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Environmental sustainability of cotton: a systematic literature review of life cycle assessments

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ABSTRACT

Cotton is the world's most used natural fiber, representing over 80% of global natural fiber use. However, its cultivation involves considerable consumption of water, energy, fertilizers, and pesticides, which impact both the environment and human health. Additional impacts arise from consumer activities such as washing and ironing. This review analyzes twenty peer-reviewed studies on cotton life cycle assessments, selected from Scopus and Web of Science according to PRISMA guidelines and covering the period 2010–2022. Among the inclusion criteria, studies addressing the cultivation phase were considered, while the exclusion criteria involved conference papers, book chapters and partial life cycle assessments. These studies indicate that cotton production—from cultivation to the final product—has the greatest impact on water use, energy consumption, greenhouse gas emissions and toxicity. Organic cotton farming demonstrates lower environmental impacts per unit area compared to conventional farming, but it exhibits higher impacts when evaluated on a mass basis. This discrepancy arises from the typically lower yields of organic systems relative to their conventional counterparts, emphasizing how the choice of functional unit can significantly influence the results and the conclusions drawn. Industrial processes like dyeing and spinning generate substantial carbon emissions, while consumer use—particularly washing and drying—accounts for over 65% of total energy consumption. The review identifies key sustainability issues in cotton production—high demand for and use of water, energy, and chemicals— and suggests strategies to mitigate the impacts across its life cycle such as efficient irrigation, optimized fertilization, the adoption of organic or Bt cotton, a shift towards renewable energy sources, and recycling.

1. Introduction

Cotton is the most widely used natural fibre in the world, accounting for over 82% of global natural fiber use [1]. The latest estimates put world cotton production at 24.2×10^6 t, with a cultivated area of 31.92 $\times$ 10^6 ha^{-1} across 80 countries and an estimated annual turnover of \$5.68 billion [2]. China, with a production of 6 million tonnes, is currently the world's largest producer, followed by India and the United States [2]. However, while cotton is economically vital, its production and use across the entire supply chain—from cultivation to processing, consumer use, and disposal— cause substantial environmental degradation. The environmental impacts associated with textile cotton are very complex and heterogeneous from country to country, also translating into human health problems.

For instance, cotton cultivation requires a significant amount of water, ranging from 700 to 1200 mm during the growing season, depending mainly on the growing area [3–5]. This high demand is exacerbated by the widespread use of low-efficiency irrigation methods, such as furrow and sprinkler irrigation systems, instead of more efficient alternatives like drip irrigation and mulched irrigation systems [6–8]. Intensive irrigation for cotton in arid regions exacerbates local water scarcity and contributes to biodiversity loss, with cases like the Aral Sea disaster in central Asia illustrating the severe ecological consequences of unsustainable water management [9]. Likewise, the extensive use of

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pesticides is a major environmental and health concern. Some authors estimate that around 50% of all pesticides in developing countries are used for cotton cultivation, while globally cotton accounts for 11% of total pesticide consumption [10]. This appears even more alarming when considering that cotton is cultivated on only 2.4% of the world's arable land [11]. According to the latest data provided by the United States Department of Agriculture [12], herbicides were used in 96% of the cotton-growing areas in the USA, in particular glyphosate isopropylamine salt, glyphosate potassium salt, paraquat, dicamba diglycolamine salt and diuron. Cases of illnesses among cotton farmers because of pesticide toxicity were reported, especially in developing countries, where there is usually a considerable lack of occupational hygiene regulations [13]. Not only that, but due to resistance phenomena, pesticides are often overused in cotton fields, with a significant portion of the applied chemicals failing to reach their intended targets. Instead, they are dispersed into surrounding ecosystems, contaminating water bodies and soil, and resulting in high eco-toxicity impacts and biodiversity loss [14].

Furthermore, cotton manufacturing is characterized by substantial energy requirements during spinning and textile manufacturing steps (such as weaving, cutting, and sewing), and by the consumption of water and the use of various chemicals in dyeing, including bleach, dyes, soaps, softeners, and salts [15,16]. The high amount of electricity considerably increases CO_2 emissions and the potential for acidification, whilst chemicals are of high potential concern for the environment, and human health (factory workers and consumers). Moreover, beyond exacerbating water depletion, improperly treated wastewater can enter local groundwater, and degrade the ecosystem [17,18].

Also, domestic usage plays a critical role in the overall environmental impact of cotton garments. For instance, the washing and drying of garments are particularly energy-intensive, often resulting in a greater environmental impact than any other stage of the production process [19]. Research indicates that energy expenditure during the consumer use phase accounts for more than 65% of the Total Energy (TE) consumption [20]. Moreover, the turnaround from production to waste is very rapid, as the lifespan of garments averages only about 3–3.5 years, after which they are often incinerated or sent to landfills, thereby generating additional greenhouse gas emissions and contributing to the growing burden of solid waste. While recycling initiatives are advancing, the share of recycled cotton remains limited, and the recycling process itself involves further water and energy use [17].

Given these complex and far-reaching impacts, it is essential to assess cotton's sustainability from a full life cycle perspective to identify key hotspots and opportunities for improvement throughout the supply chain. Several studies have assessed the environmental impacts of cotton textile products, and the Life Cycle Assessment (LCA) methodology has been largely adopted to this purpose [20]. Indeed, LCA is unique in its ability to analyze the entire life cycle of a product or service and assess the associated environmental burdens [21]. Initially developed for industrial production systems, LCA was later adapted to agricultural and food systems [22], becoming now a key tool for the sustainable management of the agri-food sector [23,24]. The aim of an LCA study can be to compare the environmental performances of alternative products, processes, or services, and identify environmental hotspots and improvement and/or mitigation strategies [25,26]. According to the ISO 14040-44 regulation [27], an LCA study follows four interconnected phases: Goal and Scope Definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation. By identifying environmental impacts at each stage, LCA promotes the development of sustainable practices and helps enhance competitiveness of environmentally sustainable products in the markets.

Previous reviews on cotton LCA [28–30] have mainly focused on summarizing general results or categorizing studies by system boundaries, such as "cradle to farm", "cradle to gate" and "cradle to grave". However, more in-depth comparative analysis of methodological choices (e.g., functional units, impact assessment methods) and contextual variables (e.g., geographic location, production methods) influence study outcomes is lacking. This review, however, not only maintains the classification by system boundaries, but also incorporates an additional level of analysis, examining how geographical and methodological variations influence reported environmental impacts. This dual-level categorization allows for a deeper understanding of LCA results and provides targeted insights into specific sustainability challenges in cotton supply chains. This approach highlights similarities and differences between studies and identifies specific areas for improvement in sustainability practices for cotton supply chains.

2. Material and methods

To gain new scientific insights into the environmental impact of cotton products, a systematic literature review was conducted in accordance with the PRISMA guidelines [31]. The search string used included the terms "Cotton" AND "Life Cycle Assessment" OR "LCA": these keywords were used as they were deemed the most representative of the research objectives. Scopus® and Web of Science® were selected for their complementarity, which helps minimize the risk of omitting relevant literature. In addition, both databases index only peer-reviewed scientific journals, thus ensuring the reliability and quality of the sources [31] included in this review. Indeed, the use of these databases increased the likelihood of capturing all relevant contributions to the central research topic of this review, thereby ensuring a high level of rigor in the search and selection process.

2.1. Research protocol

To ensure rigor in the literature review, the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was adopted [31]. Fig. 1 presents the flowchart of the search process, which follows four steps: identification, screening, eligibility, and data extraction. The diagram details the number of studies included or excluded at each step, with ultimately 20 studies included into the qualitative review.

2.2. Eligibility criteria

The selection process was carried out to include articles written in English and published in peer-reviewed journals. To ensure the inclusion of the most recent and relevant research, studies published prior to 2010 were excluded, narrowing the time range to publications between 2010 and 2022. The articles were required to present new and relevant data, analyses, or insights on the application of LCA within the cotton cultivation. In particular, they had to contribute to advancing knowledge on sustainability improvements in the cotton production process, offering either novel methodologies, case studies, or significant findings relevant to environmental impacts. Publications that were not related to the topic, despite their positive wording with the search query, were discarded to maintain a clear focus.

Specifically, the following inclusion and exclusion criteria were adopted.

- Only peer-reviewed articles written in English were considered;
- Conference reviews, and book chapters were not reviewed;
- Gate-to-gate and gate-to-grave assessments were excluded, which means that LCAs of cotton products were considered only if they included the cultivation phase;
- Preference was given to the most recent and informative studies addressing the same experimental topic, ensuring that the selected literature reflects the latest advancements and findings in the field;
- Studies were excluded if they were based on simulation or hypothetical experiments and if they used non-robust methods, such as narrative analysis or overviews with no detailed discussion of a comparison;

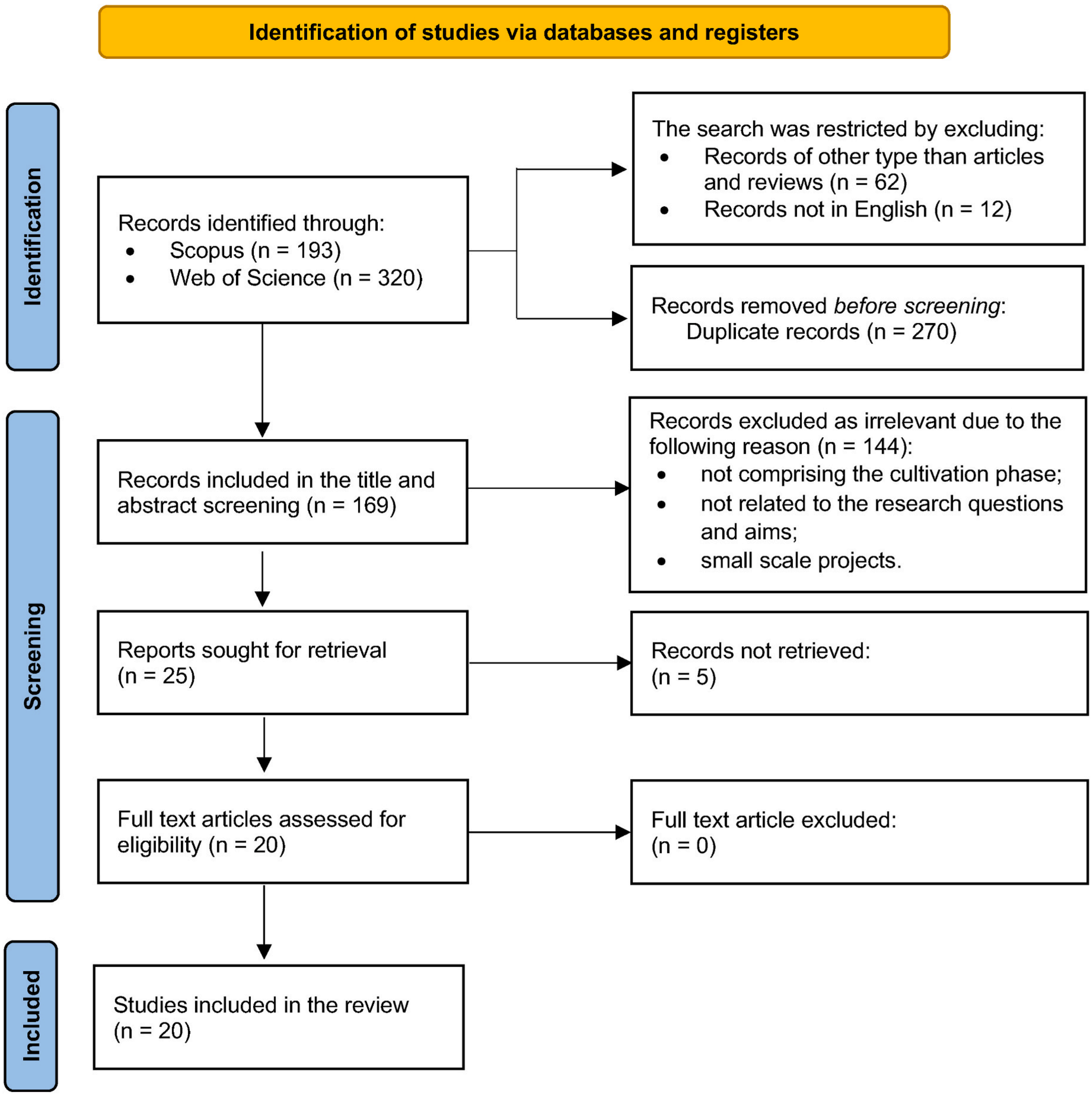

Fig. 1. PRISMA flowchart of the results of the literature search.Own elaboration following the PRISMA model.

- Interventions on small scale projects were also excluded, as they may not be representative of current production systems, and may not reflect a long-term course of action.

Among the studies published until December 2022 (the date of last research), in total, the search returned 513 results. Of these, 74 publications were removed before screening because 12 were written in other languages than English and 62 were publications of a different type than the articles. Additionally, 144 publications were excluded due to irrelevant content. The full texts of the remaining 25 publications were then reviewed and 20 eligible publications were included in the qualitative summary. Subsequently, no publications were excluded, so that because of the screening process, a total of 20 publications were qualitatively reviewed. While our review included only 20 studies, these were selected for their quality, methodological rigor, and global relevance, and together they provide a representative overview of current LCA research on cotton. We note, however, that as the field continues to evolve, future studies will be valuable to further expand and update our findings and conclusions.

2.3. Synthesis of results

After the screening, the selected publications were reviewed to provide a comprehensive and critical overview of the main environmental impacts of cotton, from cultivation to fiber production, consumption and disposal. The articles were classified based on their system boundaries, as follows.

- LCAs of cotton cropping systems (from cradle to farm): this category includes all agricultural practices involved in the cultivation of cotton from planting to harvesting, with a focus on the consumption of natural resources and agricultural inputs and the main related environmental impacts;
- LCAs of cotton fiber (from cradle to gate): this group covers the industrial processes involved in the processing of cotton into fiber, highlighting the inputs at the industrial plant and the associated waste and environmental impacts;
- LCAs of cotton textile products (from cradle to grave): these studies encompass the full life cycle of cotton products, from raw material

extraction to manufacturing, consumer use, and final disposal or recycling.

Besides this, they were also analyzed based on the year of publication, journals' subject area, country of origin, functional unit, life cycle impact assessment method, and main environmental impact results.

2.4. Bibliographic analysis

The analysis concerns the detection of the year of publication, country of origin and subject area of the publications. The selected publications were released starting in 2010 and continuing through 2022 (until December 28th). Fig. 2 shows the trend of publications over time, showing a high level of interest in the topic starting in 2020 and an increasing trend to date.

The selected publications cover a wide range of subject areas. Specifically, the articles were published in a total of twelve journals, ranging from sustainability, agricultural science, economics and others, which are shown for completeness in Fig. 3. The International Journal of Life Cycle Assessment was found to be the most prominent contributor, followed by the Journal of Cleaner Production.

The review encompasses publications that examined cotton production across all five continents. Analyzing the papers by continent, three focus on Australia, five on America (Argentina, Brazil, Mexico, United States), twelve on Asia (China, India, Iran, Pakistan, Syria, Turkey, Turkmenistan, Uzbekistan), four on Europe (Greece, Spain), and five on Africa (Egypt, Mali). For clarity, the distribution of selected documents by geographic area is shown in Fig. 4.

To provide a clear view of the distribution of the analyzed publications in relation to the stages of the production process, Fig. 5 shows the breakdown of publications based on the system boundaries.

The selected publications were also examined in terms of LCAs key methodological aspects, as shown in Table 1.

This table provides a useful overview of key methodological aspects of various LCAs on cotton production. The diversity of system boundaries, functional units, and impact assessment methods employed across these studies highlights the challenges in comparing and synthesizing LCA results for cotton. For instance, studies consider different life cycle stages, ranging from cradle-to-farm (8), cradle-to-gate (4), to cradle-to-grave (8). The functional units also vary, including 1 ton of seed cotton, 1 ha of cotton planted, 1 kg of cotton fiber or yarn, and 1 pair of jeans or t-shirt, and similar. Most of the authors adopted mass or product-based functional units, while only a few [32,35,36] used area-based functional units. It is possible to note that no one has used a monetary-based or quality-corrected functional unit. This is common in product LCAs, and understandable considering that the cotton industry works with physical quantities as the primary basis for its operations and transactions. Using

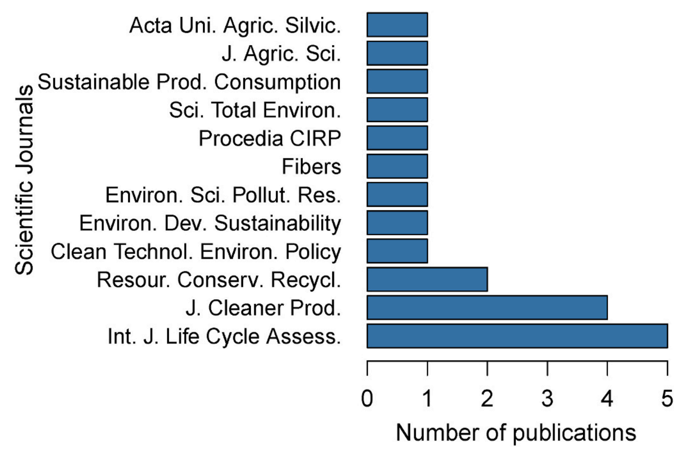

Fig. 3. Distribution of publications per journal. Own elaboration through the R software.

multiple and novel functional units could help improve the usefulness of LCA results for the many and diverse cotton stakeholders. For instance, the quality of cotton fiber is influenced by a multitude of factors, including climatic and soil characteristics, the selection of varieties, the timing and intensity of irrigation, plant nutrition, crop protection measures, harvesting and ginning techniques, storage methods, and numerous others.

Some articles focused on the impacts generally considered to be most relevant to the textile industry, such as global warming potential, water use and/or scarcity and energy-related impacts, while others preferred more comprehensive impact assessment methods such as ReCiPe, ILCD, CML, EDIP and Eco-indicator 99. These latter multi-impact methods are among the most widely used globally and vary in scope, coverage and level of detail. Despite this diversity in LCIA methods, we noticed that in most cases the authors arrive at comparable conclusions. Nevertheless, the choice of LCIA method should be made carefully and studies are needed that simultaneously apply several methods in order to compare the results in absolute terms and to reach a consensus on the most appropriate one for the specific case of cotton. Notably, also novel methods were proposed and tested, dealing with specific issues like biodiversity loss and human health impacts [33,39]. A gap in the assessment phase is the underrepresentation of impact categories related to soil quality, which could be, instead, highly relevant for cotton-based cropping systems.

To offer readers a more immediate visual representation of the primary input-output flows, and main environmental impacts in cotton systems, Fig. 6 was developed. The diagram is structured to highlight the

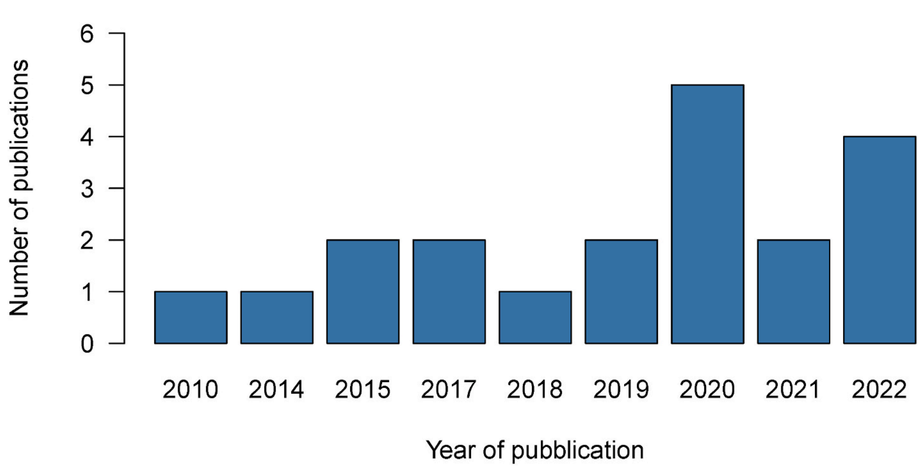

Fig. 2. Distribution of publications per year. Own elaboration through the R software.

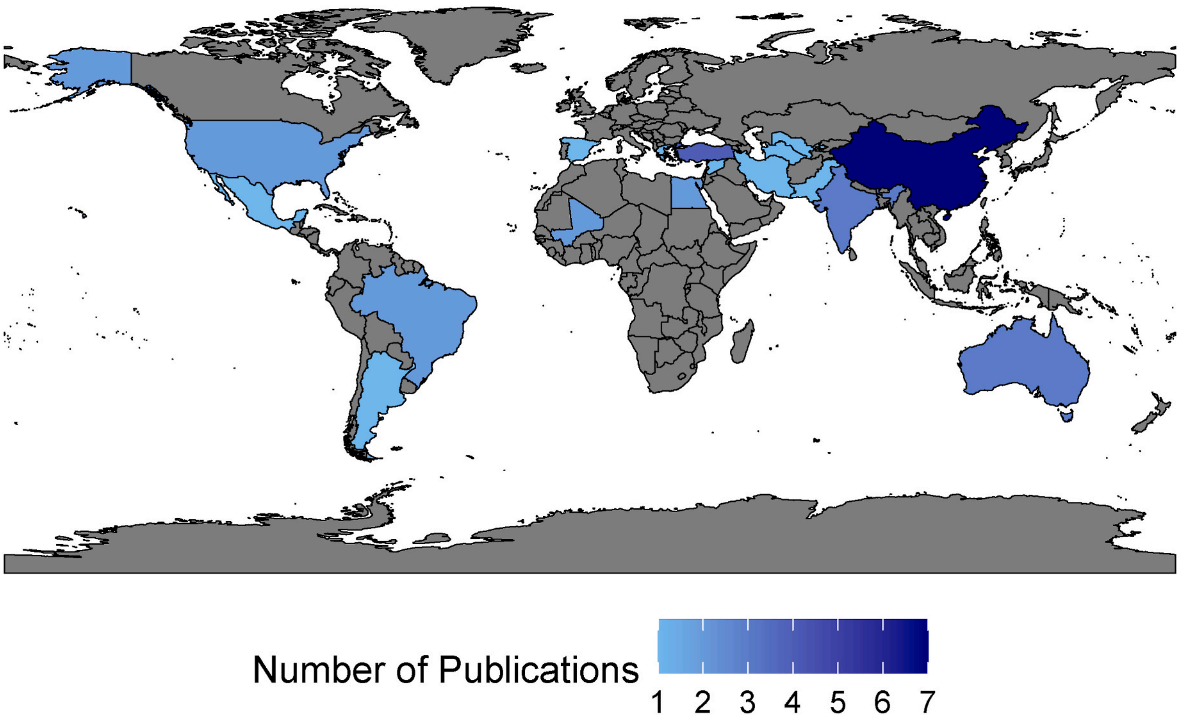

Fig. 4. Distribution of publications per country. Own elaboration through the R software.

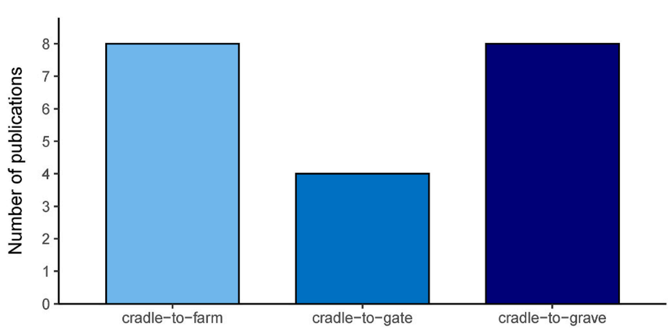

Fig. 5. Distribution of publications by phase of the production process. Own elaboration through the R software.

principal interrelations between processes and environmental outcomes for system boundaries adopted.

3. Results and discussion

3.1. LCAs of cotton cropping systems (cradle-to-farm gate)

To evaluate the environmental impact of cotton cultivation, articles presenting the "cradle to farm gate" system boundaries were analyzed. This involved identifying LCA studies that covered the entire agricultural phase, including resource extraction, machinery production, production and transport of agricultural inputs, sowing, base fertilization, weeding, phytosanitary treatments, fertilization until harvest and ginning. Different environmental impacts result from different cotton growing practices in different geographical contexts. For instance, depending on the climatic conditions and irrigation techniques, significant differences in water consumption could be observed [3,47–49]. Furthermore, the application of fertilizers and pesticides exhibits substantial variation in terms of type and intensity between regions and production methods, which has the potential to result in significantly different yields and varying degrees of impact severity. Seven teams of authors have addressed these issues by focusing on cotton cropping systems [31–38]. Such studies consistently reveal that water use, irrigation energy, and agrochemical inputs are the dominant environmental hotspots during the cotton cultivation stage.

For instance, Avadí et al. [32] conducted an LCA and WF analysis comparing conventional and organic farming systems in Mali. The authors highlight that cotton cultivation in the country is predominantly conventional, and that the pesticide use—particularly of profenofos insecticides — is the hotspot for this type of cotton production. This is mainly due to the associated toxicity impacts to humans and aquatic ecosystems. On the other hand, although organic cotton is becoming more widespread, it still represents a marginal share (0.5%) of national production. Using the production of 1 ton of cotton lint as a functional unit (FU), the study found that organic farming practices resulted in higher environmental impacts compared to conventional ones for all the analyzed impact categories, including climate change (+98% kg CO_2 eq), terrestrial eutrophication (+19% molc H^+ eq), mineral and fossil resource depletion (+124 % kg Sb eq) and acidification (+13% molc H^+ eq). The greatest impact was observed in the WF, with an average increase of 172 % in water consumption under organic cultivation compared to conventional cultivation. This is due to the comparatively lower yields of organic cotton. Conversely, the impacts of organic cotton were consistently lower per 1 ha of cultivation, due to lower input intensity. In fact, lower emissions of greenhouse gases (−29% kg CO_2 eq), terrestrial eutrophication (−57% molc H^+ eq), mineral and fossil resource depletion (−20% kg Sb eq) and acidification (−60% molc H^+ eq) were observed. Considering the WF, there was an average reduction of 2% (m^3 H_2O eq). Interestingly, at the endpoint level (single score), the impacts of organic cotton resulted lower than those of conventional, both per t of product and per ha of cultivation. This was explained by the authors Avadí et al. [32] by considering the large contribution of toxicity impact categories - which feature larger impacts for conventional cotton, due to its massive use of chemical pesticides - to the single score. Such divergent results are quite common when comparing organic and conventional systems and reflect the strong influence of the choice of functional unit, as well as the good rationale for combining midpoint and endpoint assessments for the sake of a more accurate and holistic

Table 1
LCA key methodological aspects of the reviewed studies.

Source	Country	System Boundaries	Functional Unit	Life Cycle Impact Assessment (LCIA) Method
[32]	Mali	cradle-to-farm	1 t of organic seed cotton; 1 t of conventional seed cotton; 1 ha of conventional cotton fiber; 1 ha of conventional cotton fiber	ILCD 2011 midpoint + v1.0.9, and WF
[33]	Worldwide	cradle-to-farm	1 t seed-cotton	New method, linking land occupation to health impacts
[34]	China	cradle-to-farm	1 kg of cotton	CF (CLCD 0.7, and IPCC 2019 factors)
[35]	Australia	cradle-to-farm	1 ha of cotton planted	GWP100
[36]	India	cradle-to-farm	1 ha of cotton planted	CF, GWP100, and Data Envelopment Analysis
[37]	Iran	cradle-to-farm	1 kg of cotton	GWP100 (IPCC, 2006)
[38]	China	cradle-to-farm	1 t of cotton	WF (WAVE + model), ReCiPe 2016 midpoint & endpoint
[39]	Worldwide	cradle-to-farm	1 t of cotton	New method to assess biodiversity loss
[40]	China	cradle-to-gate	1 t of the finished melange yarns	WF, GWP100 (IPCC 2001)
[17]	China	cradle-to-gate	1 t of recycled yarns and 1 t virgin cotton yarns	ReCiPe 2013 midpoint (H)
[11]	Egypt, China, India, and USA	cradle-to-gate	1 kg of dyed cotton yarn	GWP and Ecoindicator99 (H/A)
[10]	Worldwide	cradle-to-gate	1 kg of cotton fiber and textile	ILCD 2011 Midpoint +, CED v 1.09, CML-IA v3.02
[41]	China	cradle-to-grave	1 pair of cotton jeans	WF (ISO 14046), CF (PAS 2395)
[42]	Brazil	cradle-to-grave	1 pair of women's jeans	GWP100 (IPCC 2013, v 1.03), CED v 1.10
[43]	China	cradle-to-grave	100% cotton knitted dyed short-sleeved t-shirt	CLM 2001, USEtox
[1]	Turkey	cradle-to-grave	1 pair of average-sized jeans manufactured	CML-IA
[44]	Turkey	cradle-to-grave	1000 items of knitted and dyed cotton t-shirt (200 kg)	EDIP 2003
[45]	Turkey	cradle-to-grave	100 pieces of shirt (250 kg shirt)	CML 2001
[46]	Australia	cradle-to-grave	1 kg cotton knit dyed t-shirt	CML-IA v.4.4, ReCiPe 2008 midpoint v 1.11
[18]	Spain	cradle-to-grave	1 kg of colored cotton yarn, and 1 T-shirt (0.3 kg) made with 100% cotton	Multiple Impact Categories from previous published LCAs

Country of study, system boundaries (cradle-to-farm, cradle-to-gate, cradle-to-grave), functional units (area-based or mass-based), and LCIA methods (e.g., ILCD, ReCiPe, GWP, WF, CF) used in each study.

understanding of the leading environmental issues [50]. Based on these findings, some mitigation strategies were proposed by Avadí et al. [32], including.

- adopting organic farming practices;
- reducing pesticide use; and
- adopting Bt cotton varieties to increase yield and reduce insecticide use.

Moreover, the authors acknowledged that no methods were available to assess the impacts of rainwater consumption by cotton agriculture, but it is clear that Malian rainfed cotton is in principle more sustainable, regarding water use, than irrigated cotton. Future research needs to reach a consensus on modelling rainwater management practices and characterization factors for the use of this green water.

In a manner consistent with Avadí et al. [32], Zhang et al. [38] also combined a WF analysis and a full LCA to evaluate the environmental impacts of cotton production, in this case in China. The objective of this study was to identifying the most critical geographical areas where cotton production has the greatest environmental impact, as well as the key processes within the cotton life cycle that generate the highest environmental impact. The researchers highlight that at the midpoint level, there is a water scarcity footprint of 1.44×10^3 m^3 deprived, while consuming 2.49×10^3 m^3 of water per 1 ton of cotton lint produced. The endpoint analysis revealed that in China, the impact on human health and ecosystems is equivalent to 1.69×10^{-3} disability-adjusted life years (DALY) and 152.83 species · yr for 1 ton of cotton lint. The impact of water alone accounts for more than 55% of the human health category, resulting in 9.36×10^{-4} DALY. This can be attributed to the excessive consumption of water resources in areas with severe water scarcity. The concentration of cotton production in the arid region of Xinjiang exacerbates the impact of water consumption on the WF. The consumption of fertilizers and pesticides has been calculated, respectively amounting to 640.2 and 1.87 kg per 1 ton of cotton lint. The production of fertilizers alone is responsible for environmental impacts, particularly in terms of cancerogenicity, freshwater ecotoxicity, and acidification categories. Overuse of fertilizers is primarily linked to contamination of soil and groundwater [51]. Therefore, impact categories related to freshwater ecotoxicity, aquatic eutrophication, and acidification are identified, amounting to 2.25×10^4 comparative toxic units (CTU), 2.16 kg PO_4^3, and 21.6 kg SO_2 per 1 ton of cotton lint, respectively. All of this in China causes emissions of 4.59×10^3 kg CO^2 per 1 ton of cotton, as well as emissions of ammonia into the air and water (0.0015 kg and 0.14 kg) [38]. The authors suggest several mitigation strategies, such as returning cotton crop residues to the soil to enhance soil fertility and water retention capacity. They also identified the provinces of Qinghai and Inner Mongolia as those having the most favorable meteorological conditions for cotton production, thereby potentially leading to lower environmental impacts. Promoting cotton cultivation in these regions could help alleviate the concentration of production in Xinjiang and address associated sustainability challenges. However, this recommendation is based exclusively on meteorological factors, and it does not consider other crucial aspects such as soil characteristics, infrastructure, labor availability and local agricultural policies.

In addition to its high demand for water, the cultivation of cotton also requires extensive use of land. About this, Ridoutt et al. [33] examines the potential human health impacts related to agricultural land occupation (ALO) at 5-arc-minute spatial resolution. In particular, the authors developed a novel model focused on the impact pathway linking land occupation and protein-energy malnutrition, expressed in disability-adjusted life years (DALYs). The most alarming results were highlighted in India, where cotton cultivation occupies 8% of the arable land area; indeed, the average impact was 0.09 DALY $t^{-1}$of seed cotton, representing 9% of national malnutrition-related DALYs attributable to cotton production. The authors also evaluated the water equivalent

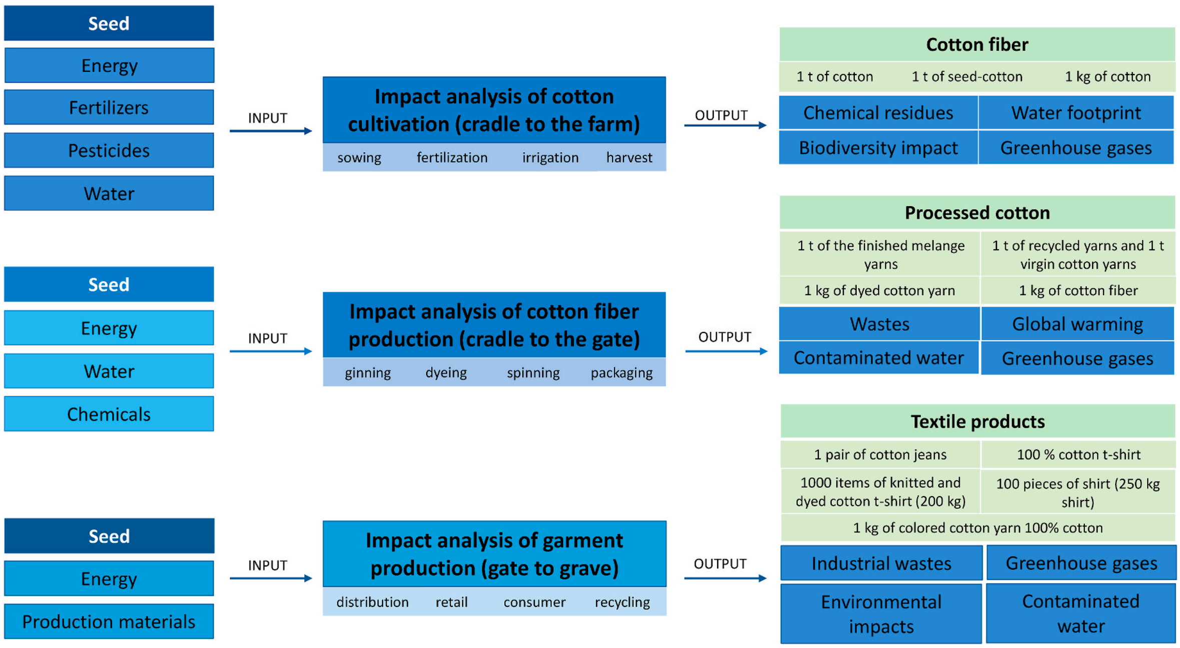

Fig. 6. Papers classification flowchart. Own elaboration.

human health impacts from ALO (m^3 m^{-2} year), indicating that tropical areas—including parts of Sub-Saharan Africa, South Asia, Southeast Asia, and Central and South America—suffer the greatest impacts from ALO in terms of potential malnutrition with values exceeding 100 m^3 m^{-2} year. On the other hand, China exhibits a strong duality between the north and south of the country regarding water availability. The ratio of potential human health impacts from ALO and water was found to be between 0.1 and 0.3 m^3 m^{-2} year in the north and 10–100 m^3 m^{-2} year in the south. In view of these results, Ridoutt et al. [33] suggested several mitigation strategies, such as.

- the sustainable intensification of agricultural practices that increase yields without expanding farmland, thus limiting land occupation; and
- the overall shift towards more sustainable production and consumption patterns to reduce pressure on natural resources.

However, the authors assume that one unit of ALO completely precludes another agricultural production activity, and they advise that this assumption may not always be true. Thereby, they highlighted that the inclusion of land-use dynamics could improve the accuracy of the model [33].

Another pioneering study from a methodological perspective was that of Verones et al. [39], who developed characterization factors for lifecycle impact assessment (LCIA) targeting biodiversity loss of various animal taxa (i.e., birds, reptiles, mammals, and amphibians) in wetlands. This study constitutes a worldwide LCA to evaluate the impact of certain crops, including cotton, on the Potentially Disappeared Fraction of Species (PDF) of species. It was found that due to the high consumption of surface water, the agronomic production of 1 ton of cotton generates an impact on animal taxa equivalent to 4.7×10^{-08} PDF global · year^{-t}, particularly in the USA and Australia. The impact increases if we also consider the groundwater used, which has a value of 2.0×10^{-09} PDF global · year^{-t}, and the countries most affected are Algeria and Tunisia.

Relevant insights on the environmental impacts at the field level were also given by Huang et al. [34]. This study shows that the Carbon Footprint (CF) for Chinese cotton production is much higher than the global average, with 3.27 kg CO_2 eq·kg^{-1} compared to 1.95 kg CO_2 eq·kg^{-1} [52]. The main reasons are the significant increase in the use of pesticides, fertilizers, and particularly irrigation electricity consumption. Data collected from 2004 to 2018 indicate that in China, pesticide usage increased by 55%, while diesel fuel consumption increased by 35%. Fertilizer application per hectare also increased significantly by 151.18 kg, from 177.39 kg^{-1} in 2004 to 328.57 kg^{-1} in 2018. This trend is particularly pronounced in the Yellow River region, where fertilizers account for over 60% of total emissions. The biggest increase was in irrigation electricity consumption, which rose from 683.73 to 1689.63 kwh·ha^{-1} during the same period, representing a 60 % increase in energy usage. Overall, these factors have led to a 35.54% increase in China's cotton CF since 2004. Thereby, the authors emphasize several mitigation strategies to reduce the CF of cotton, particularly:

- improving fertilizer efficiency—especially nitrogen—to reduce N_2O emissions;
- and optimizing the irrigation through the adoption of controlled deficit irrigation techniques.

Of similar interest is the study conducted by Maraseni et al. [35], who highlighted the relevant role of energy in cotton cultivation, especially that used for water pumping in irrigation. This study focused on the CF of three cotton cultivation systems in the Downs region of Queensland, Australia: dryland dense planting, dryland double skip row planting, and irrigated dense planting. The aim was to quantify the GHG emissions associated with various agricultural inputs in each of these systems. The authors found that CO_2 emissions were significantly higher for irrigated cotton cultivation (4841 kg CO_2 ha^{-1}) compared to dryland dense planting (1367 kg CO_2 ha^{-1}) and dryland double skip row planting (1274 kg CO_2 ha^{-1}). This is primarily due to the high energy consumption required for irrigation, which accounts for 27.5% of the GHG emissions in irrigated cotton. In line with Huang et al. [34], the results also stressed that one of the main factors contributing to total emissions is the use of fertilizers. In particular N_2O, resulting from the application of nitrogen-based fertilizers, accounts for 33.8% of total emissions in irrigated cotton. The authors emphasized several improvement strategies, mainly focusing on nitrogen management. Indeed, they underscored the need to reduce the use of nitrogen fertilizers and encourage the use of cover crops that can fix nitrogen, reducing the need for fertilizers and lowering N_2O emissions. Additionally, practices such as maintaining good soil structure, improving drainage, and increasing organic matter could further reduce GHG emissions. One of the limitations identified in the study is the potential underestimation of total GHG emissions, as the authors did not account for (1) production and transportation of cotton packaging; (2) construction of buildings and building materials; (3) use of organic manures; (4) packing and overseas exportation; and (5) soil organic carbon losses. Moreover, the study discusses the potential inclusion of the cotton industry in Australia's Carbon Pollution Reduction Scheme (CPRS) but notes that most cotton farms may not meet the minimum emission thresholds for participation.

Similar findings regarding the GHG emissions associated with of cotton cultivation were reported by Singh et al. [36] in north-western India. The aim of this study was to quantify and optimize C footprints and energy flow in cotton cultivation by integrating LCA with Data Envelopment Analysis optimization of energy use for increased C sequestration in soil, while enhancing the net ecosystem C budget of a cotton ecosystem [36]. The authors detect four main environmental hotspots: irrigation, biocides, fertilizers and fuel consumption. Energy required for pumping groundwater, particularly in water-scarce areas like north-western India, significantly contributes to high energy consumption. The irrigation-related energy input for cotton cultivation amounts to 4272.3 MJ ha^{-1}, or 17.8% of the technical efficiency (TE) and 20% of total CO_2 emissions. In addition, the TE input related to biocides, primarily used for controlling pests such as the cotton whitefly (*Bemisia tabaci*), contributes substantially to emissions. The energy input for biocides is estimated at 1034.2 MJ ha^{-1}, equivalent to 4.3% of TE and 10% of total CO_2 emissions. The study also highlights chemical fertilizers, particularly N, P_2O_5, and K_2O based ones, release 667.0, 25.3, and 11.4 kg CO_2 ha^{-1}, respectively, contributing to 44.3% of TE consumption and 46% of total CO_2 emissions. The high energy equivalence of nitrogen fertilizer production, combined with high application rates, positions fertilizers as the primary source of emissions. Furthermore, diesel fuel consumption plays a significant role, with usage reported at 4226 ± 116 MJ ha^{-1}, or 18% of TE, accounting for 13% of total CO_2 emissions. Inefficient farming practices, such as excessive tillage, cause increased fuel use. Moreover, the negative values of net ecosystem C budget revealed that cotton ecosystems act as a C source, since the crop failed to produce net biome production to offset C emissions. The overall impacts are higher when compared to those achieved by other authors [37] under similar agronomic conditions. Indeed, Sami and Reyhani [37] conducted a study with 25 cotton farmers through face-to-face interviews in the Golestan province of Iran with the aim of evaluated the impacts of cotton farming on the climate changes in terms of energy and GHG emission indices. Carbon cycle in the farms was not accounted for by the authors, since the amount of C lost via harvested crops is considered to be replaced by C uptake in the following crops and there is no significant long-term accumulation of C in crops products. As relative limitation, the study relies heavily on energy coefficients from other countries, highlighting the need for Iran-specific data to improve the accuracy of energy consumption and emissions assessments. Results showed that fertilizers, particularly nitrogen-based ones, were the primary hotspot for both energy consumption and GHG emissions. Fertilizers accounted for 45% of TE consumption and 61.9% of the total CO_2 emissions, amounting to 1285.80 kg CO_2 ha^{-1}. Fuels, mainly used for agricultural machinery, were identified as the second largest hotspot, contributing 18.4% to TE consumption (6.35 MJ ha^{-1}) and 24.3% to total CO_2 emissions, with 504.7 kg CO_2 ha^{-1}. Additionally, the study highlights irrigation as another significant factor, contributing 17.9% to TE. Therefore, in line with previous works, even these authors suggest several mitigation strategies, particularly focusing on optimizing nitrogen fertilizer use, and also adopting conservation agriculture practices to reduce fuel consumption.

Table 2 presents the environmental and health impacts of cotton cultivation across different countries and sources mentioned above, covering four key indicators: Carbon Footprint (CF), Water Footprint (WF), Disability-Adjusted Life Years (DALY), and Potentially Disappeared Fraction of Species (PDF).

The impacts vary by country and functional unit, reflecting not differences based on local environmental conditions and farming practices (including the irrigation system adopted, and the production method – e.g., conventional or organic). For example, among the countries listed Table 2, Iran [36] shows the lowest CF values per hectare of cotton (1177.7 kg CO_2 eq), followed by India [37] with 1391 kg CO_2 eq. Meanwhile, Australia [35] shows similar values only when cultivated under dryland conditions (1367 kg CO_2 eq), while emissions increase by 254.13% when the cotton is irrigated. This difference illustrates a key LCA causal pathway—the shift from rainfed to irrigated agriculture drives up both energy use (mainly for water pumping) and associated emissions. Water footprint numbers further highlight the effect of geographic and management contexts. For example, Chinese cotton production exhibits a WF of 2.49×10^3 m^3/t, much of which is sourced from heavily exploited irrigation systems, exacerbating regional water scarcity and contributing to high human health impacts as expressed by DALY (1.69×10^{-3} per ton) [38].

In general, the above-mentioned studies provide a comprehensive analysis of the environmental impacts of cotton cultivation, emphasizing the huge contribution of:

- fresh water consumption;
- land occupation and use;
- pesticide-related toxicity;
- GHG emissions.

The differences in water consumption between regions, driven by climate conditions, and the inefficiency of common irrigation methods like furrow irrigation, are major contributors to the environmental footprint. Additionally, the reliance on fertilizers and pesticides, particularly in conventional farming, exacerbates emissions and energy

Table 2
Environmental impacts of cotton cultivation in different countries.

Source	Country	Functional Unit	CF (kg CO_2 eq)	WF (m^3 of water eq)	DALY	PDF (PDF global · year^{-t})
[32]	Mali	1 t of organic seed cotton	4.85 (conventional), 9.59 (organic)	–	–	–
		1 t of conventional seed cotton	2194			
		1 ha of conventional cotton fiber	1844			
		1 ha of conventional cotton fiber				
[33]	Worldwide	1 t seed-cotton	–	–	90×10^{-3}	–
					–	
[34]	China	1 kg of cotton	3.27	–	–	–
[35]	Australia	1 ha of cotton	4841 and 1367 in dryland cultivation	–	–	–
[36]	India	1 ha of cotton	1391	–	–	–
[37]	Iran	1 ha of cotton	1177.7	–	–	–
[38]	China	1 t of cotton	–	2.49×10^3	1.69×10^{-3}	–
[39]	Worldwide	1 t of cotton	–	–	–	4.7×10^{-08}

Carbon Footprint (CF, kg CO_2 eq), Water Footprint (WF, m^3 eq), Disability-Adjusted Life Years (DALY), and Potentially Disappeared Fraction of species (PDF, PDF·year) related to cotton production, differentiated by source, country, and functional unit. "-" indicates missing data.

use, as highlighted in studies from China, India, and Iran. Although organic farming practices offer some advantages, such as reduced pesticide use, they still face challenges related to water and land efficiency due to lower yields. Nevertheless, this farming method was proposed by several authors among the mitigation strategies. Others were the adoption of more efficient irrigation systems, and the optimization of nitrogen management. Besides, the need for region-specific approaches and improved data accuracy remains crucial for optimizing cotton cultivation's sustainability.

Based on the reviewed studies, key strategies to prevent environmental pollution during cotton cultivation include implementing efficient irrigation technologies such as DI and LEPA systems; optimizing fertilizer and pesticide use through precision agriculture and integrated pest management; and promoting crop rotation, cover crops, and the adoption of organic or Bt cotton to reduce chemical inputs and emissions. These targeted interventions together address major environmental hotspots and support more sustainable cotton cultivation.

3.2. LCAs of cotton fiber (cradle-to-gate)

The "cradle to gate" approach encompasses the process starting from the ginning of raw cotton and obtaining baled cotton fiber, through the manufacturing phase (including dyeing, washing, and spinning), up to the packaging of the finished product. Studies showed that cotton fiber processing intensifies the product's carbon and water footprints, largely through high energy and water demands.

Among the cradle-to-gate LCAs reviewed, Liu et al. [40] conducted a WF and the CF of mélange yarns in Zhejiang province, China. They found that producing mélange yarn consumes a significant amount of water, averaging 3.1×10^3 m^3 per 1 ton of finished yarn. Cotton cultivation alone accounts for 2.8×10^3 m^3, representing 91.2% of the total WF. This water is mainly green water, i.e. rainwater, which is the main source for cotton production in this region of China. The second largest contributor to the total WF is the spinning stage, which accounts for 3% of the WF, significantly less than the cotton cultivation stage. However, when analyzing CF, cotton cultivation contributes only 4.0% to the overall carbon emissions of cotton yarns. The greatest impact comes from the electricity used during raw fiber processing, which represents 61.7% of the total carbon emissions. Specifically, the spinning stage alone accounts for 83% of total electricity consumption, followed by steam (13.61%) and sodium sulfate (Na_2SO_4) (11.21%), both used in the dyeing process. Overall, the production of 1 ton of finished mélange yarns results in the emission of 7.9×10^3 kg of CO_2.

Liu et al. [17] investigated in a new full LCA study the potential of using recycled yarns as a substitute for virgin cotton yarns. They found that using recycled yarns significantly reduces WF, requiring only 583 m^3 of water to produce 1 ton of recycled yarns, compared to 3514 m^3 for virgin cotton yarns. The most significant savings come from the cotton cultivation stage, where water use is reduced by 79.1%, and from the washing process before fabric conversion into fiber, where water consumption is cut by 40.3%. In terms of CF, the study estimates that growing the cotton needed to produce 1 ton of virgin cotton yarns generates 6.6×10^3 kg of CO_2 equivalent emissions. Yarn production contributes further to carbon emissions, mainly due to electricity usage. The total CO_2 emissions for producing 1 ton of virgin cotton yarns are estimated to be 1.1×10^4 kg CO_2. Recycling cotton—which includes collecting, sorting, washing, and processing textile waste—also generates CO_2 emissions; however, the total emissions for producing 1 ton of recycled yarns are significantly lower, estimated at 4.4×10^3 kg CO_2. Overall, producing recycled yarn results in 60.2% fewer CO_2 emissions compared to virgin cotton yarn production, largely due to the elimination of the resource-intensive cotton cultivation stage.

In a study conducted by Bevilacqua et al. [11], the authors performed an LCA to assess and compare the impacts of cotton dyed yarn in four different countries, namely Egypt, China, India, and USA. Based on the results related to the cultivation scenario India had the highest impact in terms of GHG emissions, with 0.89 kg of CO_2 per kg of cotton dyed yarn. This was mainly due to fuel consumption and artificial fertilizers, which together account for approximately 47% and 31% of total CO_2 emissions in Indian companies. These values were significantly higher compared to the other countries analyzed. China ranked second with 0.72 kg of CO_2, while Egypt and the USA had emissions equivalent to 0.62 kg of CO_2. The high levels of GHG emissions in India and China are also attributed to extensive land use, inefficient irrigation systems (such as flood irrigation), and the lack of crop rotation with less profitable crops. The authors also highlight that the dyeing stage has the greatest impact in terms of GHG emissions (44% of the total) and resource consumption (51.5% of the total). This high impact is due to the consumption of natural gas for steam and heat production, the use of chemical reagents, and the significant consumption of water and electricity. Additionally, the spinning process consumes the most electricity and significantly contributes to GHG emissions (23% of the total). The authors suggest several mitigation strategies that could be applied across all regions studied. In particular, they recommend the use of GMO pest-resistant varieties to reduce the heavy use of pesticides. At the industrial level, they propose the recovery and reuse of cooling water and improving the efficiency of heat exchangers. However, the study analyzes data collected from a limited number of cotton suppliers (one per country), so there is a risk that the results may not be representative of the entire cotton supply chain.

La Rosa and Grammatikos [10], in a comparative LCA of natural fibers, investigated the GHG emissions associated with cotton production in comparison to other textile fibers such as hemp, kenaf, and jute. The study shows that to produce 1 ton of cotton fiber, the average emission is 2446 kg of CO_2, significantly higher than that of jute fiber (294 kg CO_2) and kenaf fiber (360 kg CO_2). However, when analyzing the CO_2 emissions for organically produced cotton, emissions drop to 978 kg CO_2, representing a 60% reduction in this impact category. Regarding WD, the researchers reported a consumption of 1.74×10^3 m^3 of water to produce 1 ton of cotton textile (yarn), which is substantially higher than the values for jute and kenaf textiles (188 m^3 and 257 m^3, respectively). In fact, the researchers identified cotton as having the highest global warming potential (GWP) among the crops studied, and they suggest adopting alternatives such as hemp, kenaf, and jute, which are natural fibers that require less water and fewer pesticides compared to cotton.

Table 3 provides a comparative overview of CF and WF associated with various cotton-based products across different countries and production systems, from raw fiber to finished yarns.

CF varies widely depending on the cotton type and processing technology, and energy source. For example, finished melange yarns in China [40] have the highest reported emissions (7.9×10^3 kg CO_2 eq/t), which can be directly attributed to the country's heavy reliance on

Table 3
Environmental impacts of cotton production, from cradle to gate, in different countries.

Source	Country	Functional Unit	CF (kg CO_2 eq)	WF (m^3 of water eq)
[40]	China	1 t of the finished melange yarns	7.9×10^3	2.8×10^3
[17]	China	1 t of recycled yarns	4.4×10^3	0.58×10^3
[11]	Egypt, China, India, and USA	1 t virgin cotton yarns 1 t of dyed cotton yarn	6.6×10^3 2.1×10^3	3.5×10^3 –
[10]	Worldwide	1 t of conventional and organic cotton fiber	2.45×10^3 (conventional) 0.98×10^3 (organic).	1.74×10^3

Carbon Footprint (CF, kg CO_2 eq), Water Footprint (WF, m^3 eq). "-" indicates missing data. Units originally expressed in kilograms (kg) have been converted to metric tons for consistency.

coal-powered electricity for spinning and dyeing processes, as well as the high input intensity of Chinese cotton farming—including fertilization and irrigation. In contrast, the production of recycled cotton yarns in China results in a substantially lower CF [17] (4.4×10^3 kg CO_2 eq/t), indicating environmental advantages of eliminating the resource (and thus, the emission-intensive cultivation stage by substituting virgin cotton with recycled fibers). Virgin cotton yarns across Egypt, China, India, and the USA [40] show intermediate CF values (6.6×10^3 kg CO_2 eq/t), while dyed cotton yarns report lower CF (2.1×10^3 kg CO_2 eq/t), again reflecting differences in agricultural practices, energy mix used in processing, and efficiency of production technologies. Globally [10], conventional cotton fiber results in a CF of 2.45×10^3 [10] kg CO_2 eq/t, which is more than 150% higher than that of organic cotton fiber, emphasizing the environmental benefits of organic cultivation methods. WF also varies greatly depending on the type of cotton and its production process and mirror these trends. For example, in China, the WF for finished mélange yarns is 2.8×10^3 m^3 of water eq, which is approximately 382.8% higher than the WF for recycled yarns. This marked difference confirms that the use of recycled materials in yarn production can lead to substantial water savings. In fact, virgin cotton production requires large amounts of water on average, both for irrigation and industrial processes [17], while recycled yarns, by reusing existing fibers, significantly reduce overall water requirements. Together, the quantitative results in Table 3 (and previously Table 2) clearly illustrate other key causal pathways captured by LCA theory: regions and practices with greater reliance on fossil fuels, intensive irrigation, and agrochemical use consistently show higher CF and WF; conversely, organic practices or adoption of recycled input streams break these links and results in markedly lower environmental burdens.

Based on the above, cotton cultivation is the largest contributor to water consumption and pesticide use, exacerbating water scarcity, toxicity impacts and GHG emissions. On the industrial side, spinning, dyeing, and washing are the main sources of GHG emissions, with dyeing being the most energy- and resource-intensive stage. Optimizing these processes is crucial to reducing GWP impacts. Mitigation strategies include improving water and energy efficiency, using GMO pest-resistant cotton, and favoring natural fibers like hemp, kenaf, and jute, which require fewer resources. Recycling cotton yarns also offers a promising solution to lower both water consumption and carbon emissions compared to virgin cotton. These findings reinforce the critical importance of strategic interventions—such as optimizing water use, transitioning to renewable energy, and increasing recycling rates—in reducing the overall environmental impact of cotton production globally.

3.3. LCAs of cotton textile products (cradle-to-grave)

To obtain a comprehensive estimate of the environmental impact associated with the entire life cycle of cotton, LCA studies with a "cradle to cradle" system boundary were finally examined. This allows for a step-by-step description of every step in the life of the product, from cultivation to manufacturing, distribution, consumer use (including laundering, drying, and ironing), and finally to end-of-life disposal (recycling or waste disposal). Cradle-to-grave assessments are very recommended for textiles and clothing products, since the use phase plays a significant role in terms of impacts, and clothing products that are usually meant to be used for a long span are nowadays used for shorter periods as a consequence of fast fashion. The environmental impact of cotton products from a full life cycle perspective was addressed in eight of the articles reviewed.

For instance, Luo et al. [41] performed a footprint analysis comprising CF, water scarcity footprint, water eutrophication footprint and water ecotoxicity footprint under a full life cycle perspective. The results showed that the total impacts of a pair of conventional 100% cotton jeans were 90.37 kg CO_2 eq in terms of carbon footprint, 13.74 m^3 H_2O eq for water scarcity footprint, 1.67×10^{-2} kg PO_4^{3-} eq for water eutrophication and 112.41 m^3 H_2O eq for water ecotoxicity. Finishing, cotton cultivation and laundering processes were main contributors to these environmental impacts. Within the industrial manufacturing stage, finishing has the highest contribution (32.2%), followed by denim washing (25.1%) and weaving (21.8%). On the other hand, the authors emphasized that during cotton cultivation, there is a net positive impact because the plants absorb CO_2 from the atmosphere and store it as biomass. Indeed, they estimated that the carbon storage of cotton plants is about 18.04 kg CO_2 eq/pair of jeans. This figure was far greater than the total carbon emissions (3.63 kg CO_2 eq/pair of jeans), leading to the CF in the cotton cultivation process negative (−14.41 kg CO_2 eq/pair of jeans). However, this seems to be only a short-term C balance, not considering that crop residues left in the field will be decomposed within a few months or years, so that there is no or only a small sequestration effect. The authors also observed that incinerating cotton during waste disposal can generate an average of 0.85 kW h pair of jeans^{-1} of energy, equivalent to reducing about 0.82 kg of CO_2 eq. Still, it should be argued that while the study accounts for the sequestered carbon, it does not explicitly define the type of biomass (which could be fiber only, or also the other parts of the cotton plants like leaves, stems or roots). Furthermore, it does not uniquely indicate the lifespan of the jeans, as it states the fiber could be stored for a long time, but at the same time it assumes only 2 years at the consumer use stage for the washing processes. In addition, the CF results do not include the emissions from the incineration process, while only they only show the benefit associated with the energy produced from the heat generated during incineration. In contrast, the latter process would release the CO2 temporarily stored in the cotton fibers. We therefore recommend greater clarity and transparency in the description of the carbon sequestration accounting methodology, and in the presentation of the related results. In their analysis of water scarcity footprint, the authors Luo et al. [41] also noted a total consumption of 13.7 m_3 H_2O pair of jeans^{-1}, 88% of which is used during the cultivation phase, amounting to 12.27 m_3 H_2O pair of jeans^{-1}. The second highest water consumption factor is the washing process during the consumer use phase, with repeated washing using about 1.37 m_3 H_2O. Washing is also the main contributor to water eutrophication (33.7%), with phosphorus from detergents being the leading cause [52], followed by cotton cultivation (18.6%), where the eutrophication effect is mainly due to leaching of nitrogen fertilizers into water. The authors identified several mitigation strategies to lower the environmental impact during the use phase, including: reducing the frequency of washing and ironing; and opting for front-loading washing machines over top-loading ones. These actions can significantly lessen the environmental footprint of cotton jeans during their use.

Similar results were observed by Morita et al. [42], who carried out a cradle to grave analysis of impacts of GWP and primary energy demand in Brazil, using a pair of trouser jeans as a FU. This highlighted how the production of cotton determines an impact on climate change equal to 7.8 kg CO_2 jeans^{-1}. Most of the emissions, however, concern the confection/finishing stages, which contribute 51% of emissions (4.0 kg CO_2 jeans^{-1}), followed by the weaving stage with 21% of emissions (1.62 kg CO_2 jeans^{-1}). Cotton cultivation contributes 17% of total emissions (1.37 kg CO_2 jeans^{-1}), the causes of which are due to CO_2 emissions deriving from liming (359g eq), handling operations (195 g eq), N-fertilizer application (50.5 g eq) and dinitrogen oxide N_2O through degradation of the N-fertilizer in the soil (0.83 g eq). Furthermore, the study compared the energy sources used during the production processes in Brazil and the USA and highlighted that the lower CF impact (4.44 kg CO_2 eq) is associated with the production of jeans in Brazil, where wood is used as a heat source. The authors propose replacing natural gas with wood as a heat source for industrial processes as the main mitigation strategy. This is justified by the carbon neutrality of biomass, as the CO_2 released during combustion is balanced by the CO_2 absorbed during tree growth. Wood thus emerges as the optimal energy source in terms of performance (124 MJ eq).

Zhang et al. [43] agrees that the main factor of GWP is given by the industrial manufacturing stage. Through a cradle to the grave LCA conducted in China, with a 100% cotton knitted dyed short-sleeved t-shirt as FU, they observe that only the dyeing stage represents 34.8% of the total emissions due to the on-side combustion of hard coal to produce steam. The second contributor to GWP is made by making-up stage (31.96%), due to indirect CO_2 emissions given on-site electricity consumption. On the other hand, the discussion concerning water consumption is different. Water resources used for irrigation account for 78.9% of water consumption, followed by the use stage and dyeing stage. The study reveals that this high-water consumption is primarily due to the washing habits of Chinese consumers, who prefer hand-washing and sun-drying. These habits lead to significantly lower energy and water consumption compared to Germany (−73%) and the USA (−84%), where machine washing and electric drying are more common. Therefore, the authors suggest promoting water-efficient washing practices, such as:

- washing clothes less frequently:
- using shorter wash cycles;
- opting for hand washing whenever possible.

To confirm that the environmental impact of cotton cultivation is negligible compared to industrial processes and domestic consumption, Fidan et al. [1] conducted a study comparing the differences in environmental impact between organic and conventional cotton, using an end-of-life analysis approach. The study utilized a pair of average-sized jeans manufactured in Turkey as the FU, for a lifespan of 45.5 cycles. From the analyses, it was noted that organic cotton only results in a small improvement in terms of GWP and Acidification Potential (AP), with reductions of only 3.1% and 0.9%, respectively. This demonstrates that the greatest environmental impact is due to industrial processes and domestic consumption.

Similar conclusions were obtained from the LCA of cotton, conducted in Turkey by Baydar et al. [44]. The researchers found that the production of organic cotton does not differ significantly in terms of GWP from conventional cotton, as the main impact comes from the use phase, and highlighted how the use phase, due to the electricity consumed in the washing processes, causes 4140.4 kg of CO_2 emissions for the production of 1000 cotton pieces weighing 200 kg, which is four times more than the cultivation stage. Regarding AP, a 97% reduction in water eutrophication is observed in organic cotton cultivation compared to conventional cotton. This is due to the elimination of nitrogen and phosphorus-containing chemical fertilizers in the cotton cultivation stage.

Kazan et al. [45], on the other hand, claim that organic cotton leads to enormous improvements in terms of GWP. Through a cradle-to-grave study conducted in Turkey, using 100 pieces of shirt (250 kg shirt) as the FU, it was shown that organic cotton cultivation reduces GHG emissions by 71% (385 kg CO_2 eq) compared to conventional production (1341 kg CO_2 eq) during the agronomic process. The savings are due to field operations such as fertilizing, using pesticides, herbicides, insecticides, fungicides, machinery, and diesel fuel use in seeding and plowing, which account for 84% of emissions produced in cotton cultivation, on top of fertilizer production (13%) and energy supply for ginning process (3%). The authors also highlight the recycling of cotton as an essential tool for reducing GHG emissions. In fact, by reusing cotton, there are no climate-altering gas emissions during the agronomic process, as this phase is eliminated. In addition, consumption related to the dyeing phase would be eliminated. These measures would guarantee an overall reduction of GWP by 47% compared to conventional cotton production.

In the LCA analysis conducted by Moazzem et al. [46] in Australia, the authors focused on the use of organic and recycled cotton as a system to reduce the environmental impact of the textile industry. The researchers highlighted how the production of organic cotton shirts led to a reduction of 10.56% in GWP and a decrease of 88–89% in ALO. The study also revealed that organic cotton requires only 605 m^3 ha^{-1} of irrigation water, compared to 1080 m^3 ha^{-1} for conventional cotton, resulted in a reduction of WD between 79 and 83%, as also reported by Shah et al. [53]. This difference is attributed to the higher moisture retention of organically managed soils, which benefit from increased organic matter that acts like a sponge, effectively absorbing and retaining water. For this reason, the authors also examined the use of recycled cotton, finding that it can achieve an impact reduction of about 34.93% AP, 62.55% for ALO 62.97% for WD compared to virgin cotton. However, they warn that the quality of recycled cotton may be inferior to that of virgin cotton, particularly regarding fiber length and uniformity. To improve quality, recycled cotton is often blended with virgin fibers, which reduces its environmental benefits [46].

On the same research topic, Esteve-Turrillas and De La Guardia [18] conducted an LCA study in Spain with a FU of 1 kg of colored cotton yarn. The researchers highlighted, on one hand, organic cotton, which, thanks to the reduction in the use of pesticides and chemicals, allows for a significant reduction in environmental impacts. Indeed, the authors estimated, for FU, a reduction of 0.53 kg CO_2 eq for GWP (26%), 0.022 kg SO_2 eq for AP (79%), 0.028 kg $PO_4{}^{-3}$ eq for Eutrophication Potential (EP) (93%), and 4332 kg of water for WD (79%), which are notably lower than the results reported by Moazzem et al. [46]. However, organic cotton cannot disregard the industrial stages related to ginning (whose GWP impact is estimated to be from 0.128 to 0.173 kg CO_2 eq) and dyeing steps (where GWP data ranges from 7.0 to 17.3 kg CO_2). In fact, the best results were achieved with recycled cotton, resulting in savings of 13.98 kg CO_2 eq for GWP, 0.32 kg SO_2 eq for AP, 0.033 kg $PO_4{}^{-3}$ eq for EP, and 5594 kg water for WD impact category. The authors emphasize that using recycled cotton eliminates the need for new cotton cultivation, thereby reducing water, fertilizer, and pesticide consumption. Additionally, dyeing is often unnecessary since the final color of the cotton fiber can be derived from the raw materials used, further minimizing the use of water, dyes, wetting agents, softeners, and other related products.

Table 4 illustrates significant variability in key environmental indicators – CF and WF – which can be attributed to multiple interrelated factors across the product life cycle, including production location, energy sources, manufacturing technology, and cotton type.

The highest CF for a single pair of jeans is reported in China [41] (90.37 kg CO_2 eq), while much lower values are observed in Turkey [1] (ranging from 20.11 to 19.48 kg CO_2 eq) and Brazil [42] (7.8 kg CO_2 eq). Notably, garments made from organic cotton in Turkey [45] show reductions of up to 70% in the cultivation phase and 56% in the industrial phase compared to conventional cotton garments. Similarly [42], attributes Brazil's lower CF to the increased use of renewable biomass (wood) as an energy source for industrial processes. Also, the WF also varies considerably, with higher values for jeans (up to 13.74 m^3) in China [41] and considerably lower values for t-shirts in other contexts (1.5–1.77 m^3) [43,46]. These outcomes are deeply influenced by the specific geographical context, reflecting differences in agricultural practices, energy sources and mixes, production efficiency, and water availability. Also in this case, organic and recycled cotton products demonstrated major CF and WF reductions compared to conventional, and virgin alternatives.

Overall, the cradle-to-grave analysis highlights the significant environmental impacts associated with each stage of the cotton lifecycle. Especially industrial processes, like manufacturing and consumer use, severely contribute to GHG emissions and water consumption. However, even under a full life cycle perspective, cotton cultivation remains a critical phase where a high margin of improvement can be achieved by switching to sustainable agricultural practices, including organic farming. Regarding GHG emissions, we also found an inconsistency in the consideration of biogenic carbon storage between LCAs and CF analyses. In fact, the majority of authors did not consider carbon sequestration by biomass, while Singh et al. [36] and Luo et al. [41] addressed this aspect. Both authors did not follow a traditional LCA approach but performed CF analyses under other protocols [54]. This partly explains

Table 4
Environmental impacts of cotton production, from cradle to grave, in different countries.

Source	Country	Functional Unit	CF (kg CO_2 eq)	WF (m^3 of water eq)
[41]	China	1 pair of cotton jeans	90.37	13.74
[42]	Brazil	1 pair of women's jeans	7.8	–
[43]	China	100% cotton knitted dyed short-sleeved t-shirt	6.05	1.77
[1]	Turkey	1 pair of average-sized jeans manufactured	from 20.11 to 19.48	–
[44]	Turkey	1000 items of knitted and dyed cotton t-shirt (200 kg)	from 2420.7 to 1872.2	–
[45]	Turkey	100 shirts made of conventional and organic cotton (250 kg of shirts).	Organic production: 385 (cultivation) and 1221 (industrial phase). Conventional production: 1341 (cultivation) and 2772 (industrial phase)	Cotton cultivation: 1036. Industrial processes: 1.3
[45]	Australia	1 kg cotton knit dyed t-shirt	43.15	1.5
[46]	Spain	1 kg of colored cotton yarn, and 1 T-shirt (0.3 kg) made with 100% cotton	13.98	5.59

Carbon Footprint (CF, kg CO_2 eq), Water Footprint (WF, m^3 eq). "-" indicates missing data.

the reason, as LCA generally does not take into account this temporary carbon storage/sequestration, especially in the case of products such as clothing/garments that are only used for a few years. Increased durability, leading to a longer life of the garment, would keep the sequestered CO2 out of the environment for longer, but this is still a debated issue, and no consensus has yet been reached. Caution should be exercised in communicating these types of results as they are highly dependent on the methodology used and the assumptions made. Adopting strategies such as choosing organic and recycled cotton, as highlighted by Vitale et al. [55], promoting efficient washing practices, and utilizing sustainable energy sources can significantly reduce the environmental footprint of cotton products. However, challenges remain, particularly the limited adoption of organic cotton due to higher costs and lower yields, as well as the lower technological quality of recycled cotton.

4. Final remarks

Regarding the cradle-to-farm impact analysis publications analyzed, one of the recurring themes is the water use associated with cotton production. This crop requires a high-water input due to significant evapotranspiration, which ranges from 700 to 1200 mm during the growing season, depending mainly on the cultivation area, as it generally exceeds the precipitation levels in these regions [3–5,55]. In addition, there is a significant energy input associated with irrigation for pumping irrigation water, ranging from 4272.3 MJ ha^{-1} to 4374.7 MJ ha^{-1}, representing 18%–22.4% of the TE required for cotton production [36]. To effectively reduce water and energy use in cotton production, two readily achievable options are (i) the use of low-input irrigation techniques, such as DI and LEPA systems, compared to conventional FI; (ii) the relocation of cotton production to areas where frequent rainfall and low evapotranspiration allow cotton to be grown with low irrigation volumes. The massive utilization of chemical pesticides contributes significantly to the toxicity impact categories and the overall environmental profile, particularly in the context of conventional cotton. In a similar manner, nitrogen fertilizers constitute the primary source of GHG emissions, thus confirming the necessity for strategies that aim to reduce and/or optimize their efficiency. Added to this is the widespread use of pesticides. Studies indicate that they are a major environmental hotspot, particularly in regions such as Mali and China, where they exacerbate freshwater ecotoxicity and contribute to substantial biodiversity loss.

In terms of cradle-to-gate LCA, significant challenges and opportunities for improvement emerge. The results underline the critical role of cultivation for water consumption, particularly in regions facing severe water scarcity, accounting for a staggering 91.2% of the total WF in yarn production [40]. Moreover, data indicates that the production processes, especially spinning and dyeing, contribute substantially to GHG emissions and ecological degradation with figures reaching up to 1.1×10^4 kg CO_2 per ton of virgin cotton yarn, underscoring the urgent need for sustainable practices in the industry [17].

Regarding the cradle-to-grave LCA analysis, significant environmental impacts are highlighted, particularly during industrial processes and the consumer use phase. It is evident that the industrial manufacturing stage alone contributes 95.5% of the total CF, with finishing (32.2%), denim washing (25.1%), and weaving (21.8%) being the largest contributors. Organic cotton significantly reduces the use of pesticides and chemical fertilizers, with a 97% reduction in EP compared to conventional cotton [44]. However, as also highlighted by cradle-to-gate analyses, it has lower yields, requiring approximately 10–20% more area to obtain the same amount of cotton [32]. Recycled cotton, on the other hand, allows a 79% reduction in water consumption and a 60% reduction in CO_2 emissions compared to virgin cotton [17]. Despite these advantages, it represents only a small part of global production, with challenges related to the quality of the final product. In terms of water usage, cotton cultivation accounts for 88% of the total life cycle consumption (12.27 m^3 H_2O per pair of jeans), while repeated laundering during the consumer phase consumes 1.37 m^3 H_2O, contributing significantly to water eutrophication (33.7%) [41,52]. Recycled cotton offers more substantial environmental benefits, with a 34.9% reduction in AP, 62.5% in ALO, and 62.9% in WD compared to virgin cotton [46].

Furthermore, the review highlights some gaps in assessing and managing the environmental impacts associated with cotton cultivation, industrial production and consumer use. For example, most studies do not adequately address local variables that influence the sustainability of cotton production, such as soil characteristics, local agricultural policies and labor availability. Also, some authors suggest relocating cotton production to areas with more favorable climatic conditions, but do not adequately consider socio-economic factors such as infrastructure availability, local agricultural policies and access to labor. In addition, many LCAs focus on primary processes (spinning, dyeing, washing) but lack detailed data on sub-processes such as equipment maintenance, intermediate transport of materials, or the use of specific chemicals at certain stages of production. For instance, the contribution of chemicals such as surfactants or mordants used in dyeing is often neglected. Moreover, while many studies emphasize the importance of domestic use (washing and ironing) in the environmental impact of cotton, they do not sufficiently analyze the impact of new technologies such as water and energy efficient washing machines or the use of environmentally friendly detergents [43,46]. From a methodological perspective, an absence of congruence was identified in the consideration of temporal carbon storage between LCAs and CF analyses. In addition, the necessity for further research on cotton, employing multiple LCIA multi-impact methods in a concurrent manner to facilitate comparative analysis of the results in absolute terms was identified. Similarly, we advocate for the adoption of more and more diverse functional units to improve the usefulness of LCA results for the many diverse cotton stakeholders.

In future, the challenges inherent to cotton cultivation and its environmental sustainability are likely to be centered on the reduction of water and energy consumption, particularly in regions where water scarcity is prevalent, and irrigation plays a pivotal role. Additionally, optimization of chemical pesticides and fertilizers will be imperative to mitigate associated toxicity impacts and greenhouse gas emissions. Implementing low-input irrigation technologies, adopting organic farming practices, and recycling cotton fibers offer promising solutions. Nevertheless, the industrial processes of the textile industry - particularly manufacturing, finishing and laundering - remain the significant contributors to carbon emissions and environmental degradation. Therefore, a wider shift towards sustainable practices, including increased use of recycled cotton and technological innovations in organic production, will be essential to mitigate these impacts and meet global sustainability goals. Overall, the review's findings highlight the need for simultaneously targeted interventions throughout the cotton life cycle. Accordingly, the following evidence-based recommendations are proposed to address the major environmental challenges associated with cotton cultivation, processing, use, and disposal:

- Cultivation: Promote efficient irrigation systems as DI and LEPA irrigation, which, despite high initial costs, are reusable and can be amortized over time; optimize fertilizer and pesticide application through precision agriculture and integrated pest management, encourage organic and regenerative practices, and prioritize cultivation in regions less vulnerable to water scarcity and biodiversity loss.
- Processing and Manufacturing: Adopt the best available technologies to enhance water and energy efficiency, transition to renewable energy sources, utilize less hazardous chemicals during dyeing and finishing, and ensure rigorous wastewater treatment to prevent water contamination.
- Consumer Use: Support public awareness initiatives on sustainable garment care, such as reducing washing frequency, using environmentally friendly detergents, and opting for air drying. Encourage practices that extend product life, including repair, reuse, and responsible consumption.
- End-of-Life: Expand textile recycling infrastructure and capacity, develop effective collection and sorting systems, advance recycling technologies, and implement policies that discourage landfill and incineration of textile waste.
- Policy and Collaboration: Integrate LCA into sector-wide decision making, set and enforce regulatory standards for chemicals, water, and emissions, and foster cross-sector collaboration to facilitate knowledge transfer and innovation.

Implementing these strategies at each stage of the cotton value chain is essential for minimizing environmental degradation, promoting resource efficiency, and advancing the sustainability of cotton products.

As future research step of this team of authors, it is envisaged to further contribute to the LCA cotton field by developing a multifunctional LCA study [50] on organic and regenerative cotton cropping systems in the Mediterranean region.

CRediT authorship contribution statement

Giuseppe Salvatore Vitale: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicolò Iacuzzi:** Supervision, Data curation, Conceptualization. **Silvia Zingale:** Writing – review & editing, Validation, Methodology, Conceptualization. **Sara Lombardo:** Supervision, Conceptualization. **Teresa Tuttolomondo:** Validation, Supervision. **Paolo Guarnaccia:** Supervision, Resources, Project administration, Conceptualization.

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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.jafr.2025.102069.

Data availability

No data was used for the research described in the article.

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