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Life cycle assessment of bacterial cellulose and comparison to other cellulosic sources

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ABSTRACT

Bacterial cellulose (BC) is a 3D exopolysaccharide synthesized by certain acetic acid bacteria, possessing unique properties such as nanofibrillar morphology and high purity. BC has gained increasing attention for several potential market applications, including in textiles. However, along with techno-economic challenges, the industrialization of BC pulp must align with sustainable practices and minimize the environmental impact. To date, a comparative environmental assessment of BC pulp against plant-based celluloses (e.g. wood pulp or nanocellulose (NC)) or of BC-lyocell against cotton or man-made cellulose fibers (e.g. viscose and lyocell) has not been reported.

In this study, both BC pulp and BC-lyocell production were modelled for life cycle assessment (LCA). For BC pulp, the results were compared with nanocelluloses, using different life cycle impact assessment methods. For BC-lyocell, the results were compared with cotton, viscose, and lyocell fibres, using information available from the literature.

The major contributors to the environmental impact of both the BC pulp and BC-lyocell were the preparation of the culture medium, followed by cellulose washing and energy consumption. The BC pulp showed lower environmental impacts than NCs. BC-Lyocell exhibited a larger environmental impact than cotton, viscose, and lyocell in most of the environmental categories, except for land use and water depletion. Following a comprehensive impact and sensitivity analysis, several measures were identified to enhance the environmental performance of BC, such as exploring by-products for culture medium preparation and optimizing the use of chemicals (NaOH) and energy.

1. Introduction

Worldwide, several industries rely heavily on synthetic-based materials, which should desirably be replaced by more sustainable, bio-based alternatives (Felgueiras et al., 2021; Silva et al., 2020a). Cellulose is a remarkable material used in different applications and industries such as pulp & paper, cosmetics, food, biomedical, pharmaceuticals, textiles and packaging (Gupta et al., 2019; Sharma et al., 2019). This biopolymer, derived from forests, plants and crops, not only offers superb physical-chemical properties but is also highly abundant (Kim et al., 2015).

Wood pulp, the precursor for many cellulose-based products, can be produced using different industrial processes such as kraft or sulphite pulping processes (Mboowa, 2021), depending on the cellulose source and envisaged products. While Kraft pulping uses sodium hydroxide, sulphite relies on sulphurous acid to yield cellulose from wood biomass (Balkissoon et al., 2023). Textile production generally requires wood pulp with higher cellulose purity to produce man-made cellulosic fibres (MMCF). Dissolving wood pulps (DWP) may be produced using the prehydrolysis kraft process, which comprises a hydrolysis stage (biomass exposed to steam or pressurized water at 160–180 °C) prior to the cooking Kraft stage (Balkissoon et al., 2023). For textile applications,

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natural and man-made cellulosic fibres (MMCF) are used for garment manufacturing. Cotton, obtained from cotton plants by ginning to collect fibres for yarn spinning, is one of the most used natural fibres, representing about 25% of the global fibre market (Felgueiras et al., 2021; Hedayati et al., 2019). Cotton production is associated with significant environmental impact due to the extensive need for land, water, fertilizers and pesticides (Felgueiras et al., 2021). In contrast, MMCF relies on wood pulp biomass and may be produced through diverse technologies, with Viscose and Lyocell having the highest market share (Woodings, 2001). Both viscose and lyocell processes include dissolving the cellulose and spinning, via a spinneret, into a bath containing an antisolvent for coagulation (Soares Silva et al., 2023). The viscose process requires multiple steps (using NaOH and CS_2) (Krässig et al., 2012; Woodings, 2001) for cellulose derivatization and subsequent dissolution, while the Lyocell process only requires N-Methylmorpholine N-oxide (NMMO) for direct cellulose dissolution (Eckelt et al., 2009; Fink et al., 2001; Soares Silva et al., 2023). Another difference is the set-up used for fibre spinning, where the viscose process uses wet spinning (the spinneret is submerged in the regeneration bath) while the lyocell uses dry-jet spinning (air gap between the spinneret and the regeneration bath) (Felgueiras et al., 2021). After fibre regeneration, the resulting filaments undergo drawing and are subsequently collected as continuous filaments or cut further into staple fibres (1–40 cm in length).

For nanocellulose (NC) production from biomass, processes such as steam explosion, enzyme-assisted and acid hydrolysis (using sulfuric and hydrochloric acids) are used, followed by mechanical treatments (high pressure homogenization, microfluidization, and cryocrushing) to deconstruct the plant biomass (Kim et al., 2015; Silva et al., 2020a). Either cellulose nanofibres (CNF) or cellulose nanocrystals (CNC) can be obtained, depending on the methods used and the degree of processing. CNFs are characterized as longer fibres with both amorphous and crystalline regions (5–60 nm diameter with 2–10 μm in length), while CNC have a needle-like shape, being more crystalline (5–70 nm diameter with 100–250 nm in length) (de Amorim et al., 2020). BC is also classified as nanocellulose due to its fibre's dimensions, having a diameter of less than 100 nm (Ludwicka et al., 2016).

Thus, different cellulose processing methods provide distinct NC, cellulose pulps or fibres, leading to differences in both their end-use performance and environmental impact. Factors such as cellulose sourcing, manufacturing processes, chemicals, water and energy consumption, and waste management contribute to the overall environmental impact of the different celluloses (Foroughi et al., 2021; PE, 2012). This impact can be evaluated by Life Cycle Assessment (LCA). This tool is crucial for evaluating the environmental impact of any product throughout its entire life cycle, from raw material extraction to disposal (Finnveden et al., 2009). Categories like global warming potential, abiotic depletion, ecotoxicity, water depletion and land use, among others, are often used to identify the most significant environmental impacts. Several LCAs have been conducted on different kinds of cellulose: CNFs (Arvidsson et al., 2015; Gallo Stampino et al., 2021), CNCs (De Figueirêdo et al., 2012; Gu et al., 2015; Nascimento et al., 2016; Zhang et al., 2022; Katakojwala and Mohan, 2020), BC (Forte et al., 2021), cotton (Jewell, 2017; Liu et al., 2020; Shen et al., 2010), viscose (Schultz and Suresh, 2017; Shen et al., 2010) and Lyocell (Schultz and Suresh, 2017; Shen et al., 2010). However, comparing the sustainability of various cellulose sources and/or production processes based on available LCA studies is challenging, due to differences in system boundaries, assumptions and methodologies used in impact assessment (e.g. ReCiPe vs CML vs TRACI vs Impact, 2002) across different studies (Prado et al., 2022). Despite these challenges, some authors have conducted comparative studies on textile fibres (Guo et al., 2021; Schultz and Suresh, 2017; Shen et al., 2010).

Bacterial cellulose (BC) may be produced through fermentative processes using *Komagataeibacter* bacteria (Jedrzejczak-Krzepkowska et al., 2016; Jozala et al., 2016). Compared to plant cellulose, BC features high crystallinity, high degree of polymerization, high mechanical performance, and high-water holding capacity. These attributes have sparked interest across diverse industries, including biomedical, pharmaceutical, energy, bioelectronics, food, cosmetics, pulp & paper and textiles (Dourado et al., 2016; Torres et al., 2019). Forte et al. (2021) and Aragão et al. (2020) independently assessed the LCA of BC, yielding similar results. BC is commonly regarded as an eco-friendly cellulose (Blanco et al., 2018; Silva et al., 2020a; Soares Silva et al., 2023) and is claimed to be an alternative to NCs, cotton, Lyocell or viscose by the Australian company Nanollose (Nanollose). However, a comprehensive comparison between the environmental impacts associated with plant-based celluloses and BC has not been addressed so far. Therefore, this study intends to fill this gap by using data from life cycle impact assessments published in the literature, providing a more direct comparison of BC with plant-based celluloses. This approach offers new insights into the relative environmental impacts of these materials.

The present study enhances the existing knowledge by modelling the production of both BC pulp and filament (BC-Lyocell) and conducting the respective LCA. The results are compared to available LCA data (from the literature) for NCs and textile fibres (namely cotton, viscose and lyocell) using a harmonized approach through multiple impact methodologies in the LCA to ensure the reliability and generalizability of the findings. Then, an analysis is conducted to understand which process operation contributes the most to the assessed impacts. The primary goal is to foresee alternative methods for BC pulp and BC-Lyocell production, to improve their environmental performance relative to other cellulose sources.

2. Methods

2.1. Goal and scope definition and description of system boundaries

This study aimed to assess the environmental impact of BC pulp and BC-Lyocell filament in comparison to plant-based nanocelluloses (CNCs or CNFs), as well as natural cellulosic fibres from cotton and MMCF (such as Viscose or Lyocell). Two LCA models were performed, one for BC pulp and another for the BC-Lyocell filament. The analysis of the production of BC pulp primarily relied on our previously published work (Forte et al., 2021), but was complemented with new modifications. A water recycling step was added (see Fig. 1); the inventory data for molasses, corn steep liquor (CSL), NaOH and natural gas were updated; and the final pasteurization and packing processes were removed.

The LCA boundaries of the BC pulp and BC-lyocell are outlined in Fig. 1. The BC production process comprises the following sequential steps: culture medium production (where culture medium components are mixed and pasteurized); inoculum propagation (where bacteria grow through consecutive batch fermentations from 100L to 1000L); static culture fermentation (in a controlled environment room at 30 °C for 7 days) and downstream processing (where BC is ground, washed with NaOH and water, then filtered to obtain a wet pulp containing 20% of cellulose). The designed plant processes about 60,000 L/month of culture media, totalling 5 tons per year of BC (solids content), considering the BC production yield of 7.2 g/L (dry basis), as detailed in previous studies by Forte et al. (2021) and Dourado et al. (2016).

Lyocell technology was adopted for fibre manufacturing, comprising the processes of dissolution, where N-methylmorpholine N-oxide (NMMO) is used to dissolve the BC pulp; the resulting dope (13% of BC; 13.3% water and 73.7% NMMO) is subjected to dry wet spinning into a coagulation bath to regenerate the fibres which then undergo a washing process, are dried and then cut into staple fibres. The solvent is then recovered (99% recovery) from the spinning and washing processes through a multi-process (of flotation and filtration; ion exchange and evaporation) and the water is collected and recirculated for the fibre washing processes (Eckelt et al., 2009; Fink et al., 2001).

The functional unit defined in this LCA study is 1 ton of BC (which for the system boundaries case A, as specified in Fig. 1, corresponds to 4.52 ton of BC pulp at a consistency of 22% m/m cellulose; for the system

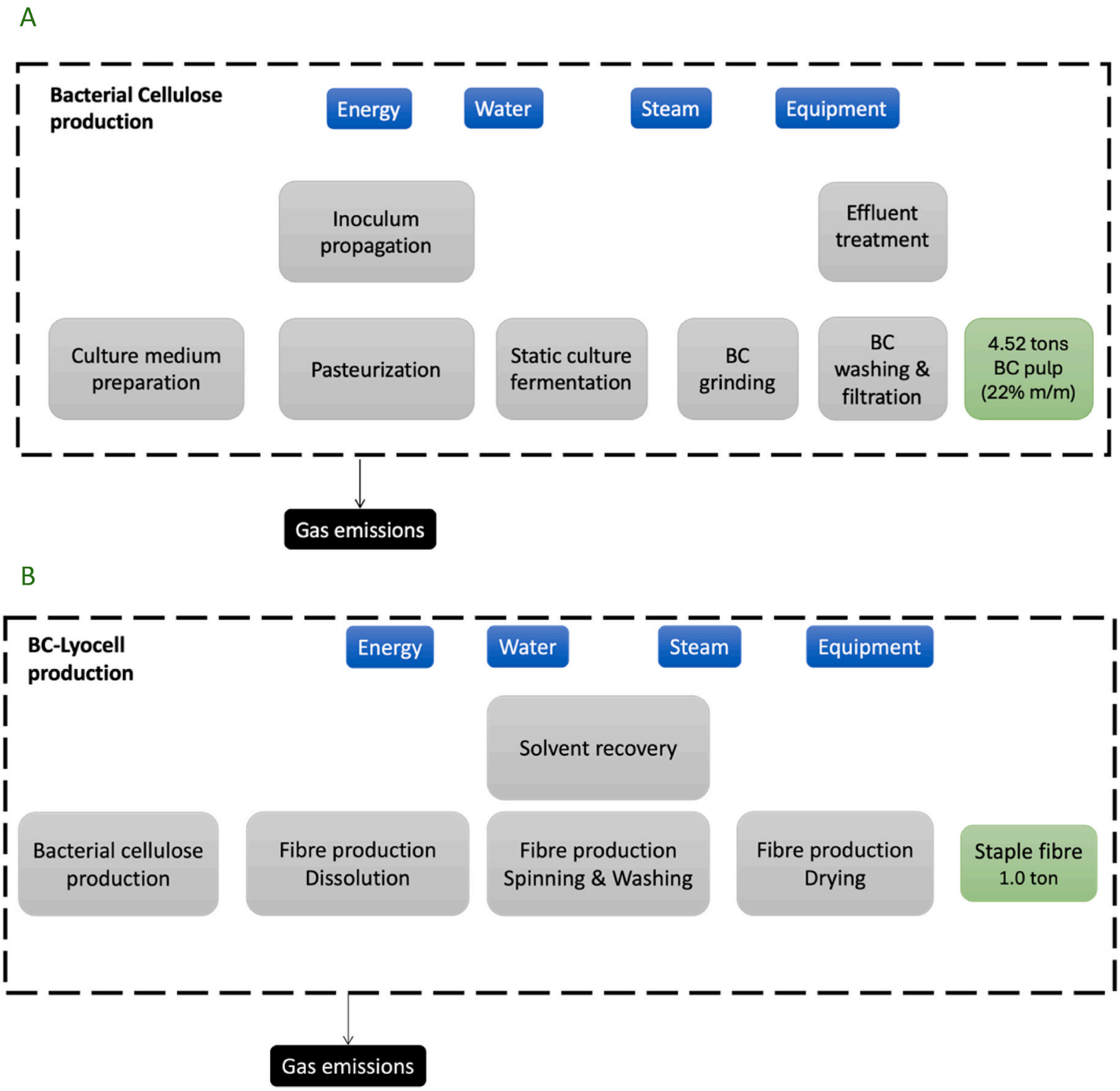

Fig. 1. Cradle-to-gate life cycle assessment system boundaries of (A) 1 ton of BC (solids content 22%) and (B) BC-Lyocell; Energy, steam, water, and equipment belong to the system boundaries and referred in Table 1, which corresponds to the life cycle inventory.

boundaries case B, it corresponds to 1 ton of staple fibres). This LCA analysed the material and energy flows from the extraction of natural resources to the production of both BC pulp and BC-Lyocell. A cradle-to-gate approach was used for the comparison with other cellulose sources. The energy and mass balances for each production stage were calculated using SimaPro software (version 9.3.0.2, ecoinvent 3.8 for windows). All flows from each process were categorized based on the type of resource used (energy or material) for input flows and the disposal site for residues in terms of output flows.

2.2. Inventory analysis

To model the production process of BC pulp, data (related to the equipment, raw materials, and electricity) from Dourado et al. (2016) and Forte et al. (2021) was used. The data pertaining to the raw materials (cells, culture medium reactants) used for biomass growth (inoculum) and corresponding CO_2 emissions from biomass growth were excluded due to their negligible contribution to the overall process. This study included water recirculation, whereby the water used to wash the BC pulp was treated and recirculated to prepare culture media and for washing the BC pulp. The wastewater generated from the BC pulp production was treated in a processing plant, using the data provided in Table S1 (from Silva et al., 2020b). A proxy for the inventory of the wastewater processing unit was used assuming a standard European municipal wastewater treatment facility, with 50% of the sludge undergoing incineration and the remaining 50% being used as agricultural fertilizer. The electricity input to produce BC pulp and BC Lyocell fibre was assessed using the (2020) Portuguese average electricity grid mix.

BC-Lyocell fibre production was modelled based on the work by Hytönen et al. (2023), Shen et al. (2010) and Guo et al. (2021). The energy consumption of the entire lyocell process (see Table S2) and fibre production chain were adapted from Hytönen et al. (2023). Relevant data concerning the main materials used in Lyocell, such as NMMO production (see Table S3) and propyl gallate (see Table S4) were sourced from Righi et al. (2011) and Khounani et al. (2020), respectively. A mass balance was performed to estimate the inputs and outputs in each process. The Ecoinvent database was used for the background system data (regarding energy resources, extraction, transformation, and transportation of materials). The following table presents the life cycle inventory used for the LCA of the BC pulp and BC-Lyocell.

2.3. Impact assessment

Before conducting the LCA for BC pulp and BC-Lyocell, a literature review was performed on LCA studies concerning nanocellulose (NCs) and textile fibres. The goal was to identify literature that offers results comparable to our modelled BC pulp and BC-Lyocell production. The screening criteria were established based on information such as raw material type, mass and energy balances, LCIA methodology and version, along with the respective database and version used to quantify the impacts. The literature review focused on identifying studies with a comparable scope to ours, including the same system boundaries, functional unit, and assumptions (the selected papers are identified in Tables 2 and 3). The subsequent step involved converting the impacts calculated for BC pulp or BC-Lyocell production to match the corresponding methodology used in each of the selected articles. Different impact methodology impedes the results to be compared among different impact assessment methods. With the data now adapted to the methodologies of the chosen articles, a direct comparison was made between BC pulp and nanocellulose and between BC-Lyocell and textile fibres, considering the system boundaries and the dataset used (discussed in the results section).

The LCA of BC pulp and BC-Lyocell was modelled using SimaPro software (version 9.3.0.2, with ecoinvent 3.8 database). As mentioned above, several impact assessment methods were used to allow comparison with other literature results that examined different cellulose sources. The environmental impacts of BC wet pulp and BC-Lyocell were assessed using various methods including ReCiPe 2016 midpoint (H) (Huijbregts et al., 2017), CML-IA baseline V3.05 using World, 2000 normalization (Guinée, 2002), TRACI 2.1 V1.06/US 2008, EF 3.0 methodology and the other methods IMPACT2002+ (Pennington et al., 2004), Eco-indicator 99 (Goedkoop and Spriensma, 2001), CML (Guinée, 2002) and ILCD 2011 midpoint (ILCD, 2011). Also, the environmental impacts were normalized to 1 ton of cellulose (solids content) for all cellulose sources and studies considered.

2.4. Sensitivity analysis

A sensitivity analysis was conducted to provide insight into the environmental impacts associated with the culture medium, in the BC production process. This was done by assessing the impact of removing two input parameters: sodium phosphate from the formulation of the culture medium, which was identified as having a large contribution to the overall impact (case 1), and all culture medium components (case 2). As a result, the environmental implications of each instance were recalculated. Case 2 contemplates a hypothetical (and challenging) case in which the culture medium for BC production is fully derived from waste streams (e.g. from the food industry). It was assumed that the impacts of such waste streams were negligible.

3. Results

The primary objective of this research is to analyse and compare the environmental impacts of various cellulose sources, providing data that can help answer questions such as: how does the biotechnological production of BC compare with that of wood pulp or cotton with regard to environmental impacts? Due to differences in the system boundaries, BC pulp was exclusively compared to CNCs and CNFs, while BC-Lyocell fibre was compared against other textile fibres, including Lyocell, viscose and cotton. The LCIA results of BC pulp and BC-Lyocell are delineated in distinct sections, namely sections 3.1 and 3.2, respectively. As outlined in the materials and methods section, different impact assessment methods were used to assess BC pulp and BC-Lyocell, to facilitate comparison with literature data from alternative sourced celluloses. The resulting different environmental impact categories impede the comparison of the results among the impact assessment methods. The only exception is the global warming potential, where the results

Table 1
Life cycle inventory of the BC (from 1.1 to 4) and BC-Lyocell model (from 5.1 onwards). Values reported to the functional unit of 1.0 ton of BC-Lyocell.

1.1 CM preparation	**Input**		
	Citric acid {RER}| production | Cut-off, U	0.15	ton
	Molasses, from sugar beet {RoW}| beet sugar production | Cut-off, U	3.03	ton
	Maize steepwater solubles, wet milling process, at plant (WFLDB)/US U	1.51	ton
	Sodium phosphate {RoW}| production | Cut-off, U	0.45	ton
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	150	MJ
	Output		
	Culture medium	151.41	ton
1.2 Pasteurization	**Input**		
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	1000	MJ
	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atmospheric non-modulating <100 kW | Cut-off, U	8440	MJ
	Output		
	Culture medium (pasteurized)	151.41	ton
1.3 Inoculum propagation	**Input**		
	Nitrogen, atmospheric	0.33	ton
	Oxygen	0.09	ton
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	7000	MJ
	Output		
	Culture medium (with inoculum)	14.77	ton
2. Static fermentation	**Input**		
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	9000	MJ
	Output		
	Carbon dioxide (emissions to air)	0.15	ton
	Water (emissions to air)	6.6	ton
	BC- Wet	137	ton
3. Cellulose grinding	**Input**		
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	7100	MJ
	Output		
	Wet grinded BC	137	ton
4. Cellulose washing	**Input**		
	Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, membrane cell | Cut-off, U	0.522	ton
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	4440	MJ
	Tap water {Europe without Switzerland}| tap water production, conventional treatment | Cut-off, U	52.97	ton
	Output		
	Wet grinded & washed BC	4.52	ton
	Wastewater	47.30	ton
5.1. Fibre production (dissolution)	**Input**		
	Methylamine {RER}| production | Cut-off, U	11.5	kg
	Diethylene glycol {RER}| ethylene glycol production | Cut-off, U	22	kg
	Hydrogen peroxide, without water, in 50% solution state {RER}|	25	kg

(continued on next page)

Table 1 (*continued*)

	hydrogen peroxide production, product in 50% solution state | Cut-off, U		
	1-propanol {RER}| production | Cut-off, U	17.93	kg
	Sulfuric acid {RER}| production | Cut-off, U	0.97	kg
	Tap water {Europe without Switzerland}| tap water production, underground water without treatment | Cut-off, U	1.49	kg
	Diethyl ether, without water, in 99.95% solution state {GLO}| diethyl ether production | Cut-off, U	1.59	kg
	Sodium bicarbonate {RER}| soda production, solvay process | Cut-off, U	4.92	kg
	Sodium sulfate, anhydrite {RER}| sodium sulfate production, from natural sources | Cut-off, U	9.91	kg
	Benzoic acid {RER}| toluene oxidation | Cut-off, U	8.69	kg
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	1078.96	MJ
	Output		
	Dope (BC + NMMO + Water + PG)	6.97	ton
	Water – emissions to air	3.94	ton
5.2. Fibre production (spinning & drying)	**Input**		
	Fatty alcohol {RER}| production, petrochemical | Cut-off, U	2.2	Kg
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	738	MJ
	Tap water {Europe without Switzerland}| tap water production, underground water without treatment | Cut-off, U	1.94	ton
	Output		
	BC fibre	1.00	ton
	Water - emissions to air	1.95	ton
6. Solvent recovery	**Input**		
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	1718	MJ
	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atmospheric non-modulating <100 kW | Cut-off, U	4220	MJ
	Sulfuric acid {RER}| production | Cut-off, U	0.003	ton
	Output		
	Solvent recovered	5.96	ton
7. Other processes (related to 5.1, 5.2; 6.)	**Input**		
	Electricity, medium voltage {PT}| electricity voltage transformation from high to medium voltage | Cut-off, U	1205	MJ
	Output		
	BC-Lyocell fibre	1	ton

can be directly compared, since this impact category is assessed by the same methodology from the intergovernmental panel on climate change (IPCC) regardless of the impact assessment method used (IPCC, 2023, 2013).

3.1. Environmental impact of cellulose pulps from different sources: NC and BC

As observed in Table 2, overall, the environmental impact of BC pulp assessed in the present study is lower than that of nanocelluloses (CNCs and CNFs) regardless of the raw material (virgin or recycled pulp), the extraction methods and processing used for their production (enzymatic (Arvidsson et al., 2015; Gallo Stampino et al., 2021), mechanical (Arvidsson et al., 2015), or chemical (Gallo Stampino et al., 2021)). Lower impacts were observed for global warming potential, ozone depletion, ozone formation, human toxicity, ecotoxicity (marine and terrestrial ecosystems), acidification, eutrophication, abiotic depletion, and water depletion (Table 2).

The energy required for BC impacted the least. However, in this case, an industrial production was modelled, whereas most studies have reported the LCA of CNCs and CNFs production based on a laboratory or pilot scale. The scale size (level of industrialization) has both techno-economic and environmental implications, since at a larger scale there will be a more efficient use of energy, leading to a reduction of CO_2 and smog emissions, which impact global warming and ozone formation, respectively (Shen et al., 2010). Another relevant issue is the use and disposal of chemicals required for nanocellulose extraction, associated with various emissions such as nitrogen (either as NOx or NH_3) and SO_2 emissions, causing toxic effects and excessive nutrient release into terrestrial and aquatic ecosystems, potentially leading to eutrophication, acidification, and ecotoxicity (USEPA, 2018). Furthermore, the use of such chemicals poses a relevant risk to human health.

In contrast to prior research, the simulation conducted in this study for BC demonstrated reduced impacts, particularly on abiotic depletion, ozone depletion, and human toxicity, as compared with those of Forte et al. (2021) and Aragão et al. (2020) (Table 2). The sole exception is ecotoxicity, where higher impacts were noticed from our LCA analysis. These notable variations can be attributed to the following alterations (previously outlined in section 2.1.): i) the inclusion of a water recycling step; ii) updates in inventory data for molasses, corn steep liquor (CSL), NaOH, and natural gas; iii) elimination of the final pasteurization and packing processes.

The identified impacts of BC pulp production are mainly related to the culture medium (although lower than in the case of NCs) and the use of NaOH, required for BC washing. Another important impact is the water depletion. The modelled BC pulp production consumes less water than the CNFs and CNCs production (Table 2). Indeed, while a substantial amount of water is used during the BC washing process, the effluent is treated to remove organic matter, allowing its recycling for further BC washing and culture medium preparation (Silva et al., 2020b). Conversely, nanocellulose production requires numerous steps involving water usage, including in the final purification. Water recycling may be an option for nanocellulose production, although it has not so far been documented in the literature.

Our comparison only includes nanocellulose in the wet state. The drying process can contribute significantly to the overall environmental footprint and therefore dry celluloses were not considered in the comparison made in Table 2.

3.2. Environmental impact of textile fibres from different sources: cotton, viscose & lyocell, BC-lyocell

To evaluate the environmental impacts of the potential use of BC in the textile industry, the BC-lyocell production was modelled and compared with established textile fibres such as lyocell, viscose and cotton, using the same impact criteria outlined in Table 2. We find it crucial to perform this analysis since BC has been considered a sustainable alternative compared to other traditional cellulose sources, since it eliminates the need for land and wood from forests (MMCF) or reduces the intensive water and pesticide usage (cotton). It must be acknowledged that BC produces a textile filament of very high quality, outperforming other MMCF (Soares Silva et al., 2023). However, this technical excellency must be weighed against the production cost and its environmental impacts. The outcomes of this study are documented in Table 3.

When contrasting BC-lyocell with cotton fibre, the former exhibited

Table 2
Midpoint environmental impacts of the life cycle of Pulp, CNCs, CNFs and BC using different impacts assessment methods. Comparisons normalized to 1 ton of cellulose.

Impact categories	Unit $^{\text{LCIA method used}}$	CNCs (De Figueirêdo et al., 2012; Gu et al., 2015; Nascimento et al., 2016)	CNF (Arvidsson et al., 2015; Gallo Stampino et al., 2021)	BC (Aragão et al., 2020; Forte et al., 2021)	BC (this study)
Global warming potential	E+03 Kg CO_2	122–247	60–930	13–16	6.22 – 6-66
Abiotic depletion	Kg Cu eq [a]			110	43
	Kg Sb eq [b]	0.0349			0.10
	Kg Sb eq [e]				0.10
	Kg oil eq [a]			6600	1700
	E+04 MJ eq [b] (fossil fuels)	150			7.1
	E+03 MJ eq [d] (fossil fuels)	600			7.0
	E+04 MJ eq [e] (fossil fuels)				7.8
Water depletion	E+03 m^3 eq [a]	2.3–140	6.5	0.47	0.21
	E+04 m^3 depriv. [e]		180–190		7.0
Land use	ha [a]			0.097	0.086
	E+03 Pt eq [e]		5200–18000		8.6
Ozone depletion	E−03 kg CFC-11 eq [a]			63.2	6.78
	E−03 kg CFC-11 eq [b]				0.76
	E−03 kg CFC-11 eq [d]	92			0.85
	E−03 kg CFC-11 eq [e]		120–130		0.82
Ozone formation	Kg NOx eq [a]			59	30.1
	Kg C_2H_4 eq [b]				1.8
	Kg O_3 eq [d]	14000			365
	Kg NMVOC eq [e]		2000–2300		190
Acidification	Kg SO_2 eq [a] (Terrestrial)		450	43.0	39.0
	Kg SO_2 eq [b]	531			45.6
	Kg SO_2 eq [c] (Aquatic)		192		46.9
	Kg SO_2 eq [d]	4500			44.4
	mol H^+ eq [e]				56
	mol H^+ eq [f]			64.2–79	56
Eutrophication	kg P eq [a] (Freshwater)		24–56.8	4.0	3.1
	Kg N eq [1] (Marine)		30.3–65	4.0	1.4
	Kg PO_4^- eq [b]	65			15.1
	Kg PO_4 P-lim [c] (Aquatic)		6		2.7
	Kg N eq [d]	416.7			29.8
	Kg P eq [e] (Freshwater)				2.8
	Kg N eq [e] (Marine)				11
	Kg P eq [f] (Freshwater)			2.92–3.99	3.2
	Kg N eq [f] (Marine)			24.1–27.6	11
Ecotoxicity	Kg 1,4-DB eq [a] (Terrestrial)			15625	29170
	Kg 1,4-DB eq [a] (Freshwater)			86	392
	Kg 1,4-DB eq [a] (Marine)			123	458
	Kg 1,4-DB eq [b] (Freshwater)				4427
	E+07 Kg 1,4-DB eq [b] (Marine)				1.14
	E+05 Kg TEG water eq [c] (Marine)	83.9			8.7
	E+05 Kg TEG soil eq [c] (Terrestrial)	19.7			2.3
	E+03 CTUe eq [d]	810			120
	E+05 CTUe eq [e] (freshwater)		200–220		2.0
	E+04 CTUe eq [f] (freshwater)			6.45–7.18	12
Human toxicity	E+03 kg1,4-Db eq [a]	35–48		15	9.1
	E+03 Kg 1,4-DB eq [b]				5.3
	E−03 CTUh eq [d]	79.5			3.5
	E−03 CTUh eq [e]		9.3–10		0.14
	E−03 CTUh eq [f]			13–15	3.5
Respiratory effects	Kg PM2.5 eq [a]			16.0	12.9
	Kg PM2.5 eq [d]	250			4.7
	Particulate matter disease inc. [e]		0.019–0.026		0.00027

[a] ReCiPe 2016 Midpoint (H).
[b] CML.
[c] Impact 2002+.
[d] TRACI.
[e] EF3.0.
[f] ILCD 2011.

Table 3
Environmental impacts of the life cycle of cotton, viscose, lyocell and BC-lyocell using different LCIA methods. Comparisons normalized to 1 ton of cellulose.

Impact categories	Unit [LCIA method used]	Cotton (Jewell, 2017; Liu et al., 2020; Shen et al., 2010)	Viscose (Schultz and Suresh, 2017; Shen et al., 2010)	Lyocell (Schultz and Suresh, 2017; Shen et al., 2010)	BC-Lyocell
Global warming potential	E+03 Kg CO_2	1.3–11	0.005–6.5	0.005–4.5	7.2–7.7
Abiotic depletion	Kg Cu eq [a] (Mineral)	12.3	8.61		45.1
	Kg Sb eq [b]	0.00083–17	14–40	7–20	0.11
	MJ eq [c] (Mineral)	149			279
	Kg oil eq [a] (Fossil fuels)	468–1240	790		2046
	E+04 MJ eq [b] (fossil fuels)		2.6	2.2	8.7
	MJ eq [c] (fossil fuels)	32.64			101878
Water depletion	m^3 eq [a]	756–3510	85		232
	m^3 eq [b]	5732	310–740	263–290	232
Land use	ha-year eq [a]	0.40–0.58	0.090		0.088
	ha-year eq [b]	0.8	0.2–0.7	0.2–0.7	0.088
	m^2 org. arable eq [c]	7261			828
Ozone depletion	E−03 kg CFC11 eq [a]	0.000025–23.4	1.79		7.1
	E−04 kg CFC-11 eq [b]	0.00047–2.0	0.30–8.6	0.70–6.9	8.4
Ozone formation	Human health eq [a]	11.9	8.76		17.0
	Terrestrial ecosystems eq [a]	12.1	8.88		17.3
	Kg C_2H_4 eq [b]	0.16	2.37	0.90	2.3
Acidification	Kg SO_2 eq [a] (Terrestrial)	5.84–31.6	21.1		42.7
	Kg SO_2 eq [b]	26–41	14–55	13–20	50.2
	Kg SO_2 eq [c] (Aquatic)	28			51.3
Eutrophication	kg P eq [a] (Freshwater)	0.0028–2.29	1.74		3.4
	Kg N eq [a] (Marine)	2.06–12.1	0.12		1.4
	Kg PO_4^- eq [b]	7.8–22	1.2–5.4	1.8–3.7	16.2
	Kg PO4 P-lim eq [c] (Aquatic)	2.0			2.8
Ecotoxicity	Kg 1,4-DB eq [a] (Terrestrial)	0.036–11000	18000		31000
	Kg 1,4-DB eq [2] (Terrestrial)	1568	11–36.5	1.3–5	15.7
	Kg 1,4-DB eq [1] (Freshwater)	0.29–379	147		413
	Kg 1,4-DB eq [b] (Freshwater)	17310	27.1–160	75–85	4739
	Kg 1,4-DB eq [a] (Marine)	0.127–198	199		486
	E+03 Kg 1,4-DB eq [b] (Marine)		2.6	2.7	1270
	E+03 CTUe eq [d]	3.9			127
Human toxicity	kg1,4-Db eq [a]	68.8–6300	4100		9700
	Kg 1,4-DB eq [b]	1700	1.2–1500	0.69–660	5601
	E−03 CTUh eq [d]	0.082			3.8
Respiratory effects	Particulate matter formation eq [a]	6.80	9.91		14.1
	Kg PM2.5 eq.[d]	1.8			4.1

[a] ReCiPe 2016 Midpoint (H).
[b] CML.
[c] Impact 2002,+.
[d] ILCD Midpoint,+.

larger impacts on ozone layer depletion, human toxicity, ozone formation, acidification, and global warming potential (Table 3). Cotton fibre production relies on just two primary stages - farming/crop rotation and ginning - simplifying the production process, resulting in a reduced impact on the mentioned categories (Chen et al., 2021; Jewell, 2017). The global warming potential and CO_2 emissions varied significantly as the impact of cotton is region dependent. Although cotton fibre production offers some advantages compared to BC-lyocell, it carries negative aspects due to the use of pesticides and fertilizers, which have detrimental effects on various categories such as abiotic depletion, ecotoxicity and eutrophication, due to the upstream production and application of these chemicals (Jewell, 2017; PE, 2012). Furthermore, cotton fibre production negatively impacts water depletion and land use, as it demands substantial quantities of water for irrigation and extensive land for cotton plant cultivation (Jewell, 2017; PE, 2012).

As for viscose, its production is recognized for being harmful to ecosystems and human health due to the use and disposal of sodium hydroxide, carbon disulphide and sulfuric acid (Felgueiras et al., 2021; Guo et al., 2021). Moreover, the production of viscose fibre is energy-intensive, resulting in larger contributions to global warming potential, ozone layer depletion, ozone formation and abiotic depletion. Nonetheless, BC-lyocell still exhibited higher impacts on freshwater ecotoxicity, eutrophication, global warming and fossil fuel depletion, whereas both materials had similar impacts on abiotic depletion, ozone layer depletion, terrestrial ecotoxicity and acidification (Table 3). BC-lyocell only exhibited lower impacts than viscose fibres on ozone formation, water depletion and land use. The high impact of viscose on ozone formation was due to the high SO_2 emissions from energy production in the pulp mills (Shen et al., 2010). As for water depletion, viscose requires a significant amount of water for pulp pre-treatment, dissolving and for washing, which contributed for higher water scarcity than BC-Lyocell (Shen et al., 2010) (Table 3).

The process for lyocell is shown to be more circular, enabling a closed loop production, where chemicals such as N-Methylmorpholine N-oxide (NMMO) and water are recycled and reused. In addition to its reduced chemical usage, NMMO is known to be less harmful and toxic, as reflected by its lower impact on human toxicity, ecotoxicity and acidification. Lyocell production is also energy-efficient, lowering gas emissions that impact ozone layer depletion, ozone formation and global warming potential (Shen et al., 2010). BC-lyocell was modelled using the same technology (lyocell), yet its environmental impacts were found to be higher than those of wood-derived lyocell fibres (Table 3). The main difference lies in the use of BC pulp. On the other hand, BC-lyocell shows lower water depletion and land use than lyocell fibres (Table 3), both of which are primarily related to pulp production.

Overall, the modelled BC-lyocell revealed significantly lower land

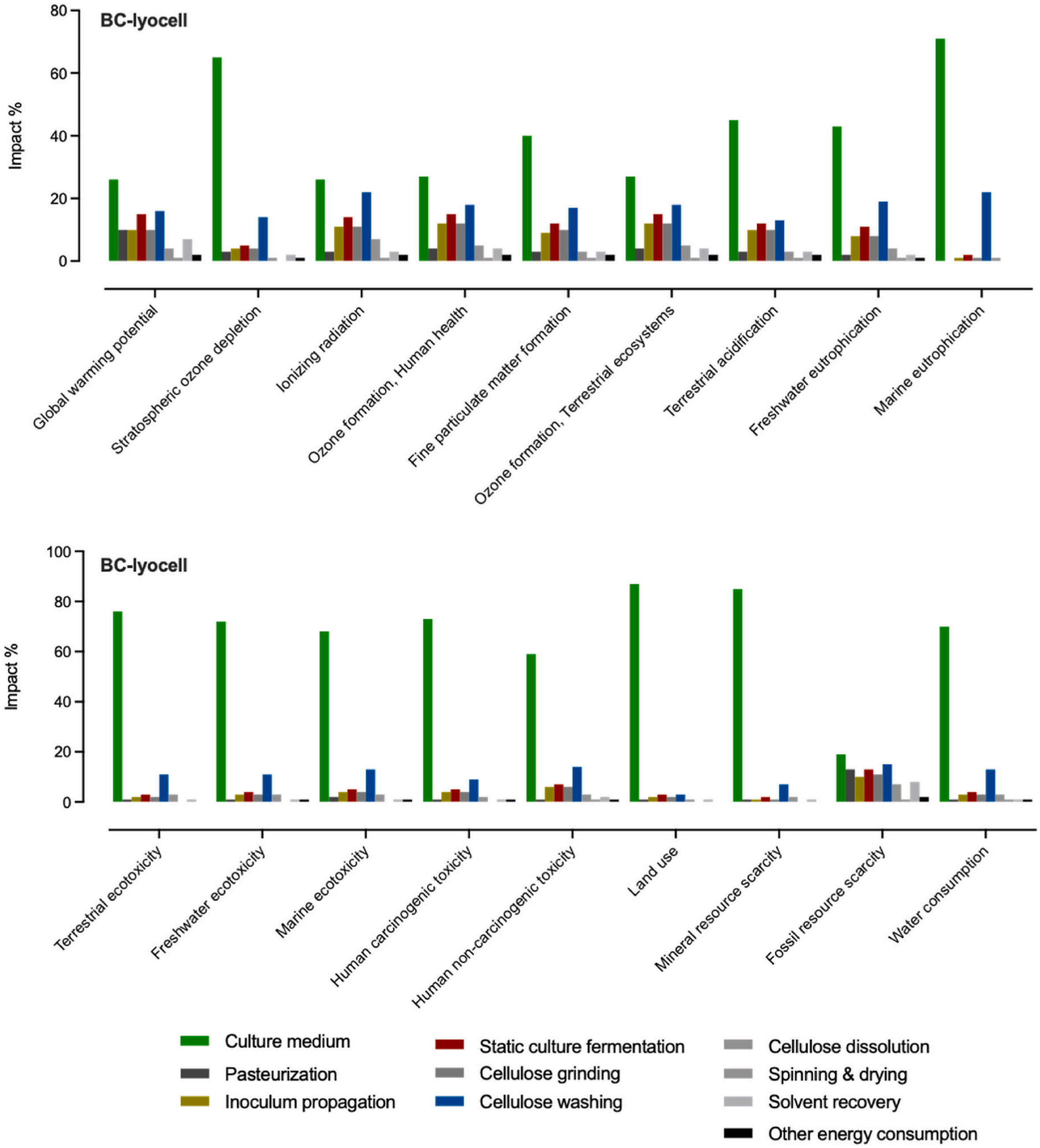

Fig. 2. LCA Mid-point impact categories (%) for each production process for BC-Lyocell, estimated using ReCiPe midpoint (H) (absolute values in Table S8).

use and water depletion when compared to cotton, viscose, and lyocell, owing to the biotechnologically-based production. Nevertheless, it displayed elevated impacts in categories associated with toxicity and gas emissions, highlighting the need to further investigate and identify the sources of the environmental impacts of BC pulp or BC-lyocell production. For this, an in-depth analysis of the LCA for the BC-lyocell was conducted as described in the following section.

3.3. BC-lyocell environmental impact analysis

In the preceding sections, the estimated BC-Lyocell environmental impacts revealed a somewhat surprisingly larger environmental burden when compared to other cellulose sources. This seems to contradict a frequently held belief that BC is a more sustainable source of cellulose, as it can be produced from industrial side streams in a circular economy framework. Consequently, an in-depth analysis was conducted to identify hotspots in the BC production process. Fig. 2 illustrates the impacts (%) estimated using the ReCiPe midpoint H method for BC-Lyocell fibre production. The data indicates that nearly all categories (excluding ionizing radiation and fossil depletion) are substantially affected by the components used in the preparation of the culture medium. Its preparation contributes to roughly 20% of the total global warming potential and approximately 60% in categories linked to ozone depletion, ecotoxicity, human toxicity, and eutrophication. It has an even more substantial impact on land use and abiotic depletion, accounting for up to 80% of these categories (Fig. 2). To thoroughly investigate the influence of each component of the culture medium, the LCA mid-point categories of the culture medium were examined in detail (Fig. 3A). Strikingly,

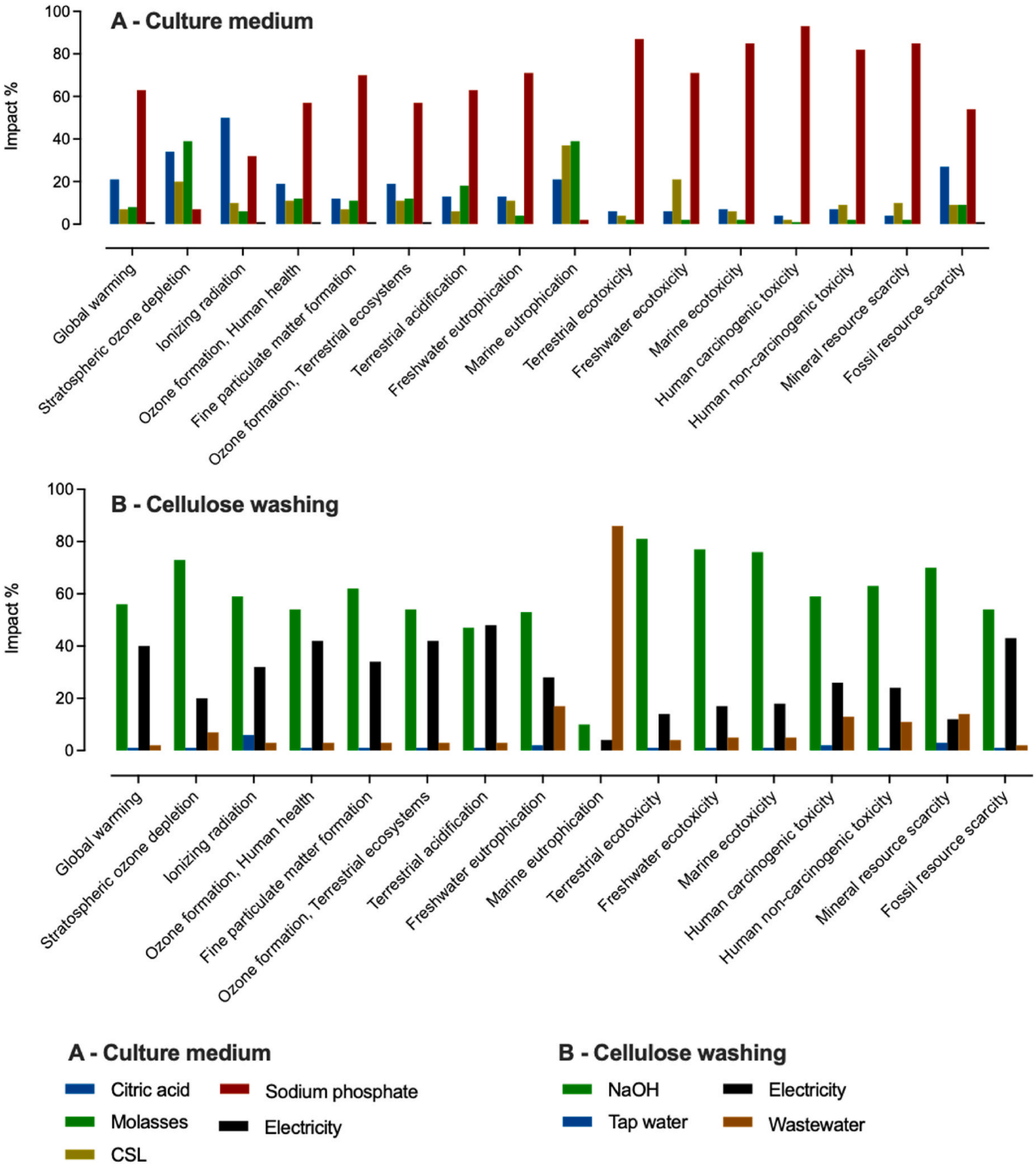

Fig. 3. LCA impact categories of the culture medium (A) and cellulose washing (B) processes used for BC-Lyocell model, estimated using ReCiPe midpoint (H) (absolute values in Tables S9 and S10).

sodium phosphate emerged as the component with the highest impact, representing approximately 60–80% of the overall impact of the culture medium across nearly all categories. The impact of sodium phosphate is closely linked to the production and use of phosphoric acid, known to be toxic to humans and to ecosystems (Gad, 2024). Citric acid also impacted significantly on ozone depletion, global warming, and ionizing radiation, whereas molasses and CSL were found to impact greatly on ozone depletion and marine eutrophication (Fig. 3A). It is worth noting that most literature emphasizes the optimization of the culture medium to increase BC yield, while overlooking its environmental impact. Consequently, LCA is a valuable tool to support efforts towards an optimized BC production, while mitigating its environmental impact. For instance, reducing or removing sodium phosphate and citric acid from the culture medium would reduce the overall environmental impact, but may also affect the BC yield.

Impact assessments are expressed per functional unit, in this case 1 ton of BC. As the culture medium significantly affects the environmental impact, improving the BC yield would not only increase the economic return of an industrial facility, but would also markedly lower the environmental burden (Dourado et al., 2016). El-Gendi et al., (2022) reported multiple studies optimizing culture media, achieving BC yields as high as 10–15 g/L. Such high yields would result in reductions in environmental impact ranging from 5% to 24% for 10 g/L yield and from 10% to 45% for 15 g/L yield, respectively (Table S7). Indeed, this analysis was performed strictly to highlight the potential environmental benefits of increasing the BC yield. These estimations should be regarded as hypothetical since, in this projection, the culture medium's composition remained unchanged.

The cellulose washing also impacted by at least 10 % of the environment across several categories such as ozone formation, fine particulate matter formation, eutrophication, human toxicity, ecotoxicity, abiotic depletion, and water consumption (Fig. 2). NaOH is the main contributor to this process, across almost all categories (contributions from 10% to 81%). It also has a relevant impact on ecotoxicity and human toxicity (Fig. 3B). NaOH is recognized for its corrosive properties (National Center for, 2025), and is known to pose a risk to human health as well as (terrestrial and aquatic) ecosystems, while also contributing to emissions of heavy metals and organochlorine compounds (Hong et al., 2014). For the other processes, the main contributor is the electricity consumption (Fig. 2).

3.3.1. *Sensitivity analysis: BC-lyocell production neglecting the impact of culture medium (CM)*

Sensitivity analyses were conducted to explore scenarios aimed at reducing the BC-associated environmental impacts. As discussed above, the culture medium showed a significant impact (Figs. 2 and 3), with sodium phosphate as one of the main contributors. Therefore, two cases were considered in this study. In case 1, the effect of the removal of sodium phosphate from the culture medium on the mid-point impact categories was studied, assuming that the BC yield would remain unchanged (7.2 g/L). As for case 2, the culture medium was disregarded, omitting its influence on the overall environmental impact of BC. Table 4 presents the reduction in environmental impact across the assessed categories using ReCiPe midpoint H, comparing the above-mentioned cases to the previously modelled BC-lyocell (standard).

Excluding sodium phosphate from the culture medium, in the first case, resulted in a significant decrease in the environmental impacts (Table 4). This was particularly notable in terrestrial and aquatic ecotoxicity, human toxicity and mineral resource scarcity, with reductions of over 50%. In the second case, reductions exceeding 60%–70% were observed in several categories, including stratospheric ozone depletion, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity, land use, mineral resource scarcity and water consumption. In Fig. 4, we compared the impacts of the second case and the 3.1 textile fibres in section 3.2. The main goal was to assess whether the production of BC (by excluding the culture medium impact) becomes environmentally competitive towards the alternatives (from 3.2.) as well as identifying other contributors for the environmental impact.

Table 4
Midpoint impact of BC-Lyocell fibre considering different cases; impact assessments using ReCiPe midpoint H.

Categories	Units	BC-Lyocell		
		Standard	Case 1 (Sodium phosphate)	Case 2 (No culture medium)
Global warming potential	Kg CO_2	7707	6446	5718
Stratospheric ozone depletion	Kg CFC11	7.1E-03	6.81E-03	2.5E-03
Ionizing radiation	kBq Co-60	431	394	320
Ozone formation, Human health	Kg NOx	17.0	14.4	12.5
Fine particulate matter formation	Kg PM2.5	14.1	10.2	8.5
Ozone formation, Terrestrial ecosystems	Kg NOx	17.3	14.7	12.7
Terrestrial acidification	Kg SO_2	42.7	30.7	23.7
Freshwater eutrophication	Kg P	3.4	2.3	1.9
Marine eutrophication	Kg N	1.4	1.4	4.12E-01
Terrestrial ecotoxicity	Kg 1,4-DCB	30584	10444	7455
Freshwater ecotoxicity	Kg 1,4-DCB	413	203	116
Marine ecotoxicity	Kg 1,4-DCB	486	207	158
Human carcinogenic toxicity	Kg 1,4-DCB	796	257	216
Human non-carcinogenic toxicity	Kg 1,4-DCB	8902	4573	3627
Land use	m^2a crop	876	693	115
Mineral resource scarcity	Kg Cu	45.1	12.7	6.8
Fossil resource scarcity	Kg oil	2046	1833	1653
Water consumption	m^3	225	164	67

As observed in Fig. 4, the second case displayed lower impacts than BC-lyocell, yet it exhibited a larger environmental impact than the alternative cellulosic fibres in categories such as fossil fuel depletion, human toxicity, freshwater and marine ecotoxicity. The former categories are highly influenced by processes that rely on electrical consumption. The energy consumption estimates for BC-Lyocell's industrial production (both scenarios), obtained from SuperPro software, were based on a worst-case scenario. Conversely, estimates for the energy consumption for lyocell and viscose fibre production were derived from data directly collected at the production site (Shen et al., 2010). This difference led to distinct impacts since the energy consumption may be overestimated for BC-lyocell production, resulting in higher impacts than those estimated from models with data directly obtained from industrial processes. The ecosystems and human toxicity impacts were still high, due to the impact of NaOH in cellulose washing, as well as the total energy estimated for the second case of BC-Lyocell (Fig. 4). Contrarily, in categories like global warming, terrestrial toxicity, eutrophication, acidification, and ozone formation, significant improvements were made, under the premisses of case 2, to the extent where they became comparable to the environmental impacts of commercial fibres. Regarding global warming, the second case demonstrated a lower impact than viscose fibres, but a higher impact than cotton and lyocell. This discrepancy is attributed to the fermentative process of BC

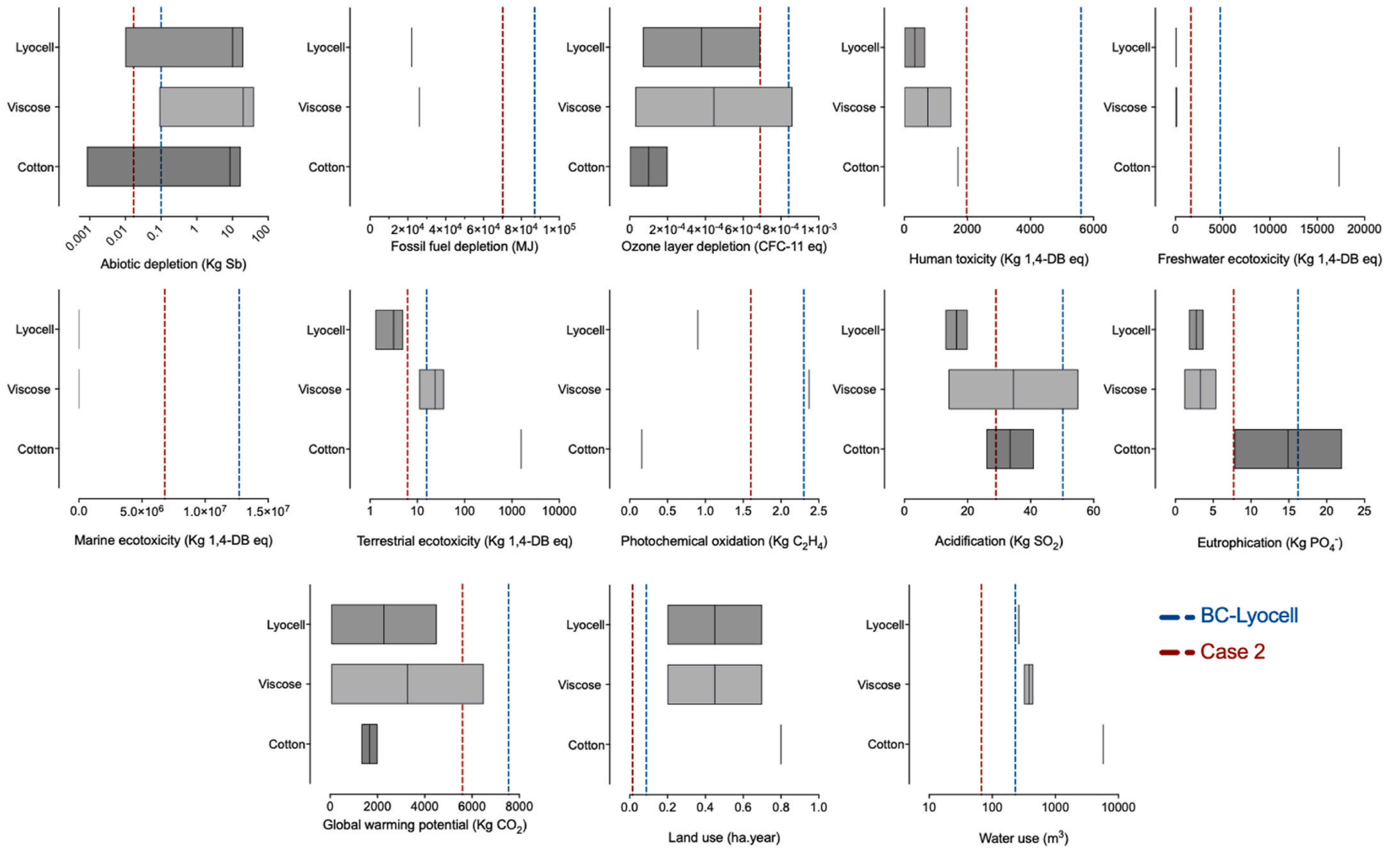

Fig. 4. Comparison between the Environmental impact of commercial textile fibres (Cotton (Jewell, 2017; Shen et al., 2010); Viscose (Schultz and Suresh, 2017; Shen et al., 2010); Lyocell (Schultz and Suresh, 2017; Shen et al., 2010)) and the base model of BC-Lyocell (blue dotted line) and case 2 of BC-Lyocell (red dotted line); Impact categories estimated using CML IA baseline V3.05/World 2000; (absolute values in Table S13). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

production, which results in CO_2 emissions, as well as the electrical energy consumption required for BC-lyocell fibre production. Concerning the terrestrial ecotoxicity, the impact of BC-lyocell (excluding the culture medium) was comparable to that of lyocell fibres and substantially lower than that of viscose and cotton fibres. The ecotoxicity impact formerly linked to the culture medium preparation, was now mitigated by removing the culture medium's impact.

Regarding acidification and eutrophication, the second scenario (case 2) exhibited slightly higher values than Lyocell fibres. These impacts are associated with the deposition of nutrients in terrestrial and aquatic ecosystems. The generation of effluents, although treated for recirculation, had a significant impact on eutrophication and acidification. Categories such as Abiotic depletion (mineral resources) and ozone depletion were substantially reduced, resulting in a lower impact than the commercial textile cellulosic fibres. Abiotic depletion, highly linked to the exploration of mineral resources was reduced by disregarding the impact of the culture medium, as most of this impact was due to the phosphoric acid (used for sodium phosphate production). Stratospheric ozone depletion was also reduced to values comparable to those of commercial fibres, after disregarding the culture medium. In the prior analysis using the BC-Lyocell base case scenario, ozone depletion was already slightly higher than that of the commercialized fibres.

3.4. *Discussion of BC environmental impact*

Both BC-Lyocell and BC pulp (even excluding impacts associated with the culture medium) show larger impacts when compared with commercial textile fibres and dissolving pulp, respectively. This can be attributed to the high impact of BC washing, which includes the use of NaOH and effluent treatment. Fig. S1 demonstrates that washing has a significant impact across all categories (varying from 20 to 60%) especially those related to abiotic depletion (shows a 60% contribution), ozone layer depletion (63%) and toxicity (human toxicity 41%), ecotoxicity (28–40%) and eutrophication (34%)).

The data here gathered highlights that, while the industrialization of the BC production is challenging but technically feasible, it is advisable to reassess the production process aiming at devising strategies to improve sustainability. The culture medium was the major contributor to the BC global impact and its formulation represents a great challenge. Components such as citric acid and sodium phosphate (Hestrin and Schramm, 1954), which contribute heavily to the environmental impact (up to 30–40% of the global impact), should be excluded or replaced. Multiple alternatives to carbon and nitrogen source are reported in the literature but their environmental impact needs to be assessed (Aswini et al., 2020; Soares Silva et al., 2019). Many of these alternative sources also bring along some complex challenges such as variability (quality and availability), seasonality and the generation of effluents with high organic matter content. Culture medium optimization is strain-dependent (Lahiri et al., 2021) and therefore the BC yield should be studied along with the environmental impact of the chosen culture medium. Another impactful process is the NaOH used in cellulose washing. Our modelled process yields a highly pure BC pulp. This may not be required in some applications. Thus, the washing process can in some instances be significantly shortened, reducing the impact of washing process by 30–50%. As observed in this study, energy consumption also has its impact on BC production. It is incremental to get reliable data to avoid overestimations of the energy needed for industrialization. Additionally, shifting to renewable energy sources would lower its global environmental impact. Countries like Portugal, which rely on high hydroelectric and wind energy generation (Administration, 2024), represent a good option for a BC production plant. Additionally, the anaerobic digestion of the wastewater (originated from the BC fermentation and washing) generates electricity through CH_4 production (Ahring, 2003; Hijazi et al., 2016). Anaerobic digestion would enable the BC production process to be less reliant on fossil fuels, thereby significantly decreasing its environmental footprint by 5–10%. Indeed, the valorisation of the effluents from BC fermentation for biogas production through anaerobic digestion has been demonstrated in our previous work (Silva et al., 2020b).

BC stands out when compared to nanocelluloses from an environmental perspective, thus representing a more sustainable alternative in applications such as cosmetic, food and food packaging. Particularly in cosmetics and food, where both BC and NC pulps demonstrated a good technological performance as texturizing agents, thickeners, or emulsion stabilizers (Soares Silva et al., 2022; Martins et al., 2020, 2021), the LCA results show that BC is likely to be a better option. However, while cost represents an additional strong barrier, BC-lyocell can hardly compete with currently available textile cellulose fibres, from a sustainability perspective. Despite the larger environmental impact compared to cellulosic fibres, its application in the textile industry for some niche opportunities should not be discarded. Recently, BC has proven to be an interesting additive to upcycle end-of-life fibres, using lyocell based technology (Soares Silva et al., 2023). In this case the use of low amounts of BC supporting the recycling of end-of-life fibres could represent an overall positive balance from a sustainability perspective. This application has been demonstrated by our group by upcycling viscose fibres with low amounts of BC (Silva et al., 2024).

Although it should be possible to analyse the comparative sustainability of BC and plant-based celluloses, many studies were deemed non-comparable due to differing system boundaries or functional units. The lack of comparable data on celluloses, nanocelluloses (NCs) and textile fibers highlights a significant limitation in the field. Standardizing and systematizing the analysis using a single LCIA methodology, and establishing consistent system boundaries, would be advantageous. This approach would facilitate a more comprehensive and accurate assessment and comparison of the environmental impacts of various products.

4. Conclusions, limitations, and future research

This study demonstrated that BC pulp has a lower overall environmental footprint than NCs. As for BC-Lyocell, it has a larger environmental impact for most environmental categories when compared to cotton, viscose, and lyocell, except for the impact categories of land use and water depletion. The primary contributor to BC's environmental impact can be ascribed to the production of components used in the culture medium, with sodium phosphate being identified as the most influential one. The sensitivity analysis showed that the culture medium contributes to 54% of the estimated environmental impacts. The data here gathered highlights the importance of the careful choice of the process options, namely with regards to the culture medium formulation, water recycling, wastewater processing & valorisation and the envisaged product purity. Several limitations have been recognized, including the absence of energy data on an industrial scale for BC production, to avoid overestimation of LCIA impacts; and the lack of comparable literature related to celluloses, NCs, and textile fibres. Standardizing the LCIA used within the community would prove advantageous in assessing and comparing the impacts of various products. Nevertheless, the comparative LCA analysis supports the conclusion that BC may have good opportunities for application (in addition to biomedicine) in the food, composites, and cosmetic industries (competing with nanocelluloses which, like BC pulp, demonstrated good technical performance) and for some niche applications in the textile field. In future investigations, it is crucial to identify potential carbon and nitrogen sources, as well as environmentally friendly additives or by-products. The goal is to select the most efficient options in each category for optimizing a culture medium, aiming to achieve high yields of BC with reduced environmental impacts. Additionally, characterizing wastewater becomes essential, as a lower organic load presence proves beneficial in reducing the amount of NaOH required during the washing process.

CRediT authorship contribution statement

Francisco A.G.S. Silva: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis. **Sara Branco:** Writing – review & editing, Methodology, Investigation. **Fernando Dourado:** Writing – review & editing, Validation, Supervision, Formal analysis. **Belmira Neto:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Miguel Gama:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.144876.

Data availability

Data will be made available on request.

References

Administration, I.T., 2024. Portugal - Country commercial guide [WWW Document]. https://www.trade.gov/country-commercial-guides/portugal-energy. accessed 2.15.24.

Ahring, B.K., 2003. Biomethanation I. Adv. Biochem. Eng. Biotechnol. 81, 1–217.

Aragão, J.V.S., Costa, A.F.S., Silva, G.L., Silva, S.M., Macêdo, J.S., Galdino, C.J.S., Milanez, V.F.A., Sarubbo, L.A., 2020. Analysis of the environmental life cycle of bacterial cellulose production. Chem. Eng. Trans. 79, 445–450. https://doi.org/10.3303/CET2079075.

Arvidsson, R., Nguyen, D., Svanström, M., 2015. Life cycle assessment of cellulose nanofibrils production by mechanical treatment and two different pretreatment processes. Environ. Sci. Technol. 49, 6881–6890. https://doi.org/10.1021/acs.est.5b00888.

Aswini, K., Gopal, N.O., Uthandi, S., 2020. Optimized culture conditions for bacterial cellulose production by Acetobacter senegalensis MA1. BMC Biotechnol. 20, 1–16. https://doi.org/10.1186/s12896-020-00639-6.

Balkissoon, S., Andrew, J., Sithole, B., 2023. Dissolving Wood Pulp Production: a Review, Biomass Conversion and Biorefinery. Springer Berlin Heidelberg. https://doi.org/10.1007/s13399-022-02442-z.

Blanco, A., Monte, M.C., Campano, C., Balea, A., Merayo, N., Negro, C., 2018. Chapter 5 - nanocellulose for industrial use: cellulose nanofibers (CNF), cellulose nanocrystals (CNC), and bacterial cellulose (BC). In: Mustansar Hussain, C. (Ed.), Handbook of Nanomaterials for Industrial Applications, Micro and Nano Technologies. Elsevier, pp. 74–126. https://doi.org/10.1016/B978-0-12-813351-4.00005-5.

Chen, F., Ji, X., Chu, J., Xu, P., Wang, L., 2021. A review: life cycle assessment of cotton textiles. Ind. Textila 72, 19–29. https://doi.org/10.35530/IT.072.01.1797.

de Amorim, J.D.P., de Souza, K.C., Duarte, C.R., da Silva Duarte, I., de Assis Sales Ribeiro, F., Silva, G.S., de Farias, P.M.A., Stingl, A., Costa, A.F.S., Vinhas, G.M., Sarubbo, L.A., 2020. Plant and bacterial nanocellulose: production, properties and applications in medicine, food, cosmetics, electronics and engineering. A review. Environ. Chem. Lett. 18, 851–869. https://doi.org/10.1007/s10311-020-00989-9.

De Figueirêdo, M.C.B., De Freitas Rosa, M., Lie Ugaya, C.M., De Souza Filho, M.D.S.M., Da Silva Braid, A.C.C., De Melo, L.F.L., 2012. Life cycle assessment of cellulose nanowhiskers. J. Clean. Prod. 35, 130–139. https://doi.org/10.1016/j.jclepro.2012.05.033.

Dourado, F., Fontão, A., Leal, M., Cristina Rodrigues, A., Gama, M., 2016. Chapter 12 - process modeling and techno-economic evaluation of an industrial bacterial NanoCellulose fermentation process. In: Gama, M., Dourado, F., Bielecki, S. (Eds.), Bacterial Nanocellulose. Elsevier, Amsterdam, pp. 199–214. https://doi.org/10.1016/B978-0-444-63458-0.00012-3.

Eckelt, J., Eich, T., Röder, T., Rüf, H., Sixta, H., Wolf, B.A., 2009. Phase diagram of the ternary system NMMO/water/cellulose. Cellulose 16, 373–379. https://doi.org/10.1007/s10570-009-9276-2.

El-Gendi, H., Taha, T.H., Ray, J.B., Saleh, A.K., 2022. Recent advances in bacterial cellulose: a low-cost effective production media, optimization strategies and applications. Cellulose 29, 7495–7533. https://doi.org/10.1007/s10570-022-04697-1.

Felgueiras, C., Azoia, N.G., Gonçalves, C., Gama, M., Dourado, F., 2021. Trends on the cellulose-based textiles: raw materials and technologies. Front. Bioeng. Biotechnol. 9, 608826.

Fink, H.P., Weigel, P., Purz, H.J., Ganster, J., 2001. Structure formation of regenerated cellulose materials from NMMO-solutions. Prog. Polym. Sci. 26, 1473–1524. https://doi.org/10.1016/S0079-6700(01)00025-9.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Foroughi, F., Ghomi, E.R., Dehaghi, F.M., Borayek, R., Ramakrishna, S., 2021. A review on the life cycle assessment of cellulose: from properties to the potential of making it a low carbon material. Materials 14, 1–23. https://doi.org/10.3390/ma14040714.

Forte, A., Dourado, F., Mota, A., Neto, B., Gama, M., Ferreira, E.C., 2021. Life cycle assessment of bacterial cellulose production. Int. J. Life Cycle Assess. 26, 864–878. https://doi.org/10.1007/s11367-021-01904-2.

Gad, S.C., 2024. Phosphoric acid. In: Wexler, P. (Ed.), Encyclopedia of Toxicology, fourth ed. Academic Press, Oxford, pp. 605–610. https://doi.org/10.1016/B978-0-12-824315-2.00813-7.

Gallo Stampino, P., Riva, L., Punta, C., Elegir, G., Bussini, D., Dotelli, G., 2021. Comparative life cycle assessment of cellulose nanofibres production routes from virgin and recycled raw materials. Molecules 26, 1–20. https://doi.org/10.3390/molecules26092558.

Goedkoop, M., Spriensma, R., 2001. The eco-indicator 99 - a damage oriented method for life cycle impact assessment. Assessment 144.

Gu, H., Reiner, R., Bergman, R., Rudie, A., 2015. LCA study for pilot scale production of cellulose nano crystals (CNC) from wood pulp. LCA XV Pap. Proc. – A"Bright"Green"Future 33–42.

Guinée, J.B., 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Springer Science & Business Media.

Guo, S., Li, X., Zhao, R., Gong, Y., 2021. Comparison of life cycle assessment between lyocell fiber and viscose fiber in China. Int. J. Life Cycle Assess. 26, 1545–1555. https://doi.org/10.1007/s11367-021-01916-y.

Gupta, P.K., Raghunath, S.S., Prasanna, D.V., Venkat, P., Shree, V., Chithananthan, C., Choudhary, S., Surender, K., Geetha, K., 2019. An update on overview of cellulose, its structure and applications. Cellulose 201, 84727.

Hedayati, M., Brock, P.M., Nachimuthu, G., Schwenke, G., 2019. Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: an Australian perspective. J. Clean. Prod. 212, 974–985. https://doi.org/10.1016/j.jclepro.2018.11.190.

Hestrin, S., Schramm, M., 1954. Synthesis of cellulose by Acetobacter xylinum. II. Preparation of freeze-dried cells capable of polymerizing glucose to cellulose. Biochem. J. 58, 345–352. https://doi.org/10.1042/bj0580345.

Hijazi, O., Munro, S., Zerhusen, B., Effenberger, M., 2016. Review of life cycle assessment for biogas production in Europe. Renew. Sustain. Energy Rev. 54, 1291–1300. https://doi.org/10.1016/j.rser.2015.10.013.

Hong, J., Chen, W., Wang, Y., Xu, C., Xu, X., 2014. Life cycle assessment of caustic soda production: a case study in China. J. Clean. Prod. 66, 113–120. https://doi.org/10.1016/j.jclepro.2013.10.009.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Hytönen, E., Sorsamäki, L., Kolehmainen, E., Sturm, M., von Weymarn, N., 2023. Lyocell fibre production using NMMO–A simulationbased techno-economic analysis. Bioresources 18.

IPCC, 2023. Summary for policymakers: synthesis report. Clim. Chang. 2023 synth. Report. Contrib. Work. Groups I, II III to sixth assess. Rep. Intergov. Panel Clim. Chang. 1–34.

IPCC, 2013. Climate change 2013—the physical science basis. Chem. Int. https://doi.org/10.1515/ci-2021-0407.

Jedrzejczak-Krzepkowska, M., Kubiak, K., Ludwicka, K., Bielecki, S., 2016. Chapter 2 - bacterial NanoCellulose synthesis, recent findings. In: Gama, M., Dourado, F., Bielecki, S. (Eds.), Bacterial Nanocellulose. Elsevier, Amsterdam, pp. 19–46. https://doi.org/10.1016/B978-0-444-63458-0.00002-0.

Jewell, J., 2017. LCA update of cotton fiber and fabric life cycle inventory. Cott. Counc. Int. 162.

Jozala, A.F., de Lencastre-Novaes, L.C., Lopes, A.M., de Carvalho Santos-Ebinuma, V., Mazzola, P.G., Pessoa-Jr, A., Grotto, D., Gerenutti, M., Chaud, M.V., 2016. Bacterial nanocellulose production and application: a 10-year overview. Appl. Microbiol. Biotechnol. 100, 2063–2072. https://doi.org/10.1007/s00253-015-7243-4.

Katakojwala, R., Mohan, S.V., 2020. Microcrystalline cellulose production from sugarcane bagasse: sustainable process development and life cycle assessment. J. Clean. Prod. 249, 119342. https://doi.org/10.1016/j.jclepro.2019.119342.

Khounani, Z., Hosseinzadeh-Bandbafha, H., Nizami, A.-S., Sulaiman, A., Goli, S.A.H., Tavassoli-Kafrani, E., Ghaffari, A., Rajaeifar, M.A., Kim, K.-H., Talebi, A.F., 2020. Data on environmental analysis of natural antioxidant production from walnut husk by a solar photovoltaic-driven system as a replacement for potentially carcinogenic synthetic antioxidants. Data Br 28, 104933.

Kim, J.H., Shim, B.S., Kim, H.S., Lee, Y.J., Min, S.K., Jang, D., Abas, Z., Kim, J., 2015. Review of nanocellulose for sustainable future materials. Int. J. Precis. Eng. Manuf. - Green Technol. 2, 197–213. https://doi.org/10.1007/s40684-015-0024-9.

Krässig, H., Schurz, J., Steadman, R.G., Schliefer, K., Albrecht, W., Mohring, M., Schlosser, H., 2012. Ullmann's encycl. Ind. Chem. - heterogenous catalysis and solid catalysts 1. Fundamentals. Ullmann's encycl. Ind. Chem. 565–582. https://doi.org/10.1002/14356007.a05.

Ludwicka, K., Jedrzejczak-Krzepkowska, M., Kubiak, K., Kolodziejczyk, M., Pankiewicz, T., Bielecki, S., 2016. Medical and cosmetic applications of bacterial nanocellulose. In: Bacterial Nanocellulose. Elsevier, pp. 145–165.

Lahiri, D., Nag, M., Dutta, B., Dey, A., Sarkar, T., Pati, S., Edinur, H.A., Kari, Z.A., Noor, N.H.M., Ray, R.R., 2021. Bacterial cellulose: production, characterization and application as antimicrobial agent. Int. J. Mol. Sci. 22, 1–18. https://doi.org/10.3390/ijms222312984.

Liu, Y., Huang, H., Zhu, L., Zhang, C., Ren, F., Liu, Z., 2020. Could the recycled yarns substitute for the virgin cotton yarns: a comparative LCA. Int. J. Life Cycle Assess. 25, 2050–2062. https://doi.org/10.1007/s11367-020-01815-8.

Martins, D., de Carvalho Ferreira, D., Gama, M., Dourado, F., 2020. Dry Bacterial Cellulose and Carboxymethyl Cellulose formulations with interfacial-active performance: processing conditions and redispersion. Cellulose 27, 6505–6520. https://doi.org/10.1007/s10570-020-03211-9.

Martins, D., Rocha, C., Dourado, F., Gama, M., 2021. Bacterial Cellulose-Carboxymethyl Cellulose (BC:CMC) dry formulation as stabilizer and texturizing agent for surfactant-free cosmetic formulations. Colloids Surfaces A Physicochem. Eng. Asp. 617, 126380. https://doi.org/10.1016/j.colsurfa.2021.126380.

Mboowa, D., 2021. A review of the traditional pulping methods and the recent improvements in the pulping processes. Biomass Convers. Biorefinery 1–12. https://doi.org/10.1007/s13399-020-01243-6.

Zhang, L., Jia, X., Ai, Y., Huang, R., Qi, W., He, Z., Klemeš, J.J., Su, R., 2022. Greener production of cellulose nanocrystals: an optimised design and life cycle assessment. J. Clean. Prod. 345. https://doi.org/10.1016/j.jclepro.2022.131073.

European Platform on Life Cycle Assessment. In: ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European context, 2011. European Commission, Joint Research Centre.

Nascimento, D.M. do, Dias, A.F., Araújo Junior, C.P. de, Rosa, M. de F., Morais, J.P.S., Figueirêdo, M.C.B. de, 2016. A comprehensive approach for obtaining cellulose nanocrystal from coconut fiber. Part II: environmental assessment of technological pathways. Ind. Crops Prod. 93, 58–65. https://doi.org/10.1016/j.indcrop.2016.02.063.

Pe, C.I.I., 2012. Life Cycle Assessment of Cotton Fiber & Fabric 156.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G., 2004. Life cycle assessment Part 2: current impact assessment practice. Environ. Int. 30, 721–739. https://doi.org/10.1016/j.envint.2003.12.009.

Prado, V., Seager, T.P., Guglielmi, G., 2022. Challenges and risks when communicating comparative LCA results to management. Int. J. Life Cycle Assess. 27, 1164–1169. https://doi.org/10.1007/s11367-022-02090-5.

Righi, S., Morfino, A., Galletti, P., Samorì, C., Tugnoli, A., Stramigioli, C., 2011. Comparative cradle-to-gate life cycle assessments of cellulose dissolution with 1-butyl-3-methylimidazolium chloride and N-methyl-morpholine-N-oxide. Green Chem. 13, 367–375.

Schultz, T., Suresh, A., 2017. Life Cycle Assessment: Comparing Ten Sources of Manmade Cellulose Fiber 158.

Sharma, A., Thakur, M., Bhattacharya, M., Mandal, T., Goswami, S., 2019. Commercial application of cellulose nano-composites – a review. Biotechnol. Reports 21, e00316. https://doi.org/10.1016/j.btre.2019.e00316.

Shen, L., Worrell, E., Patel, M.K., 2010. Environmental impact assessment of man-made cellulose fibres. Resour. Conserv. Recycl. 55, 260–274. https://doi.org/10.1016/j.resconrec.2010.10.001.

Silva, F.A.G.S., Dourado, F., Gama, M., Poças, F., 2020a. Nanocellulose bio-based composites for food packaging. Nanomaterials 10, 1–29. https://doi.org/10.3390/nano10102041.

Silva, F.A.G.S., Oliveira, J.V., Felgueiras, C., Dourado, F., Gama, M., Alves, M.M., 2020b. Study and valorisation of wastewaters generated in the production of bacterial nanocellulose. Biodegradation 31, 47–56. https://doi.org/10.1007/s10532-020-09893-z.

Silva, F.A.G.S., Schlapp-Hackl, I., Nygren, N., Heimala, S., Leinonen, A., Dourado, F., Gama, M., Hummel, M., 2024. Upcycling of cellulosic textile waste with bacterial cellulose via Ioncell® technology. Int. J. Biol. Macromol. 271, 132194. https://doi.org/10.1016/j.ijbiomac.2024.132194.

Soares Silva, F.A.G., Fernandes, M., Souto, A.P., Ferreira, E.C., Dourado, F., Gama, M., 2019. Optimization of bacterial nanocellulose fermentation using recycled paper sludge and development of novel composites. Appl. Microbiol. Biotechnol. 103, 9143–9154. https://doi.org/10.1007/s00253-019-10124-6.

Soares Silva, F.A.G., Matos, M., Dourado, F., A M Reis, M., C Branco, P., Poças, F., Gama, M., 2022. Development of a layered bacterial nanocellulose-PHBV composite for food packaging. J. Sci. Food Agric. https://doi.org/10.1002/jsfa.11839.

Soares Silva, F.A.G., Meister, F., Dourado, F., Gama, M., 2023. Regenerated bacterial cellulose fibres. Int. J. Biol. Macromol. 253, 127310. https://doi.org/10.1016/j.ijbiomac.2023.127310.

Torres, F.G., Arroyo, J.J., Troncoso, O.P., 2019. Bacterial cellulose nanocomposites: an all-nano type of material. Mater. Sci. Eng. C 98, 1277–1293. https://doi.org/10.1016/j.msec.2019.01.064.

Nanollose, n.d. Nullarrbor Fibre [WWW Document]. URL https://nanollose.com/products/nullarbor/(accessed 3.31.23).

Niblick, B., B. Morelli, T. Hawkins, A. Henderson, H. Golden, J. Compton, E. Cooter, J. Bare. Eutrophication Model Development for Life Cycle Impact Assessment in the United States (ICOSSE '18 presentation). ICOSSE '18: 7th International Congress on Sustainability Science & Engineering, Cincinnati, Ohio, August 12 - 15, 2018.

Woodings, C., 2001. Regenerated cellulose fibres. Regenerated cellulose fibres. https://doi.org/10.1533/9781855737587.

National Center for Biotechnology Information (2025). PubChem Compound Summary for CID 14798, Sodium Hydroxide. Retrieved January 28, 2025 from https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-Hydroxide.