partnership for the goals

The entrenchment of responsible production by the industry, aided by technological and process innovations, and infrastructure development, alongwith the realisation that cooperation and collaboration are indispensable for success, leads to optimised water use and improved wastewater treatment. Any conflicts between SDGs 6 and 7 must be minimised, so that water-use-optimisation leads to net energy savings, and thereby contributes to climate change mitigation. SDG 14 is addressed directly, as a drop in the volume of freshwater withdrawn from the hydrosphere, coupled with improved effluent treatment, ensures that the much-feared irreveersible damage to the salubriousness of aquatic and marine habitats, does not come to pass.

## 1. Methodology

The first four authors worked in two teams of two each, and carried out their literature-searches separately. Thereby, the choice of searchphrases (looked for in Title, Abstract or Keywords) was quite different, though both the duos resorted to OneSearch, accessed through the library of Karlstad University, and sought after peer-reviewed scientific journal publications. Apart from employing different searchphrases to 'cast the net over a wider area of the ocean of published literature', the authors intentionally decided to spread out the geographical scope, so as to encompass countries around the world. The paper and pulp sector, in genarl, globally, consumes a lot of water, and over the years, efforts have been made in this sector to optimise (by way of treating and recycling, as many times as possible, and using water is a cascade). For this very reason, the temporal scope was relaxed, resulting in some relatively older publications which ended up forming part of the mix which was finally read carefully and reviewed. Bearing in mind that this is a brief review (extremely streamlined), they narrowed down the list of journal articles to be reviewed, to 10 each. Table 1 summarises the approach. It goes without saying, and is fully acknowledged by the authors, that reviewing 20 articles or less from the sizable library of publications focusing on this topic, is far from

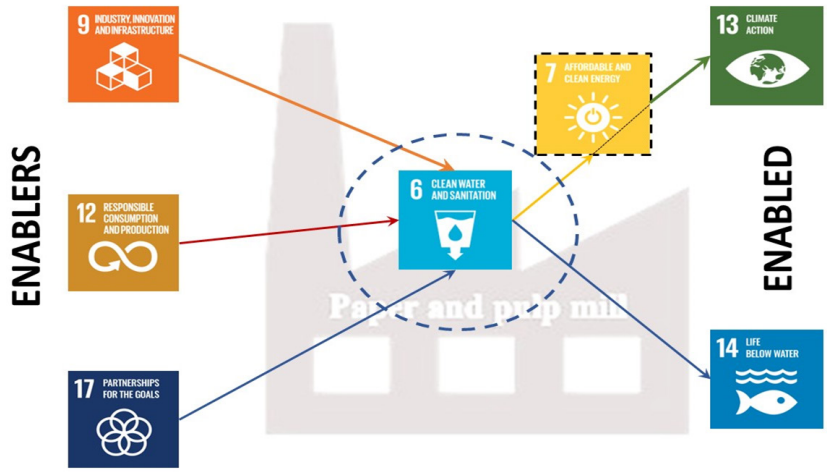


**Figure 1. The enabling and the enabled – complementarities among the SDGs**

**Table 1: Summary of the searches carried out by the first four authors (entries in italics in the third row belong to the intersection set of the two searches of 10 each)**

| Searchphrase | Total matches | Selected for the review | Countries in the fray (based on first author's professional affiliation) |
|---|---|---|---|
| "Freshwater pulp paper" | 365 | Esmaeeli and Sarrafzadeh (2023)<br>*Sousa et al (2023)* | Iran<br>*Portugal* |
| "Water loop paper mill" | 165 | Pizzichini et al (2005)<br>*Karthik et al (2011)* | Italy<br>*India* |
| "Water optimization pulp mills" | 247 | *Chew et al (2013)*<br>Ahmetovic et al (2021) | *Malaysia*<br>Bosnia-Heregovina |
| "Water consumption pulp industry" | 468 | Francisco et al (2014) | Brazil |
| "Technique wastewater pulp mills" | 241 | Kamali and Khodaparast (2015)<br>Toczyłowska-Mamińska (2017) | Portugal<br>Poland |
| "Sustainable freshwater paper industry" | 271 | Boguniewicz-Zablocka and Klosok-Bazan (2020) | Poland |
| "Water reduction pulp" | 3649 | Atkins et al (2012)<br>*Chew et al (2013)*<br>Wising et al (2005)<br>Rosado Corrêa Filho et al (2023)<br>*Sousa et al (2023)* | New Zealand<br>*Malaysia*<br>Sweden<br>Brazil<br>*Portugal* |
| "Water reduction papermill" | 10 | Möbius and Helble (2004) | Germany |
| "pulp mill + reuse water" "paper mill + reuse water" | 15 | Han et al (2021) | Australia |
| "paper + effluent treatment"<br>"pulp + effluent treatment"<br>"paper + efficient water"<br>"pulp + efficient water" | 5837 | Tewari et al (2009)<br>Patel et al (2021) | India<br>India |
| "paper mill" | 179 | *Karthik et al (2011)* | *India* |

all-encompassing. The objective though is to condense, communicate and convey essential knowledge to readers, and motivate thereby further reading and research in the field of sustainable management of natural resources.

## 2. Results and Discussions

The authors have organised this section on the basis of the answers to the question words – Who, When, Where, Why, How and What, inspired by the quartet from a poem "I Keep Six Honest Serving Men" written by Nobel Laureate Sir Rudyard Kipling[1].

### 2.1. The 'By', 'For', 'From' and 'In'

The authors of the 17 discrete articles which form a part of this streamlined, brief review, are all researchers and academics affiliated to universities around the world. The articles are written for a wider readership encompasssing researchers, professionals in the pulp and paper sector and university students. The selection of these 17 articles (a negligibly-small share of the publications in this particular field of research, as also acknowledged earlier) was motivated by an urge to introduce geographical diversity. As gathered from Table 1, India (3), Iran (1) and Malaysia (1) represent Asia, Sweden (1), Italy (1), Portugal (2), Germany (1), Poland (2) and Bosnia-Herzegovina (1) are the Europeans in the fray, Australia (1) and New Zealand (1) account for Australasia, with Brazil (2) representing the Americas.

1 "I keep six honest serving-men / (They taught me all I knew); / Their names are What and Why and When / And How and Where and Who."

The journals in which these articles have been published encompass a range of disciplines – water treatment, chemistry, sustainability, environmental engineering and process engineering. Of the fifteen journals in the picture, Desalination and Applied Thermal Engineering account for two articles each. The temporal span chosen is wide, with the two oldest articles of the lot, being published way back in 2004, and the three most-recent ones in 2023. Water-use optimisation has been an area of interest for researchers and pulp-and-paper mill industry professionals for many years now, and the oldest article which the authors chanced upon – from 1911 – bears testimony to that fact.

### 2.2. Motivations Behind the Research

The leitmotif of all the articles is water-use optimisation, but the approaches adopted vary ... quite like 'all roads leading to Rome', Rome here being 'water-use optimisation'. The effectiveness of process integration to achieve this goal, appeals to Atkins et al (2012) and Wising et al. (2005). In the former, the biorefinery concept of 'integrating to valorise' was propounded, with the additional motivation of recommending resource recovery from process water, even while fulfilling the primary purpose of reducing water-use in the mills. Sousa et al. (2023) have been motivated by the need to identify and overcome the limitations to water-use optimisation in the pulp-bleaching step, while Rosado Correa Filho et al. (2023) intend to focus on the treatment of the alkaline effluent and brownstock water from the bleaching and drying steps respectively, with the purpose of recirculating and reusing the treated (waste)water in some other suitable process within the mill.

What prompted Karthik et al. (2011) was the water scarcity which has been more marked of late, in many parts of India, threatening not just the operations of the pulp and paper mills, but also intensifying the conflicts among competing water-users (both industrial and otherwise). Market opportunities are hidden behind adversities which are after all, cues for entrepreneurs, researchers and innovators. As Winston Churchill is said to have remarked, 'Do not let a crisis go to waste' (Laestadius 2023). If pre-empting socio-economic instabilities motivated these Indian authors, Chew et al. (2013) took off with the intention of addressing the need to strike a balance between environmental sustainability and economic growth – which has always been imperative but not recognised as such. Patel et al. (2021), perhaps stirred purely by environmental concerns, focus on the need to invest in advanced wastewater treatment technologies in-situ, in pulp and paper mills, not just to treat the effluent prior to discharge, but also to recirculate it for reuse within the mills. If Möbius & Helble (2004) saw the need for further advancement in wastewater treatment technologies two decades ago, Han et al. (2021), writing from Australia which has been plagued by water scarcity for quite some time now, have based their research on the urgency of 'circularising' water as much as possible, not just in pulp and paper mills, but in the wider anthroposphere in general.

### 2.3. Modus Operandi

Similar motives may call for different methods, while the same methodology can be adopted to fulfil diverse motivations (many-to-one, and one-to-many). Case studies (which may be considered as a methodology-type in research) may avail of different methods, tools and approaches; in effect creating a nesting of methodologies. The gamut of methodologies which the authors came across in the publications reviewed, includes literature reviews, personal interviews, laboratory experiments and numerical modelling, with some of them being specific case studies.

There are a handful of literature reviews in the mix – Pizzichini et al. (2005) who presents a good synopsis of earlier case-studies; Ahmetovic et al. (2021) who have presented an overview of the state-of-the-art, Kamali

and Khodaparast (2015), Toczyłowska-Mamińska (2017) and Atkins et al. (2012) who have based their recommendations on future courses of action on experiments and case studies conducted earlier; and Patel et al. (2021) and Han et al. (2021) who have directed attention to the importance of effluent treatment (motivated by the possibility of recirculation and reuse). In one of the oldest articles in the mix – Möbius and Helble (2004) – the German authors had described a tertiary advanced oxidation system for wastewater treatment, and recommended it for use in pulp and paper mills. The main purpose of any review is to understand what has been done (the past), the status quo (the present), and therefrom help the readers targeted, to chart out the paths to be trodden upon in the future; in this case, towards sustainable operation of pulp and paper mills. While this particular review may be a brief one, the authors would like to recommend the afore-named articles to readers keen on charting out such paths in their own research efforts.

Water-pinch analysis has been an effective technique adopted by researchers in case studies encompassing several industrial sub-sectors, including pulp and paper [Venkatesh, 2018B; Li et al (2018)]. Wising et al. (2015), Sousa et al. (2023), Francisco et al. (2014) and Esmaeeli & Sarrafzadeh (2023) have availed of it too, the former for a case study in Canada, the second inspired by a literature review of previously-published case studies, the third and the last-named for case studies in Brazil and Iran, respectively.

Experiments in the laboratory have been the preferred modus operandi of Karthik et al. (2011) [Indian case study], Pizzichini et al. (2005) [Italian case study] and Rosado Correa Filho et al. (2023), all of whom have focused on ultrafiltration (and the membranes needed for this separation technique) as a wastewater treatment method. More specifically, the first two have carried out a techno-economic analysis, to understand the feasibility of employing ultrafiltration membranes in pulp and paper mills.

Chew et al. (2013) resorted to mathematical modelling to redesign a Brown Stock Washing system for a pulp-and-paper mill case-study in Malaysia, while Boguniewicz-Zablocka and Klosok- Bazan (2020), in their Polish case study, evaluated different techniques/technologies which could be adopted for improving water-use efficiency in the mill, after gathering relevant site-specific data. It is important to remember that gathering data entails communication, and communication can involve interviews. Tewari et al. (2009) had done precisely this, by reaching out in person to the employees of 31 different pulp and paper mills in India, to understand the 'lay of the land', so to say.

## 3. Findings

*Water use reduction possibilities and positive spillovers:* Pinch analysis in combination with mathematical optimisation has been adopted by Wising et al. (2015), Sousa et al. (2023), Francisco et al. (2014) and Esmaeeli & Sarrafzadeh (2023). While not being easy to implement, considering the modifications on-site which are necessary for process integration, it turns out that the gain is worth the pain, so to say – water-use reduction in the range of 35-40% can be achieved, as reported in two of the case studies (Esmaeeli et al. 2023; Francisco et al. 2014). Wising et al. (2015) showed in their Canadian case study, that a reduction in steam demand, equivalent to 4 GJ/t output, is possible; water-pinch and heat-pinch essentially being 'comrades-in-arms'. In addition to adopting water-pinch analysis and using water in a cascade (while also recovering heat energy therefrom), a sure-shot strategy recommended by most of the researchers is the optimisation of wastewater treatment on-site (among others, Atkins et al. 2012; Kamali and Khodaparast 2015; Karthik et al. 2011). This, quite obviously, enables a greater degree of recirculation, providing the pulp-and-paper mills with economic benefits, while decreasing their water footprints and enhancing their environmental credentials.

Möbius and Helble (2004) had reported that ozonation and bacterial-biofilm-based biodegradation, working in tandem could achieve a 60% removal of the COD (chemical oxygen demand) in the effluent, thus reducing the eutrophication potential of the same. Tagging on another stage, improved the degree of removal to 85%. Tertiary treatment – ultrafiltration (and perhaps even nano-filtration) to complement the primary chemical and the secondary biological treatment steps – has been shown to contribute significantly to the augmentation of the degree of recirculation by restoring the effluent's quality to suit the requirements of many processes in the mill (Pizzichini et al. 2005; Kamali and Khodaparast 2015). Han et al. (2009) write about an ideal case in which availing of multi-stage effluent treatment, using different types of treatment processes may very well end up closing the water loop within the pulp and paper mill for a long time. Indeed, that may very well be a case of aiming for the moon, and being able to hit a star instead. Karthik et al. (2011) observed that ultrafiltration, by achieving a 93% removal of suspended solids and 91.7% COD (chemical oxygen demand), could very well be an effective solution to countering the water-crisis in India during the summer months, and ensuring that pulp and paper production is not impeded. However, Rosado Correa Filho et al. (2023), while agreeing that ultrafiltration may indeed be effective, have pointed out that there are limitations as regards the processes in which the ultrafiltered wastewater can be reused. While observing that the permeate from the ultrafiltration equipment may still have high concentrations of some natural organic matter imparting colour, sodium, potassium and chlorine, the authors consider cooling and steam-generation as likely applications for it. Patel et al. (2021) recommend hybrid-membrane reactors, which, according to them, separate the inorganic constituents of the effluent, quite effectively. Toczyłowska-Mamińska (2017) have referred to the microbial fuel cell (one of the possible mainstays in a circular bioeconomy in the future), which produces energy even as it separates the contaminants from the effluent; and does all this without the need for any chemical inputs.

Sousa et al. (2023) have pointed out in their literature review that many pulp-and-paper mills, by introducing an aeration (oxygen addition, more specifically) step upstream of the bleaching process, and resorting to counter-current washing of the pulp, have been able to reduce their freshwater demand by up to 50%, vis-à-vis the 1980s. They recommend more research in the direction of lab-to-mill upscaling, the advice resulting from the results of lab-scale simulations. Likewise, the mathematical modelling done by Chew et al. (2013) to redesign the Brown Stock Washing System is verily a proof-of-concept, which can be extended to the other process within pulp and paper mills – delignification, bleaching and drying for instance. Ahmetovic and co-authors (2021), while claiming that numerical simulation can provide optimisation solutions; have recommended feasibility studies to identify the possibilities of recovery of substances from the process water in the bleaching process, and subsequent valorisation thereof.

In their survey-based analysis of 31 mills in India, which (secondary) pulp agricultural residues and recycled paper, Tewari et al. (2009) had shown that even though availing of wastes instead of virgin wood fibres is highly recommended – from the point of view of a circular bioeconomy in which deforestation is curbed – problem shifting occurs in the guise of an increase in freshwater demand. The effluent is highly polluted, to boot. Looking for opportunities in adversities, silver linings in dark clouds, will be the leitmotif of a future circular bioeconomy. Bearing this in mind, these Indian authors had pointed out that the 'sticks and carrots' top-down approach was indispensable, if the pulp and paper mills had to keep functioning sustainably into the future. Mandating effluent treatment for recirculation

will uncover possibilities for recovering chemicals and materials therefrom, for sale as by products, in addition to the primary paper products. Contrary to the observations made by Tewari et al. (2009), Han et al. (2009) were of the opinion that paper production from recycled fibres, placed lesser demand on freshwater vis-à-vis that from virgin fibres. They added that the degree of required effluent treatment would ideally vary from mill to mill depending on the raw materials used and the end-products supplied. But one would then conclude that the concentrations of the contaminants in the effluent wastewater in the former case would be much higher.

*Sustainability and the SDGs:* It goes without saying that the pulp and paper mills, in general, can play a key role in contributing to the progress towards a ckutch of sustainable development goals (SDGs). Especially in those parts of the world where water-scarcity threatens social welfare and economic development, any and all efforts made in reducing freshwater use, will be most welcome. By decreasing their own demand for freshwater (and thus making more clean water available for other socio-economic applications), and by ensuring a high degree of effluent treatment before final dispoal into the hydrosphere (unless of course, what Han et al (2009) visualised – a closed water loop – manifests itself), the mills will be contributing to SDG 6 – Clean water and sanitation. Subjecting innovative technologies (SDG 9), processes and methods to techno-economic analyses, will enable pulp and paper mills to make the right choices in favour of sustainable development.

Motivated by the desire to contribute to SDG 12 (Sustainable Production and Consumption), mills will strive to decrease their resource footprints by availing of new technologies or combinations thereof (SDG 9). Here is where the microbial fuel cell written about by Toczyłowska-Mamińska (2017) needs to be mentioned. To reiterate, it operates without the need for chemicals, and also generates energy in the process of treating the effluent. That would be bioenergy and we see a coupling to SDG 7 right away. SDG 17 which is all about cooperating for the goals, calls upon governments and decision-making bodies in general to beef up top-down policy-making (Tewari et al. 2009). Thanks to all these efforts, the hydrosphere – freshwater bodies especially – and the biota (both flora and fauna) therein, will benefit. This will be a much-needed step forward, as far as SDG 14 is concerned.

## 4. Recommendations Based on the Review

The articles in this brief review were published in the time-period 2004-2023. It would be interesting to expand the temporal scope, to understand the historical aspect of the water-paper nexus, so to say. Here are some take-away messages:

- More research on system-optimisation and water-pinch analysis, with respect to both the use of energy and water, commissioned by pulp and paper mills to improve their sustainability performance, will be a win-win situation for academic researchers (including students like the first four authors of this particular article) and the pulp and paper sector.
- The microbial fuel cell technology can be researched further, as it holds promise for the future, in a circular bioeconomy where such a (waste)water-energy nexus, will be highly valued.
- The economic feasibility and environment-friendliness (from a wider systems perspective, and not just limited to water-use reduction) of process modifications need to be studied carefully. If there are many alternatives to choose from, a good balance between an attractive net present value (determined by conducting a Life-Cycle Costing analysis) and a lowered environmental footprint (again not merely the global warming potential, but a more diverse swathe of impact categories), must be sought. This opens up possibilities

for research projects for students in universities.

- Reiterating from Figure 1, progress made in advancing towards the goals of SDG 9, aided by SDG 12 and SDG 17, will spur innovations which will benefit:
  - SDG 6 (efficient use of water, so that conflicts among water users are minimised, especially in developing countries gearing up for impending water scarcity),
  - SDG 7 (looking upon the water streams in the pulp and paper mills, as carriers of recoverable energy),
  - SDG 14 (improving wastewater treatment to an appreciable extent and avoiding environmental impacts like marine ecotoxicity, freshwater ecotoxicity and eutrophication).
  - Needless to say, these efforts will be good for the bottom-lines of the pulp and paper mills, in the medium-term.
- Just as wastewater treatment plants have been recast as suppliers of energy and materials recoverable from the wastewater, pulp and paper mills can evolve into biorefineries valorising the bio-wastes carried by the (waste) water streams, as demonstrated by Pervaiz and Sain (2011), among many others. One would thus be applying a host of Rs related to a circular bioeconomy to the water within pulp and paper mills – reducing use, reusing/recirculating whatever you use, as many times as possible, and recovering (heat energy and useful bio-products).

**Author contributions:** Conceptualisation, F.O., W.H., K.L, and L.L.; Methodology, F.O., W.H., K.L., and L.L.; Formal Analysis, F.O., W.H., K.L., and L.L.; Investigation F.O., W.H., K.L., and L.L.; Writing – F.O., W.H, K.L, and L.L.; Original Draft Preparation, G.V.; Visualisation, G.V. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional review board statement:** Not applicable

**Conflicts of interest:** The authors declare no conflict of interest.

## References

Ahmetović, Elvis, Zdravko Kravanja, Nidret Ibrić, Ignacio E. Grossmann, and Luciana E. Savulescu. 2021. "State of the art methods for combined water and energy systems optimization in Kraft pulp mills." *Optimization and Engineering* 22(3): 1831-1852. https://doi.org/10.1007/s11081-021-09612-4.

Atkins, Martin, Michael Walmsley, Andrew Morrison, and James Neale. 2012. "Process integration in pulp and paper mills for energy and water reduction – A review." *Appita Journal* 65(2): 170-177.

Boguniewicz-Zablocka, Joanna, and Iwona Klosok-Bazan. 2020. "Sustainable Processing of Paper Industry Water and Wastewater: A Case Study on the Condition of Limited." *Polish Journal of Environmental Studies* 29(3): 2063-2070. https://doi.org/10.15244/pjoes/111676.

Chew, Irene Mei Leng, Dominic Chwan Yee Foo, Jean-Christophe Bonhivers, Paul Stuart, Alberto Alva-Argaez, and Luciana Savulescu. 2013. "A model-based approach for simultaneous water and energy reduction in a pulp and paper mill." *Applied Thermal Engineering* 51(1-2): 393–400. https://doi.org/10.1016/j.applthermaleng.2012.08.070.

Esmaeeli, Ali, and Mohammad-Hossein Sarrafzadeh. 2023. "Reducing freshwater consumption in pulp and paper industries using pinch analysis and mathematical optimization." *Journal of Water Process Engineering* 53: 103646. https://doi.org/10.1016/j.jwpe.2023.103646.

Francisco, Flavio, Reinaldo C. Mirre, Ewerton Emmanuel da Silva Calixto, Fernando Luiz Pellegrini Pessoa, and Eduardo Mach Queiroz. 2014. "Management of water consumption in pulp and paper industry–a case study using water sources diagram." *Chemical Engineering Transactions* 39: 1255-1260. https://doi.org/10.3303/CET1429310.

Han, Ngoc, Jianghua Zhang, Monh Hoang, Stephen Gray, and Zongli Xie. 2021. "A review of process and wastewater reuse in the recycled paper industry." *Environmental Technology and Innovation* 24: 101860. https://doi.org/10.1016/J.ETI.2021.101860.

Kamali, Mohammadreza, and Zahra Khodaparast. 2015. "Review on recent developments on pulp and

paper mill wastewater treatment." *Ecotoxicology and Environmental Safety* 114: 326-342. https://doi.org/j.ecoenv.2014.05.005.

Karthik, Manikavasagam, Rita Sandeep Dhadapkar, Pravin Manekar, Pawan Aswale, and Tapas Nandy. 2011. "Closing water loop in a paper mill section for water conservation and reuse." *Desalination* 281: 172-178. https://doi.org/j.desal.2011.07.055.

Laestadius, Staffan. 2023. *Större än du nånsin tror [Bigger than you sometimes believe]*. Sweden: Verbal Forlag.

Li, Yugang, Huanbin Liu, and Jinsong Tao. 2018. "Optimizational analysis of heat-recovery in drying-section of coating machine based on pinch technology." *Zhongguo Zaozhi Xuebao/ Transactions of China Pulp and Paper* 25(2): 71-75.

Määtta, Linda. 2019. "Reduction of Chemical Oxygen Demand from Pulp Mill Wastewater with Intergrated Membrane Filtration." Bachelor's thesis submitted to the Tampere University, Finland, in January 2019. Accessed November 17, 2023. https://trepo.tuni.fi/handle/123456789/27118.

Möbius, Christian, and A. Helble, A. 2004. "Combined ozonation and biofilm treatment for reuse of papermill wastewaters." *Water Science and Technology* 49(4): 319–324. https://doi.org/10.2166/wst.2004.0294.

Patel, Kartik, Niky Patel, Nilam Vaghamshi, Kamlesh Shah, Srinivas Duggirala, and Pravin Dudhagara. 2021. "Trends and strategies in the effluent treatment of pulp and paper industries: A review highlighting reactor options." *Current Research in Microbial Sciences* 2(100077-). https://doi.org/10.1016/j.crmicr.2021.100077.

Perin-Levasseur, Zoe, Luciana Savulescu, and Marzouk Benali. 2011. "Lignin production path assessment: Energy, water, and chemical integration perspective." *J-FOR* 1(3): 25-30.

Pervaiz, Muhammad, and Mohini Sain. 2011. "Protein extraction from secondary sludge of paper mill wastewater and its utilisation as a wood adhesive." *BioResources* 6(2): 961-970. https://doi.org/10.15376/biores.6.2.961-970.

Pizzichini, Massimo, Claudio Russo, and Chiara Di Meo. 2005. "Purification of pulp and paper wastewater, with membrane technology, for water reuse in a closed loop." *Desalination* 178: 351-359. https://doi.org/j.desal.2004.11.045.

RI.SE (Research Institutes of Sweden). (n.d. A). "Så påverkas låg vattenkvalitet produktionsprocessen [This is how poor water quality affects the production processes]." Accessed November 17, 2023. https://www.ri.se/sv/berattelser/sa-paverkar-lag-vattenkvalitet-produktionsprocessen.

RI.SE (Research Institutes of Sweden). (n.d. B). "Industrin behöver minska sin vattenförbrukning [The industry needs to reduce its water usage]." Accessed November 17, 2023. https://www.ri.se/sv/berattelser/industrin-behover-minska-sin-vattenforbrukning.

Rosado Corrêa Filho, Jose Roberto, Claudio Mudadu Silva, Daiane Cristina Diniz Caldeira, Leandro Coelho Dalvi, Deyvisson Araújo Nascimento, and Rodrigo Silva Leite. 2023. "Ultrafiltration and reuse opportunities of sectorial effluents from a kraft pulp mill in Brazil." *Nordic Pulp & Paper Research Journal* 38(1): 171–179. https://doi.org/10.1515/npprj-2022-0030.

Sousa, Ana, I.S.S Pinto, Luis Machado, Licinio Gando-Ferreira, and Margarida Quina. 2023. "Sustainability of kraft pulp mills: Bleaching technologies and sequences with reduced water use." *Journal of Industrial and Engineering Chemistry* 125: 58-70. https://doi.org/10.1016/j.jiec.2023.05.033.

Tewari, Prahlad Kumar, S. Vidya Batra, and Malini Balakrishnan. 2009. "Efficient water use in industries: Cases from the Indian agro-based pulp and paper mills." *Journal of Environmental Management* 90(1): 265–273. https://doi.org/10.1016/j.jenvman.2007.09.001.

Toczyłowska-Mamińska, Renata. 2017. "Limits and perspectives of pulp and paper industry wastewater treatment – A review." *Renewable and Sustainable Energy Reviews* 78: 764-772. https://doi.org/10.1016/j.rser.2017.05.021.

Venkatesh, G. 2018A. "Recovery of different types of resources from wastewater – A structured review." *Vatten* 74(2): 65-82.

Venkatesh, G. 2018B. "Water pinch analysis – a review of recent peer-reviewed publications." *Vatten* 74(3): 147-152.

Wising, Ulrika, Thore Berntsson, and Paul Stuart. 2005. "The potential for energy savings when reducing the water consumption in a Kraft Pulp Mill." *Applied Thermal Engineering* 25(7): 1057–1066. https://doi.org/j.applthermaleng.2004.07.023.

WWF (World Wildlife Fund, Sweden). 2015. "Globalt WWF-index visar: Ökat fokus på miljö bland pappersjättar [Global WWF-index shows that there is a growing awareness of environmental sustainability among the paper-sector giants]." Accessed November 17, 2023. https://www.wwf.se/pressmeddelande/globalt-wwf-index-visar-okat-fokus-pa-miljo-bland-pappersjattar-2030093.

Zetterlund, Selma, Olivia Schwartz, Maria Sandberg, and G. Venkatesh. 2023. "Computation modelling to advise and inform optimization for aeration and nutrient-dosing in wastewater treatment: case study from pulp and paper mill in south-central Sweden." *Journal of Water Process Engineering* 56: 104508. https://doi.org/10.1016/j.jwpe.2023.104508.