Quantifying Social and Environmental Impacts through the Life Cycle Assessment

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Abstract

This paper presents an overview of the measures linked to social and environmental sustainability. Then, it proposes an empirical analysis of these impacts with an example of cotton production in India. The application of the Life Cycle Assessment (LCA), as outlined by ISO 14040, allows one to quantify both the social and the environmental impact and define a strategy to mitigate both of them simultaneously. Hence, the paper presents a set of trade-offs emerging when companies seek to optimize both environmental and social impact of their businesses. We demonstrate that, through the adoption of LCA, the pair social and environmental impact can be simultaneously optimized and sustainable strategies can be effectively created.

Keywords: Environmental impact, Social Impact, Performance, LCA.

Quantificare gli impatti sociali e ambientali attraverso il Life Cycle Assessment

Sommario

Questo articolo presenta una panoramica delle misure legate alla sostenibilità sociale e ambientale, proponendo un'analisi empirica di questi impatti con un esempio

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della produzione di cotone in India. L'applicazione del Life Cycle Assessment (LCA), come delineata dalla norma ISO 14040, permette di quantificare sia l'impatto sociale che quello ambientale e di definire una strategia per mitigarli entrambi simultaneamente. Pertanto, l'articolo analizza una serie di trade-off emergenti quando le aziende cercano di ottimizzare contemporaneamente sia l'impatto ambientale che quello sociale delle proprie attività. Si dimostra che, attraverso l'adozione della LCA, gli impatti legati agli aspetti sociali e ambientali possono essere ottimizzata simultaneamente attraverso strategie sostenibili efficaci.

Parole chiave: Impatto ambientale, Impatto Sociale, Performance, LCA.

1. Introduction

Recently, some firms faced accusations of greenwashing since their decarbonization plans failed to report credible sustainable initiatives (Johnsson *et al*., 2020). These criticisms highlight the absence of a thorough and verifiable approach in substantiating the environmental benefits claimed in their sustainability initiatives. Firms are mandated to draft their decarbonization plans to achieve both the 2030 and the 2050 targets, necessitating the quantification of their CO2 emissions and the identification of initiatives to reduce these emissions (Pollok *et al*., 2021). To accomplish this target, the Life Cycle Assessment (LCA) can be effective in enabling companies to create credible and effective decarbonization plans by providing a comprehensive analysis of environmental impacts across the entire life cycle of their products and services (Finkbeiner and Bach, 2021). In fact, the integration of sustainability and LCA methodologies has been proposed as a pathway for addressing the complexity of greenwashing issues in many heavy industries such as textiles (Mousavi *et al.*, 2024).

The whole process of LCA analyzes various "impact categories", each of which uses certain indicators to calculate potential impacts, making it possible to evaluate the effects of production, utilization, and disposal of products on the environment. Accordingly, firms can set environmental strategy to manage products sustainably. In detail, the most common impact categories are Global Warming Potential (GWP), which tracks the emissions of greenhouse gases and the effects of these gases on earth's temperature, and Ozone Depletion Potential (ODP), which determines the substances reducing the ozone layer (McClelland *et al*., 2018). However, other measures like Human Toxicity Potential (HTP) consider the possible harmful effects of a specific environmental pollution on human health along with Ecotoxicity, which accounts for the impact of biological, chemical, or physical factors on the ecosystems (Raymond *et al*., 2020). Furthermore, Acidification Potential (AP) involves emissions that contribute to the depletion of rain, which is an important factor as air, farm soil, and water bodies get affected, along with Eutrophication Potential (EP), which includes the nutrients that travel through discharges that over-fertilize the water bodies. Subsequently, the water bodies become overloaded with algae, and oxygen will be reduced (Pennington *et al.*, 2004). The negative list, as reported by the ISO 14040, also includes the Photochemical Ozone Creation Potential (POCP), which measures emissions for ground-level ozone formation, a major component of smog (Guinée, 2015). Also, Resource Depletion shows the depletion of finite resources, whereas the Water Use and Land Use categories evaluate the water resources and biodiversity and ecosystem services respectively (Hauschild *et al.*, 2013). Finally, the ISO 14040 requires the quantification of the Particulate Matter Formation, including the emissions that make air quality and health suffer (Rigon *et al.*, 2019). Recent developments in the field highlight advancements in assessing these categories to ensure sustainability (Finnveden *et al.*, 2009).

Along with the environmental impact, the LCA can also be used to assess the social impact, through its variant, the Social Life Cycle Assessment (S-LCA). The S-LCA presents the social effects from the manufacturing to the disposal of products, which draw the attention of stakeholders and the ecosystem (D'Eusanio *et al.*, 2022). CSR is often the first place to look for lists of "social impact categories", since it directly links to ethics and human rights firms consider in their sustainable strategies (Tsalidis *et al.*, 2021). As ISO 26000 outlines a set of practices and patterns crucial for organizations to adhere to for their sustainability, S-LCA represents a structured tool to evaluate the social impacts of products during their entire life cycle (Bhatnagar and Niinimäki, 2024).

Both S-LCA and ISO 26000 are based on analyzing the consequences that firms can have on stakeholders like workers, communities, consumers, and the surroundings. With the help of this analysis, firms can reinforce social accountability and transparency (Pollok *et al.*, 2021). Finally, the integration of S-LCA with ISO 26000 principles not only endorses a thorough approach to sustainability but also results in more ethical, responsible, and sustainable business practices (Ilhan and Tanyer, 2019). In fact, these methodologies aid firms in aligning with social responsibility standards (Norris and Norris, 2014), and advances a deeper understanding of social impacts (Tsalidis *et al.*, 2021).

Given its amplitude and complexity, this paper measures social sustainability in terms of: a. *Child Labor*, which measures the extent to which children are employed in the production process (D'Eusanio *et al.*, 2022); b. *Fatal Accidents*, which tracks the number of lethal accidents occurring within the production chain and reflects the safety standards and working conditions (Bhatnagar and Niinimäki, 2024); c. *Life Expectancy at Birth*, which reflects the long-term health impacts of working in the industry (e.g., exposure to pesticides and other chemicals can affect workers' health severely) (Pollok *et al*., 2021); d. *Expenditure on Education*, which reports the investment made in education for communities involved in production (Ilhan and Tanyer, 2019); and e. *Violation of Employment Laws*, which assesses compliance with local and international employment laws, including those relating to wages, working hours, and working conditions (Tsalidis *et al*., 2021).

This paper seeks to provide a deep examination of the social and environmental sustainability by considering the production of cotton in India as reference product. The study uses the LCA framework of the ISO 14040 standard to quantify the environmental impacts along with some parts of the ISO 26000 to address the social aspects, thus helping to form combined strategies to mitigate both. Using the Ecoinvent dataset, we demonstrate how LCA can quantify the impact and, consequently, help identifying how to write decarbonization plans; specifically, we seek to answer these two research questions (RQ):

RQ1. Which input contributes the most to social and environmental impacts in the cotton production process?

RQ2. What measures can be implemented to mitigate the adverse social and environmental impacts associated with the key input identified in cotton production?

These research questions encourage the identification of specific solutions for life-threatening functioning processes in the cotton industry, which has significant social and environmental impact and focuses in one of the most important agricultural sectors. Through the identification of the main ingredients, this research makes sure that the discussion around sustainability continues to be not only theoretically robust but also practically relevant, identifying actionable recommendations and giving the necessary space for the industry shareholders and policymakers for ad hoc interventions, while contributing to the wider context of sustainable development and responsible resource management.

Therefore, the paper proposes an objective approach to quantify both the social and the environmental impacts that firms should definitely embrace to create effective and credible sustainable strategies. This paper is structured as follows. Section 2 introduces a literature review on the topic of measuring the performance. Then, Section 3 describes the source of data and Section 4 proposes an empirical analysis using LCA methodology. Finally, Section 5 briefly concludes.

2. Literature Review on Cotton Environmental and Social Impacts along the Life Cycle

The quantification of social and environmental impacts is a central topic in sustainable development discourse. This short review, proposed with the only aim to better framing the focus of the paper, explores initiatives to measure and mitigate the above-mentioned impacts, integrating insights on technical quantification methods, and specific industrial supply chain applications such as cotton production.

Cotton is among the most extensively cultivated crops globally, serving as a cornerstone for the textile industry and supporting millions of smallholder farmers across numerous countries. Its significant contribution to global economies and livelihoods underscores its importance (Nikam *et al.*, 2022).

The cotton industry employs 250 million people globally, with 7% of the labor force in developing countries. It is the leading non-food agricultural commodity, with five countries producing 74% of global output. Supporting 150 million livelihoods in 75 countries, the sector is vital to developing economies and the 2030 Sustainable Development Agenda.

However, the cultivation and processing of cotton present severe environmental and social challenges, including excessive water consumption, reliance on pesticides, and labor inequities. These issues have prompted an urgent shift toward sustainable practices in the sector.

LCA has become a crucial tool for evaluating and addressing the environmental impacts of cotton production. By analyzing resource use and emissions throughout the cotton lifecycle – from cultivation to disposal – LCA provides valuable insights for developing sustainable policies and practices. This approach helps pinpoint key areas for improvement, such as reducing water and pesticide use while promoting environmentally friendly technologies (Zhang, 2015). LCA further empowers stakeholders to make data-driven decisions to pursue, also through digitalization, resource efficiency and promoting a transition toward more sustainable models (Maleki Vishkaei and De Giovanni, 2025).

This analysis places particular emphasis on India, a leading cotton producer, exploring the social and environmental initiatives aimed at fostering sustainability. Programs like farmer education and integrated pest management (IPM) are highlighted for their role in reducing input costs and improving yields. Simultaneously, LCA applications demonstrate the potential to optimize resource efficiency and minimize ecological footprints, advancing the cotton sector toward a more sustainable future and promoting durable ecological stewardship and social empowerment (De Giovanni, 2025).

As previously stated, cotton production in India plays a significant role in the agricultural and textile sectors, providing livelihoods to millions of farmers (Nikam *et al.*, 2022). Various social initiatives aim to address challenges such as low productivity, resource inequity, and the exploitation of labor. Many programs promote farmer education, equitable labor practices, and sustainable livelihoods.

Organizations like Better Cotton Initiative (BCI) work extensively in India to train farmers on sustainable farming practices, focusing on reducing input costs and improving yields while safeguarding worker rights. The BCI framework emphasizes equitable labor practices and empowers smallholder farmers by providing access to resources and knowledge on pest management and water conservation.

However, social barriers such as gender disparities continue to hinder progress. Women, who perform most of the labor-intensive tasks like planting and harvesting, are often excluded from decision-making roles. These inequities limit resource access and sustainable farming practices adoption (Omollo, 2023). Studies have recommended community development programs to address these disparities and enhance the overall sustainability of the sector (Omollo, 2023).

India's cotton sector also faces significant environmental challenges, including high water usage, pesticide dependency, and soil degradation. Various initiatives have been launched to promote eco-friendly farming methods. For instance, organic cotton farming practices have gained traction, reducing dependency on chemical fertilizers and pesticides. These practices also help in conserving soil health and reducing water consumption.

Efforts to mitigate environmental impacts also include the promotion of integrated pest management (IPM) and biological control techniques. IPM reduces pesticide use and improves ecological balance, though adoption rates remain low due to the high costs and limited awareness among smallholder farmers. Furthermore, environmental non-governmental organizations (NGOs) have advocated for the adoption of drip irrigation and laser leveling to enhance water efficiency. These practices have shown promising results in reducing resource consumption, though scalability remains a challenge (Nikam *et al.*, 2022).

LCA is a critical tool for understanding the environmental impacts of cotton production across its entire life cycle, from cultivation to disposal.

Studies conducted in India have highlighted key hotspots in the cotton production chain, such as water consumption, pesticide use, and energy-intensive processing stages like dyeing (Zhang, 2015).

In the agricultural phase, excessive use of fertilizers and pesticides contributes to eutrophication and soil acidification. LCA studies indicate that water consumption during irrigation accounts for a significant proportion of the environmental burden in cotton cultivation. Transitioning to more efficient irrigation methods and using organic farming techniques could substantially reduce these impacts (Zhang, 2015; Abagnato, 2024).

The processing phase, including dyeing and fabric finishing, is another significant contributor to environmental degradation. These processes are energy-intensive and rely heavily on non-renewable resources. Studies have shown that adopting renewable energy sources and low-impact dyeing methods can significantly reduce greenhouse gas (GHG) emissions (Semba, 2024; Zhang, 2015).

LCA of cotton reveals that irrigation, pesticide implementation and dyeing processes constitute substantial sources of environmental impact. However, it is essential to recognize that these elements cannot be assessed in isolation, as their repercussions extend to water management and the textile waste cycle.

To address these issues and mitigate the overall impact of the textile sector, complementary solutions are required. These include wastewater treatment and the adoption of circular economy approaches (De Giovanni and Ramani, 2024). The analysis further emphasises the significance of integrated solutions, as evidenced by the comparison between conventional and biological approaches, in reducing greenhouse gas emissions and minimising resource consumption.

The wastewater management research on wastewater treatment in India's textile industry demonstrates that advanced treatment technologies like reverse osmosis and ultrafiltration can mitigate water pollution (Nakhate, 2020); while the circular economy approaches focus on circular practices, such as recycling textile waste into new fabrics or biochar, have shown potential for reducing environmental impacts (De Giovanni and Folgiero, 2023). Studies reveal that recycling pre-consumer textile waste has lower impacts compared to post-consumer waste due to its consistent composition (Abagnato, 2024).

Finally, studies on comparative impact assessment comparing organic versus conventional cotton highlight that organic practices result in lower GHG emissions and reduced water consumption. However, organic yields are generally lower, requiring more land to produce the same amount of cotton (Zhang, 2015; Abagnato, 2024).

3. Data and Methodology

The data that was taken from Ecoinvent to assess both areas social and environmental. This database gives a deep insight into the life cycle of a product, for many processes and products. Ecoinvent is highly recognized worldwide as LCA databases since it includes more than 5000 firms around the world. The database has life cycle inventory data related to international industrial energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services. As of now, the database has more than 20000 reliable datasets in it.

The database really is transparent and consistent and each data set is served as a unit process and as an aggregated system process. Ecoinvent is a Zurich, Switzerland-based non-profit organization that is dedicated to guaranteeing the availability of high-quality data for sustainability assessments all over the world. Its mission is to address environmental data dissemination and exchange issues, such as life cycle inventory data compilation, linking and distribution, and data and database management. Ecoinvent coordinates various initiatives aiming at promoting awareness and good practices in the creation and use of life cycle inventories around the world, making data available and involving policy-makers, private enterprises, NGOs, and the academic community globally to update and enrich it. The dataset is available at https://ecoinvent.org/.

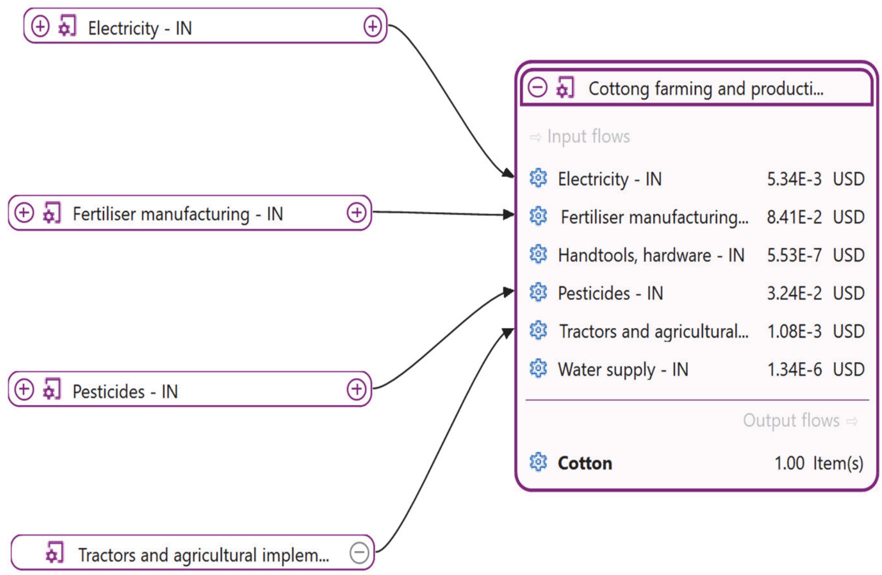
4. Analysis of a Reference Product

Indeed, to make the quantification of both the social and environmental impact, we selected a reference product to analyze. Considering the data available, we focus on the production of 1kg of cotton in India. In the context of cotton production, the electricity, fertilizer, pesticides, and tractors represent various inputs and resources that are essential for the cultivation and harvesting processes, which are therefore important components of the bill-of-material as displayed in Figure 1. Each of them has a distinct role and impact on both the crop yield and the environmental and social footprint of cotton farming, as specified below:

- **Electricity**. Among the primary ways one can use electricity in cotton production are running irrigation systems, providing light, and feeding the equipment. The energy used for the different stages of the cotton farming process includes the water pumps that are powered for irrigation to the ginning and pressing process. The type of energy used and its efficiency is one of the aspects that are likely to affect the impact of this process. For instance, the use of electricity with low emissions and low energy consumption may decrease the environmental impact of cotton fabric production process;

- **Fertilizer**. Fertilizers are products that are given to plants in order to help them grow faster and better. They are substances such as nitrogen, phosphorus, and potassium that plants need to grow and are, as a rule, rich in nutrients. As regards cotton farming, fertilizers are the major player in delivering the desired crop which can only be achieved through high yields and proper plant health. Nevertheless, the production, transportation, and application of synthetic fertilizers are accompanied by water pollution due to the release of runoff, soil degradation, and the emission affecting the climate it causes. The demand for these chemicals is also affected, especially in relation to the health risks for farmworkers who get in contact with them;
- **Pesticides.** Pesticides, which are chemicals used to kill or control pests that damage or inhibit plant growth, are the cause of the problems. In cotton farming, pesticides make the cotton plant resistant to a wide range of insects, weeds, and diseases. Moreover, the pesticides used were also very effective in improving crop productivity and reducing losses through pest control, but they have led to various health problems, such as water pollution, the reduction of vital species (not only harmful insects, but also beneficial insects), and the decline in the biodiversity. Furthermore, the long-term exposure to these chemicals can increase health risks by the eco-system;
- **Tractors and farming equipment**. Tractors and other agricultural machinery are most likely adopted in cotton farming to plow, plant, spray fertilizers, and pesticides, and harvest. These machines greatly diminish the amount of labor while augmenting their efficiency. Nevertheless, their use involves the burning of fossil fuels, thus, reducing the emissions of greenhouse gases and particulates. Besides, the production and maintenance of agricultural machinery lead to resource depletion and environmental pollution.

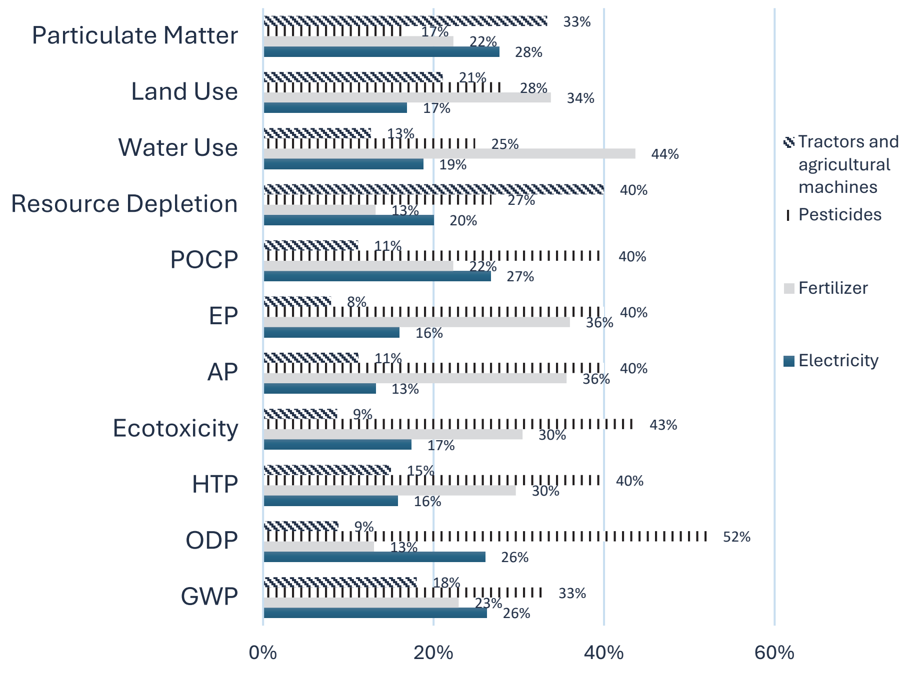
Figure 1 – LCA boundaries



4.1 ISO 14040 and the environmental impact

A comprehensive approach that incorporates the most critical environmental sources is indeed necessary for cotton production in India to have an innovative environmental impact harnessing in full its potential. Figure 2 displays the impact category reported in the ISO 14040 and the impact of each operational component. As it emerges from Figure 2, the first task is to reduce the use of pesticides, which are the major problem in many areas, contributing 43% to Ecotoxicity, 40% to Human Toxicity Potential (HTP), and 36% to both Eutrophication Potential (EP) and Acidification Potential (AP), by improving the utilization of integrated pest management (IPM) strategies. Clearly, IPM emerges as the ideal solution as it harnesses the power of nature and thus at the same time decreasing the dependence on artificial chemical pesticides, generating an improvement of the quality of the environment as well.

Figure 2 – Analysis of the Environmental impacts



On the one hand, fertilizers, which dominate the environmental impact by 44% in Water Use, 34% in Land Use, and 36% in EP, are the primary factors that may have an effect on aquatic ecosystems. Improving efficiency with the help of smart agriculture tools like those for precision application of fertilizers is vital in that the amount of fertilizers used, runoff, and overheating of the soil are concerns. Thus, the strategy of large-scale irrigation and the application of chemical fertilizers for a prolonged period of time would be rather obsolete, if no rescue strategy is applied.

The general effects of energy, particularly in terms of the Global Warming Potential (52% from Electricity) and the Photochemical Ozone Creation Potential (40% from Electricity), might be solved by using energy from renewable sources like solar and wind power. This would of course make existing electric "dirty" technologies obsolete but at the same time render the overall ecological footprint smaller.

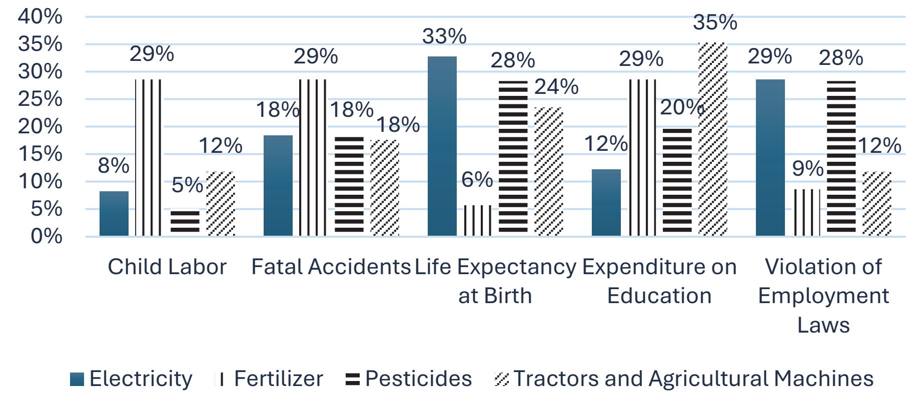
Tractors and other types of agricultural machinery cause resource depletion (40% contribution from tractors and machinery) and release particulate matter into the atmosphere (33% contribution from tractors and machinery). Converting to more electric and fuel-efficient models can definitely reduce the amount of resource and emissions. Constant machinery service to enhance the performance of machinery and the implementation of no-till farming methods also can reduce the usage of heavy machinery, thus, the negative impact on particulate matter and land use.

4.2 Social impact

To address the social impacts of cotton production in India, it is important to consider the specific challenges posed by various inputs such as electricity, fertilizers, pesticides, and tractors & agricultural machines. Each of those inputs will affect different social and labor conditions, they will need specific strategies for mitigation.

Electricity, a vital input in cotton production, has been associated with significant life expectancy exposures of 33% and labor violations of 29%. The measures to curb these effects would be better safety standards for electrical installation and enhancing workers' safety, as well as the use of cleaner energy instead of those derived from fossil fuels. Also, the companies need to be strict about safety protocols and train the workers on how to maintain a clean workplace, and then, the workers will benefit a comprehensive working environment along with fewer legal violations.

Figure 3 – Analysis of the Social impacts



Fertilizers, which are indispensable for crop growth, have serious risks, equitably dividing contributing factors between the child labor and the fatal accidents (29% each). The replacement of the hazardous chemical fertilizers by non-harmful organic substances that are eco-friendly can lessen the risks associated with health and child labor abuses. The insistent safety rules and incessant sessions of training are key requirements to decreasing accidents and ensuring the safety of all workers.

Pesticides, often applied to keep the crops healthy, have a negative effect on life expectancy at birth (28%) as well as being often the cause of violating employment laws (28%). The switch to integrated pest management methods can lessen the usage of harmful chemical pesticides. It is also very important to do regular audits and to punish hazardous conditions and exploitation of workers through employment laws.

Tractors and other heavy equipment required for modern farming are, however, not only rather costly in terms of health expenditure and life expectancy from birth. Investing in community education programs on vehicle and machine operations safety and providing high-tech machinery should be the primary route to the prevention of accidents and casualties among workers, ultimately leading to decreased injuries. Besides, these actions will also strengthen the life expectancy of the workers right from the point of future generations, which will be a safer and more efficient one.

5. Conclusions

This paper reviews both the social and the environmental initiatives that are currently running in the cotton production sector in India. Our main goal is to examine and evaluate both the social and environmental benefits that result when decarbonizing the operations. We use the LCA to quantify and analyze the impacts resulting from each stage of the cotton production process. Our results demonstrate that practices such as organic farming techniques can lead to a significant reduction of the negative effects of synthetic chemicals and harmful pesticides that are the main factors in environmental degradation and human health. Organic methods, on the other hand, usually require less water and energy, solving issues like water use and greenhouse gas emissions.

As a result of the social impact analysis, strict regulations on labor practices should be implemented to favor sending children to school instead of working in unclear conditions, avoiding accidents and investing in worker education and health. Therefore, the education programs can educate on safe handling of the agricultural chemicals, proper using of the machinery and informed workers' rights. This, in turn, directly impacts the life expectancy of workers and reduces the violations of the employment laws. Fostering new technologies such as those to reduce the necessity of labor and exposure to dangerous substances can make the workers' environment safer, as well as help nature, as the impact from the very beginning to the very end of a life cycle can be reduced. The use of technologies like drip irrigation and solar-powered systems makes it possible to owe the same job to a lower possible number of people, while providing ecological benefits.

Through this study, we can identify some recommendations for policy makers:

- Promote the use of integrated pest management (IPM) in order to reduce the amount of chemical pesticides used, and therefore decrease ecotoxicity and human toxicity, while at the same time, maintaining worker health at a safe level, and community safety and well-being improvement;
- Sponsor the use of precision agricultural methods for the application of fertilizers can produce the maximization of resource use, the minimization of environmental runoff, the preservation of aquatic ecosystems, as well as the reduction of the risks of car accidents;
- Take offshore energy sources such as solar and wind energy to endorse the decrease of greenhouse gas emissions, and improve air quality of the surroundings, consequently, the diminishing of environmental impacts and the minimal exposure of the workers to hazardous conditions;
- One of the steps to technological advance of agriculture is the use of power machines that run on biofuels and electricity because it allows for the lowering of resource depilation and air pollution. Thus the operation of safe machinery is assured;
- Ensure the adoption of safety protocols and continuous staff training at every production process to change the perception of environmental management and worker satisfaction, and, therefore, to build up a sustainable culture.

This paper has some limitations, which are taken here to inspire future research projects. The reliability of the environmental and social impact data produced by the LCA and its variations is very much dependent on the accuracy of the data, which requires further investigation confronting the Ecoinvent dataset with other sources. Besides that, the intrinsically dynamic nature of agriculture – where technologies, practices, and regulations are in constant flux – makes these findings temporary valid. Bringing in a wider variety of cotton sorts and looking at the issue from a more global perspective would profit the study by providing a deeper understanding of the global cotton market. Furthermore, future research should delve into the transition to sustainable technologies by linking sociological and financial strategies, thus providing a more holistic perspective of the most efficient sustainability practices. While this case study application offers a new view for analyzing sustainability, more cases and empirical studies are required to generalize the findings and make the recommendations more robust.

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