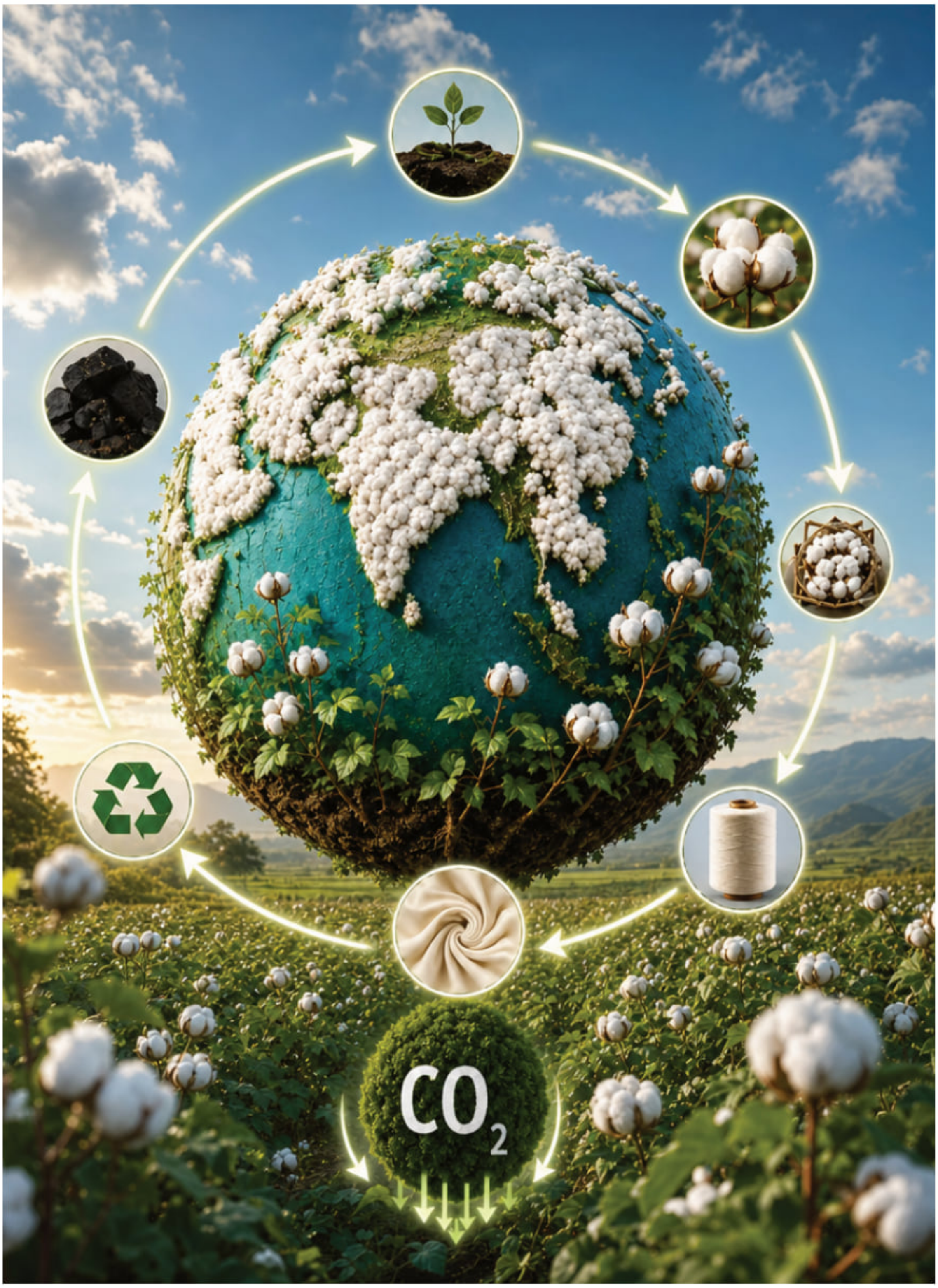
LIFE CYCLE ASSESSMENT STUDY



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KASTURI COTTON BHARAT

Regeneratively Grown Kasturi Cotton

For the Year 2025 - 2026

Organization	:	**Beetle Regen Solutions Pvt. Ltd.**
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Abbreviations

Abbreviation	Meaning
BAU	*Business-as-Usual*
BCI	*Better Cotton Initiative*
CBAM	*Carbon Border Adjustment Mechanism*
CEA	*Central Electricity Authority*
CO_2e	*Carbon Dioxide Equivalent*
DEFRA	*Department for Environment, Food & Rural Affairs (UK)*
EC	*Energy Consumption*
FYM	*Farm Yard Manure*
GHG	*Greenhouse Gas*
GWP	*Global Warming Potential*
HP	*Horsepower*
IPCC	*Intergovernmental Panel on Climate Change*
LCA	*Life Cycle Assessment*
LCI	*Life Cycle Inventory*
LCIA	*Life Cycle Impact Assessment*
MJ	*Megajoule*
NPK	*Nitrogen–Phosphorus–Potassium Fertilizer*
PAC	*Persistent Aromatic Carbon*
PV	*Photovoltaic*
SPC	*Semi-Persistent Carbon*
WC	*Water Consumption*

Acknowledgements

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We sincerely thank the participating Kasturi Cotton farmers for their time, cooperation, and willingness to share field-level data essential to this assessment. We also acknowledge Amit Cot Fibres for facilitating data collection and providing access to ginnery operations.

We extend our appreciation to Texprocil for its trust, guidance, and the opportunity to undertake this Life Cycle Assessment of Kasturi Cotton. We also thank Control Union for conducting the independent critical review and site verification in accordance with ISO 14071, thereby strengthening the transparency and credibility of the study.

Finally, we acknowledge all partners and technical experts whose inputs and collaboration contributed to the successful completion of this assessment.

Executive Summary

This study evaluates the environmental performance of cotton production systems in **Jalgaon district, Maharashtra, India**, for the 2025-2026 cultivation season using a Life Cycle Assessment (LCA) approach in accordance with ISO 14040, ISO 14044, and ISO 14067. The assessment compares three cotton production systems:

- Regenerative Kasturi Cotton cultivation (overall farmer sample)
- Regenerative Kasturi cotton cultivation with biochar application (subset of regenerative farmers)
- Conventional cotton cultivation (reference scenario based on secondary data)

Primary inventory data were collected from a representative sample of approximately **264 farmers** (including a 5-6% buffer) selected from nearly **1,200 participating farmers** producing around **3,000 bales of Kasturi Cotton**. The study covers the cradle-to-ginnery end gate system boundary, including cultivation, irrigation, transportation, ginnery processing and, where applicable, artisanal biochar production using cotton stalks and subsequent field applications.

The study represents the cotton value chain through the participation of regenerative Kasturi Cotton farmers, Biochar-producing farmers (a subset of regenerative Kasturi Cotton farmers), Cotton Ginnery and supporting transport activities from farm to gin. Primary data collected from farmers and ginnery operations were complemented with recognized secondary datasets and published emission factors for the conventional baseline.

The study evaluates the Global Warming Potential (i.e. Product Carbon Footprint), Blue Water Consumption, and Primary Energy Consumption of regenerative Kasturi cotton cultivation upto ginnery end gate. To further understand the influence of operational practices on environmental performance, four scenario analyses were conducted, assessing the impacts of diesel-powered irrigation, grid-powered ginning, rainfed cultivation and solar-powered ginning on greenhouse gas emissions.

Snapshot of the Study:

Parameters	Description
Project Location	Jalgaon, Maharashtra
Study Period	2025 – 2026
Functional Unit	1 kg cotton lint at ginnery end gate
System Boundary	Cradle-to-Ginner end Gate
Total Farmers	1200
Sample Size	250 (with 5-6% buffer)
Biochar Farmer Subset	20
Cotton Production	Approximately 3000 bales
Key Stakeholders	Farmers, Biochar-producing Farmers, Ginnery, Transporters
Environmental Indicators	Global Warming Potential, Blue Water Consumption, Primary Energy Consumption
Standards Followed	ISO 14040, ISO 14044, ISO 14067

Comparative Environmental Performance:

Indicator	Conventional Cotton	Regenerative Kasturi Cotton (Overall Project)	Regenerative Kasturi Cotton with Biochar (Project 2)[1]
Global Warming Potential (kgCO2e/kg lint)	4.17	1.92	1.69*
Blue Water Consumption (m3/kg lint)	3.17	1.382	1.523
Primary Energy Consumptiton (MJ/kg lint)	10.96	3.53	3.50

*A carbon sequestration potential of 0.67 Kg CO2e per Kg of cotton lint hasn't been factored here to adhere to the reporting methodology but essentially this group is insetting carbon into the farms and supply chains for brands thus creating a overall reduction potential of 75% in comparison with conventional farmers (At 1 Kg CO2e per kg of lint post CDR / sequestration accounting).

The findings demonstrate that, compared with conventional cotton production, regenerative Kasturi Cotton cultivation (per Kg of lint) helps reduce global warming potential (CO2e) by 54%, primary energy demand by 78.1%, and blue water consumption by 56.4%, demonstrating the significant environmental benefits of regenerative agricultural practices in India's Kasturi cotton.

Across all production systems irrigation practices remain the dominant contributors to blue water use. Also, energy consumption for irrigation results in higher primary energy demand. Fuel consumption for agricultural machinery, agricultural inputs and transportation to the Gin and ginnery operations lead to greenhouse gas emissions across the assessed systems.

Table 1: Impact of Biochar with Regenerative Agriculture

Parameters	Value
Net Biochar Carbon Removal	29.61 tCo2e
Carbon Removal per kg of lint cotton	0.67 kgCo2e

With the production and application of biochar with 20 project farmers, a 29.61 tCO2e is sequestered within the current Regenerative Kasturi Cotton with Biochar (Project 2) value chain.

This led to 75% reduction in carbon footprint for Biochar enhanced Regenerative Kasturi cotton as compared to conventional cotton farming. This was on account of Biochar incorporation sequestering 0.67 kg CO_2e into the soil of these farmers per kg of lint produced. This also creates opportunity for insetting emissions by the apparel brands to meet their net-zero goals.

Overall, the study highlights the potential of regenerative agriculture and biochar integration to strengthen the environmental sustainability of Kasturi Cotton Bharat production while supporting climate mitigation, improved soil health, and more resource-efficient farming systems.

Kasturi cotton, with its regenerative production practices and with the new Sustainability SOP implemented, has a potential to **reduce emissions by 1.1 Mn MT of CO2e per annum** (in comparison to conventional cotton production) to reach its target of 5 lakh bales per annum in the next 5 years.

This report has completed the first stage of an independent critical review by Control Union in accordance with ISO 14071. The final Critical Review document has been attached in Annexure 1 (page 56-69).

[1] A group of 20 farmers, within the study farmer population of 264, practicing regenerative agriculture along with biochar application on their farmland as a part of this project.

[2] **Regenerative Kasturi cotton farming** includes approximately 90% of irrigated farms, leading to blue water consumptions.

[3] **Regenerative Kasturi Cotton with Biochar** has higher blue water consumption, due to quenching water requirement post pyrolysis.

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1. Introduction

1.1 Background and Context

Quantifying and mitigating the environmental impacts embedded within agricultural supply chains has become pivotal in combating systemic climate risk, resource scarcity, and land degradation. Cotton (***Gossypium hirsutum***) is an economically vital global commodity, yet conventional production systems are historically resource intensive. Conventional cultivation frameworks rely heavily on synthetic agrochemical inputs, intensive tillage regimes, and fossil-fuel-dependent irrigation infrastructure, which together contribute significantly to global greenhouse gas (GHG) emissions, ground and surface water depletion, and soil organic carbon (SOC) exhaustion.

To address these environmental challenges, a paradigm shift toward regenerative agriculture has emerged. Regenerative agriculture represents a holistic, outcomes-based ecosystem management strategy focused on restoring soil health, maximizing biodiversity, improving water retention, and enhancing biological carbon sequestration within the soil matrix. Within the assessed system boundary, targeted interventions have been deployed across a regional network of farmers to shift cultivation dynamics away from conventional baselines toward low-impact, regenerative pathways.

1.2 Defining the Comparative Intervention Framework

A common misconception in carbon and environmental accounting is to interpret localized agricultural interventions as isolated, parallel systems. To ensure absolute methodological transparency and strict adherence to international standard definitions, this Life Cycle Assessment (LCA) does not compare biochar farmers against non-biochar farmers as entirely separate agricultural systems.

Instead, this study evaluates a broad transition across a regional supply chain from a Conventional Baseline (Business-As-Usual) to an advanced Regenerative Intervention Scenario (Regenerative Kasturi Agriculture Framework). The core comparison is structured across two primary intervention levels within the assessment system boundary:

- **Regenerative Kasturi Cotton System (Overall Project):** A coordinated agricultural program comprising approximately 1,200 participating farmers producing 3000 bales from Kasturi cotton under regenerative agricultural practices in Jalgaon, Maharashtra. Primary inventory data were collected directly from participating farmers and supporting ginnery operations to represent the ground realities post project interventions:

  a) Biochar-Enhanced Regenerative Kasturi Cotton (Project 2): A specialized operational subset within the regenerative cohort (consisting of 20 pilot farmers) who actively integrated on-farm pyrolytic carbon capture and storage. These pilot farmers collected agricultural residues (cotton stalks) from their own farms to produce biochar using decentralized, low-emission artisanal setups (e.g., earth cone pit kilns), subsequently applying the stable carbon directly back into their field soils to achieve long-term C-sink stability.

- **Conventional Baseline System:** Characterized by high synthetic fertilizer applications (N, P, and K), intensive tillage operations, dependence on conventional irrigation energy sources, and limited use of organic soil amendments. Inventory data for the conventional system were obtained from two different published reports, i.e. the Textile Exchange Life Cycle Assessment for Cotton (2026) and Better Cotton Initiative LCA report (2017) studies. The Textile Exchange study was used for comparing global warming potential and blue water consumption practices in India. Better Cotton Initiative LCA report was used for comparing the primary energy consumed representing conventional cotton cultivation practices in Maharashtra, India.

1.3 Decarbonization at the Processing Gate (Ginning Interventions)

The scope of this LCA extends beyond field-level agricultural practices to capture critical industrial interventions at the primary processing stage.

The processing facility evaluated in this study, **Amit Cot Fibres**, utilizes a hybrid electricity system consisting of grid electricity supplemented by on-site solar photovoltaic generation operating under a net-metering arrangement. Primary operational data related to energy consumption and processing activities were collected directly from the facility and incorporated within the life cycle inventory.

The conventional reference dataset utilized in this assessment primarily provides inventory information at the cultivation stage. To maintain a consistent system boundary up to cotton lint production, the assessment's ginnery-stage inventory data that were collected from **Amit Cot Fibres**, were added to the conventional dataset of BCI LCA study for primary energy consumption to complete scope that matches our study scope. This approach ensured methodological consistency and comparability across all assessed scenarios by applying a common processing stage while evaluating differences arising from cultivation practices and associated agricultural interventions.

In contrast, the processing facility evaluated in this study, **Amit Cot Fibres**, utilizes a hybrid electricity system consisting of grid electricity supplemented by on-site solar photovoltaic generation operating under a net-metering arrangement. Primary operational data related to energy consumption and processing activities were collected directly from the facility and incorporated within the life cycle inventory.

Environmental burdens associated with ginnery operations were allocated between cotton lint and cottonseed in accordance with the mass-economic allocation methodology adopted for this study. Based on primary ginnery observations, approximately 34% of seed cotton mass is converted into cotton lint while the remaining 66% is recovered as cottonseed.

1.4 Standard Compliance and Study Objectives

This comprehensive environmental profile has been quantified using primary activity inventories collected directly from field operations and processing lines. The final assessment model addresses three core environmental performance indicators: Global Warming Potential (GWP), Blue Water Consumption, and Primary Energy Consumption. For the Biochar-Enhanced Regenerative Kasturi Cotton (Project 2) scenario, carbon removals associated with biochar application are quantified and reported separately from life cycle emissions to maintain transparency between emission reductions and carbon sequestration benefits.

To guarantee that the findings are robust, verifiable, and eligible for international sustainability markets, the study has been strictly executed in accordance with the following consensus standards:

- ISO 14040:2006 – *Environmental Management – Life Cycle Assessment – Principles and Framework*
- ISO 14044:2006 – *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*
- ISO 14067:2018 – *Greenhouse Gases – Carbon Footprint of Products – Requirements and Guidelines for Quantification*

At the end, this report serves to establish a transparent, science-based performance benchmark for regeneratively grown Kasturi cotton. By highlighting clear operational hotspots and documenting the exact climate mitigation benefits of soil carbon stabilization and renewable processing energy, this study supports strategic decision-making for sustainable textile value chains, corporate carbon in setting initiatives, and regional climate mitigation programs.

And to ensure comparability across all assessed systems, environmental inventories were normalized to a common functional unit of 1 kg cotton lint at the ginnery end gate. Conventional inventory data sourced from literature were converted from seed cotton to lint-equivalent values using primary ginnery yield observations collected during the study.

2. Goal of the Study

The primary goal of this Life Cycle Assessment (LCA) is to rigorously quantify, evaluate, and compare the environmental profiles of cotton cultivation and primary processing systems under conventional practices against a structured regenerative agriculture framework for Kasturi cotton.

The study evaluates the environmental implications of transitioning from conventional cotton cultivation practices toward regenerative agricultural systems implemented under the Kasturi Cotton program. The assessment examines how changes in input management, soil health practices, resource utilization, and biochar application influence greenhouse gas emissions, water consumption, and primary energy demand across the cotton value chain. It establishes a Conventional Baseline (Business-As-Usual) against which the mitigation impacts of system-wide Regenerative Practices and specialized Biochar-Enhanced Regenerative Cultivation. The biochar production is scientifically validated under Global Artisanal C-Sink Registry.

Furthermore, the study includes primary processing activities at the ginnery stage to ensure a consistent system boundary across all assessed scenarios. Primary operational data collected from the processing facility were incorporated to represent cotton lint production and enable comparison of environmental impacts beyond the farm gate. It evaluates the decarbonization potential of transitioning from a conventional 100% grid-reliant energy baseline to a hybrid energy matrix powered by on-site solar photovoltaic (PV) systems integrated via net metering.

2.1 Techincal Objective

To achieve this goal, the assessment is guided by the following technical objectives:

- **Carbon Footprint Quantification:** Quantify the Global Warming Potential (GWP), expressed as $kgCO_2e$ per functional unit, associated with each assessed cotton production system. For biochar-enhanced systems, life cycle emissions and biochar-related carbon removals are quantified and reported separately to distinguish operational emissions from long-term carbon sequestration benefits.

- **Resource Footprint Evaluation:** Quantify total water consumption and primary energy demand associated with cultivation, transportation, and ginnery operations to evaluate resource efficiency across the assessed production systems.

- **Industrial Co-Product Allocation:** Apply a robust mass-economic allocation methodology to distribute ginnery-stage environmental burdens between cotton lint and cottonseed, ensuring consistency with the functional unit and system boundary defined for the assessment.

- **Hotspot Analysis:** Identify major environmental impact drivers across agricultural life cycle stages including synthetic fertilizer inputs, diesel-powered tillage, groundwater extraction, and industrial ginning, to guide future carbon in setting and regenerative supply chain interventions.

2.2 Intended Application

The results of this study are designed to support data-driven decision-making, regulatory alignment, and market-facing transparency. The intended audience and applications include:

- **Internal Project Developers & Agronomists:** To optimize field-level resource scheduling, refine biochar application protocols, and scale regenerative agricultural strategies across the broader farmer network.

- **Supply Chain Partners & Sustainability Stakeholders:** To provide verified primary impact data for scope 3 emissions accounting, brand-level carbon in setting claims, and sustainable textile supply chain reporting under the Kasturi cotton framework.

- **External Reviewers & Certification Bodies:** To demonstrate methodological alignment with ISO 14040, ISO 14044, and ISO 14067 standards, ensuring transparent quantification and reporting of environmental impacts, emission reductions, and biochar-related carbon removals within the assessed cotton production systems.

All environmental results presented in this assessment are expressed relative to the functional unit of 1 kg cotton lint. Conventional reference data obtained from published literature sources were harmonized to this functional unit using observed ginnery conversion factors to ensure comparability with primary data collected from regenerative and biochar-enhanced production systems.

3. Scope of the Study

The scope of this study defines the system boundary, functional unit, environmental indicators, data collection approach, and methodological assumptions adopted for the Life Cycle Assessment of cotton cultivation and primary processing systems under biochar and non-biochar farming conditions.

The scope of the assessment has been defined in accordance with the requirements and guidelines specified under ISO 14040:2006, ISO 14044:2006, and ISO 14067:2018.

3.1 Functional Unit

The functional unit provides a standardized reference against which all biophysical input and output data are normalized to ensure exact comparability between the conventional baseline and the project intervention systems. For this study, the selected functional unit is defined as:

Functional Unit = 1 kg of Cotton Lint at Ginnery end Gate

All on-farm agricultural operations, transportation segments, processing energy demands and packaging, and carbon sequestration dynamics are calculated, allocated, and reported relative to this functional unit.

The conventional agricultural baseline used in this assessment was derived from the Textile Exchange Life Cycle Assessment for Cotton (2026) for Global Warming Potential (GWP) and Blue Water Consumption, as it employs the same functional unit (1 kg of cotton lint at the gin gate) as the present study. For Primary Energy Consumption, reference data were obtained from the Better Cotton Initiative (BCI) Life Cycle Assessment (2017), which reports results per ton of seed cotton at the farm gate. To ensure methodological consistency with the selected functional unit and system boundary adopted in this assessment, the energy associated with the ginning process from the present study was incorporated into the conventional baseline, thereby enabling a like-for-like comparison.

3.2 System Boundary

The system applies to a tailored Cradle-to-Ginner end Gate system boundary restricted to direct operational processes. To maintain a clean focus on foreground activities managed directly by the system boundary network, this study explicitly excludes the capital infrastructure and downstream processes.

The system boundary, shown in Figure 1, follows guidance given in ISO 14040:2006, ISO 14044:2006, and ISO 14067:2018 and encompasses three interconnected operational phases:

System Boundary Diagram:

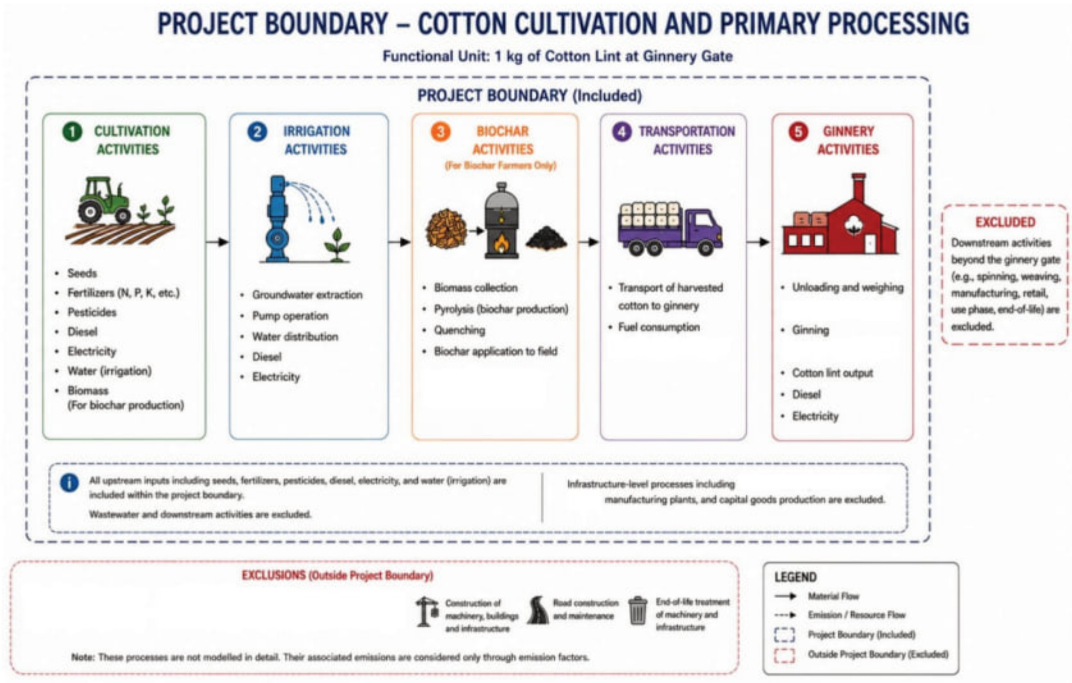


Figure 1: System Boundary for LCA

The above Figure 1 visually explains the system boundary, where the following activities are included:

a) Cultivation Activities

- Land preparation and tillage operations
- Sowing and crop establishment
- Fertilizer application
- Agrochemical application
- Farm Yard Manure (FYM) application
- Irrigation activities
- Electricity consumption for irrigation pumps
- Fuel consumption for agricultural operations
- Harvesting activities

b) Biochar Activities

- Biomass collection from selected farmers for biochar production
- Biochar production activities
- Transportation of biochar to the selected farmer's field
- Biochar application to agricultural fields for selected biochar farmers

c) Transportation Activities

- Transportation of harvested cotton from farm to ginnery

d) Ginning Activities

- Electricity consumption during ginning
- Water consumption during ginning
- Cotton lint production
- Packaging material for bales (khol)
- Cotton seed generation
- Trash and dust generation

The assessment excludes certain upstream and downstream processes from the system boundary. Upstream processes excluded from the assessment include manufacturing of agricultural machinery and infrastructure, manufacturing of production facility of fertilizers, pesticides and agrochemicals, manufacturing of machinery used for fossil fuel extraction, construction of facility for electricity generation, and construction of ginnery units.

Downstream processes excluded from the assessment include packaging of biochar, downstream textile processing, product use phase and end-of-life stages of cotton-based products.

3.2.1 Biochar Production Process and Emission Hotspots

For the subset of 20 farmers adopting regenerative agriculture integrating carbon-sink protocols, Biochar was produced through artisanal biomass pyrolysis processes operated under oxygen-limited conditions. Agricultural biomass (cotton residues) collected from nearby cultivation areas including our 20 study farmers were subjected to controlled thermochemical conversion for production of biochar intended for agricultural soil application, that would otherwise decompose or be subjected to unmanaged open-air burning in conventional baseline practices.

The artisanal biochar production system operational stages of this project intervention loop are defined below:

➢ **Feedstock Collection & Preparation:**
Manual extraction and collection of residual cotton stalks from the field. Stalks undergo manual sizing/chopping and open sun-drying to lower moisture thresholds and maximize thermal conversion efficiency.

➢ **Pyrolysis Process (Primary Hotspot):**
Prepared biomass is tightly stacked into decentralized artisanal setups, specifically local earth cone pits. Carbonization is executed under strict oxygen-limited conditions, operating at stable firing temperatures between 600-700 degree Celsius. Because this thermochemical conversion releases non-condensable biogenic gases and combustion products during the active carbonization phase, the pyrolysis stage represents the primary operational greenhouse gas emission hotspot within the biochar boundary subset.

➢ **Quenching & Cooling:**
Once carbonization concludes, the incandescent biochar is immediately pulled from the heat zone and quenched with water to stop open combustion and lock in the stable carbon structure. This quenching phase consumes a controlled operational average of 1.5 Liters of water per kilogram of biochar generated. Because the direct water-quenching interaction yields negligible, hence excluded from the LCA study, it is tracked strictly under the project's consumptive water footprint rather than a gaseous emission vector.

➢ **Packaging, Transportation and Application:**
The stabilized biochar is blended directly into organic compost matrices or Farm Yard Manure (FYM) batches. These blending steps help condition the biochar's porous structure with nutrients and native microbiology. The biochar-amended organic fertilizer is then transported back to the active agricultural plots by bullock carts and incorporated into the top soil manually using broadcasting method, initiating long-term biogenic carbon storage C-sink dynamics.

The assessment incorporated operational emissions associated with biochar production, transportation, and field application activities. In addition, long-term biogenic carbon storage associated with biochar application was quantified separately and reported independently from life cycle greenhouse gas emissions to maintain transparency between operational emissions and carbon removals.

3.2.2. Biochar Carbon Removal Accounting Assumptions

➢ **Baseline Counterfactual:** Under the baseline scenario, agricultural residues, predominantly cotton stalks, would have been openly burned or left to decompose after harvest, resulting in no long-term carbon storage. Therefore, the baseline carbon sink is considered zero, and carbon removals occur only under the project scenario through conversion of biomass into stable biochar.

➢ **Permanence:** The project follows the Global Artisan C-Sink Standard, which classifies soil-applied biochar into Persistent Aromatic Carbon (PAC) and Semi-Persistent Carbon (SPC) fractions based on biochar properties. The persistent fraction represents long-term carbon storage, whereas the semi-persistent fraction is assumed to degrade gradually over time according to the methodology.

➢ **Decay:** Carbon decay is incorporated through the persistence functions specified by the Global Artisan C-Sink Standard, which accounts for gradual degradation of the semi-persistent carbon fraction while maintaining long-term storage of the persistent fraction.

➢ **Monitoring & Verification:** Biochar production and application activities are monitored through the project's digital Monitoring, Reporting and Verification (dMRV) system. Operational records include feedstock type, moisture content, biochar production, carbon content, H/C ratio, application records, and periodic verification through annual inspections and laboratory analyses.

➢ **Leakage:** Leakage was considered negligible because the feedstocks comprised agricultural residues that are conventionally burned or discarded after harvest and have no significant competing economic use. Consequently, leakage emissions were assumed to be zero in accordance with the project methodology.

➢ **Uncertainty:** Uncertainty associated with carbon removal estimates was minimized through standardized feedstock selection, laboratory determination of biochar properties (including carbon content and H/C ratio), digital monitoring, and application of conservative assumptions prescribed under the Global Artisan C-Sink Standard.

➢ **Reversibility:** Biochar was incorporated into agricultural soils following blending with compost or farmyard manure. Long-term persistence of the stored carbon was represented using the permanence assumptions prescribed under the project methodology, and biochar application records were maintained through the project monitoring system.

System Boundary Diagram:

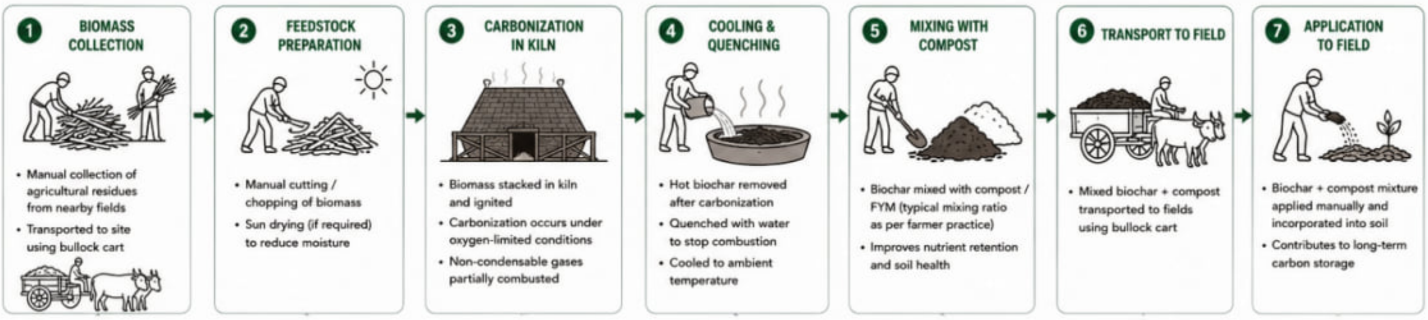


Figure 2: Artisanal Biochar Production Process

3.3 Environmental Indicators

The environmental indicators evaluated within the assessment were selected based on the availability of primary activity data collected from farmers, transportation activities, biochar operations, and ginnery processes within the study boundary.

The environmental indicators assessed in the study are presented in Table 1.

Environmental Indicators	Unit	Abbreviation	Sources
Global Warming Potential	kg CO_2 eq	GWP	CBAM Default factor 2025 / DEFRA 2025 / Ecoinvent 3.12 / CEA v21.0 / UNFaCCC / Ademe v17.0
Energy Consumption	kWh / MJ	EC	IPCC 2019 guidelines to refinement from 2006 guidelines
Water Consumption	L	WC	-

Table 1: Environmental Indicators Included in LCA study

In addition to the above indicators, biogenic carbon removals associated with biochar production and field application were quantified in accordance with ISO 14067:2018 requirements. To maintain methodological transparency, carbon removals associated with biochar application were reported separately from life cycle greenhouse gas emissions and are presented as an additional climate benefit rather than being deducted from gross emissions.

The environmental impact assessment was carried out using primary activity data collected from participating farmers and ginnery operations, along with secondary emission factors and calculation approaches adopted for carbon, water, and energy footprint estimation.

3.4 System Description

The object of the assessment is a restructured, sustainable cotton value chain evaluated against a conventional regional benchmark. The assessment spans cultivation activities, irrigation operations, biochar-related activities for selected farmers, transportation of harvested cotton to ginnery facilities, and ginnery operations up to the production of cotton lint and packaging of bales at the ginnery end gate. The system model captures two main scenarios:

Project Area and Agro-Climatic Characteristics

The project is located in Jalgaon district, Maharashtra, a major cotton-growing region situated in the semi-arid tropical zone of India. The district predominantly comprises deep black cotton (Vertisol) soils, which are well suited for cotton cultivation due to their high moisture retention capacity.

The region receives an average annual rainfall of approximately 650-750 mm, with most precipitation occurring during the southwest monsoon season (June to September). As rainfall is seasonal and variable, cotton cultivation depends on both monsoon rainfall and supplemental irrigation through groundwater extracted using electric (renewable and nonrenewable) or diesel-powered pumps. These agro-climatic conditions influence irrigation requirements, crop productivity, and environmental performance assessed in this study.

The system model captures two main scenarios:

The Project Intervention Scenario:
The project location is shown in Figures 3 and 4.

Figure 3: Location of the project - National View

Figure 4: Location of the project - Locality View

This scenario covers a coordinated network of approximately 1,200 participating project farmers contributing to the production of nearly 3,000 Kasturi cotton bales within the regional supply network in Jalgaon, Maharashtra. It includes system- wide implementation of conservation tillage, optimized resource scheduling, heavy incorporation of organic soil inputs (FYM), and decentralized pyrolytic carbon capture for the pilot sub-cohort. At the centralized processing gate managed by Amit Cot Fibres, the facility operates an integrated, grid- connected solar PV array under a net- metering configuration to displace standard grid dependency.

The Conventional Baseline Scenario (Business-As-Usual):

This scenario establishes the regional standard against which project performance is measured. Cotton cultivation is driven by standard, intensive synthetic fertilizer matrices (Urea, DAP, Ammonium Nitrate) and multi-pass conventional tillage. Irrigation demands rely entirely on fossil fuels or standard grid-powered groundwater extraction, and postharvest stalk residues are typically burned openly or left to decompose unmanaged.

a) Regenerative Agricultural Practices Included in the Assessment

The assessed farming systems include regenerative agricultural practices implemented by participating farmers under the Kasturi Regenerative Cotton program. The practices adopted within the study area aim to improve soil health, optimize resource utilization, enhance carbon sequestration potential, and support sustainable cotton cultivation practices.

The regenerative agricultural practices considered within the assessment include:

- Farm Yard Manure (FYM) application
- Reduced Tillage practices
- Reduced dependency on conventional chemical agricultural inputs
- Application of organic fertilizers
- Biochar production (for selected farmers)
- Application of biochar mixed with organic fertilizer (for selected farmers)
- Irrigation management practices
- Crop residue retention practices (for selected farmers)
- Biomass utilization for other agricultural activity like mulching etc

b) Hybrid Powered Ginning Processing Included in the Assessment

Executed at the centralized facility of Amit Cot Fibre, the ginnery operates an integrated, grid-connected solar PV array under a net-metering configuration. Core daytime mechanical processing draws directly from zero-emission solar generation, while supplemental power demands are managed via the utility grid.

Details of Activity Category and Structured Inventory Data collection method are described in section 3.3; sub-section c and d.

c) Summary Scope of Assessment

Table 2: Structural scope of LCI collection

Activity Category	Scope Status	Remarks
Cultivation Activities	Included	Field-level agricultural activities included
Fertilizer & Agrochemical Application Activities	Included	Field-level application activities included
Irrigation Activities	Included	Irrigation water & electricity consumption included
Biochar Activities	Included	Included only for selected biochar farmers
Transportation Activities	Included	Farm-to-ginnery transportation included
Ginning Activities	Included	Electricity & water consumption included
Agricultural Machinery Manufacturing	Excluded	Outside system boundary
Construction of factory/facility for production of Fossil Fuel & Electricity	Excluded	Upstream energy generation process excluded
Textile Processing	Excluded	Downstream activities excluded
Product End-of-Life	Excluded	Outside system boundary

d) Inventory Data Collected for the Assessment

Table 3: Operational scope of LCI collection

Inventory Category	Scope Status
Farmer & Farm Information	• Farmer name • Farm ID • Ownership type • Village, district • Geographic corodinates
Farm Characteristics	• Total farm area • Cotton cultivated area • Agro-climatic zone • Rainfall, temperature • Soil type • Soil texture
Cultivation Practices	• Cropping system • Previous crop • Tillage type • Tillage depth • Number of tillage passes
Fertilizer Application (*application quantities & derived nutrient composition data*)	• Urea • DAP • SSP • MOP • NPK fertilizers • Total nitrogen • Phosphorus • Potassium fertilizer
Organic input Application	• Farm Yard Manure (FYM) usage • Biochar application (to selected farmers)
Agrochemical Usage (*application & active ingredient related data*)	• Herbicides • Insecticides • Fungicides
Irrigation Information	• Pump type • Pump capacity • Pump depth & usage duration
Fuel Consumption	• Tillage • Ploughing • Rotavator • Knapsack
Production Data	• Cotton production • Rate
Transportation Data	• Farm-to-ginnery distance • Road type • Transport mode • Transport Fare • Vehicle efficiency
Ginning Data	• Ginnery electricity consumption (in project scenario) • Water consumption • Cotton lint output • Cotton seed generation • Packaging materials for bales • Trash & dust generation
Biochar Activities	• Biomass collection • Biochar production • No. of Firings • Water used for quenching • Biochar field application

The system description adopted for the assessment is represented through the system boundary diagram presented in Figure 1.

3.5 Cut-off Criteria

The cut-off criteria conform to ISO 14044 guidelines, ensuring that field data collection and impact modeling target the dominant operational drivers. Activities, materials, or energy flows contributing less than 1% to the cumulative mass or environmental impact category were excluded from the primary inventory model.

The specific exclusions applied are:

- **Capital Infrastructure:**

  The manufacturing, maintenance, and structural disposal of heavy farm tractors, field implements, irrigation pumps and the physical building infrastructure of the centralized ginnery.

- **Downstream Processing:**

  Secondary value chain stages beyond the ginnery gate, including textile spinning, fabric weaving, chemical wet dyeing, retail logistics, consumer use and end-of-life apparel landfilling or recycling.

The applied cut-off approach was considered appropriate for the goal and scope of the study and is not expected to significantly influence the overall interpretation of results.

3.6 Allocation

To isolate the true environmental footprint of the functional unit of 1 kg of cotton lint at ginnery end gate, a robust allocation framework must be applied at the processing stage. Mechanical ginning at Amit Cot Fibres separates raw seed cotton into three distinct output components: cotton lint, commercial-grade cotton seeds, and process trash/dust residues.

Cotton seed and trash/dust generated during ginnery operations were recorded as coproducts. These outputs flow into completely different commercial markets and possess distinct functionalities. Mass-Economic Allocation methodology was selected as the most accurate and methodology-compliant framework under ISO 14044.

Wherever, it was possible to avoid allocation, it has been avoided, but in some places masseconomic allocation approach was used considering the mass and economic difference of the product and by-product.

The operational environmental inventory accumulated from the cultivation field, transportation logistics, and ginnery processing encompassing fuel inputs, grid energy draw, structural bale ties, and protective packaging wraps are split among the co-products using their relative mass-economic value at the ginnery gate. This ensures that the primary textile fiber (lint) is not unfairly burdened with the environmental impacts generated by the production of commercial seeds.

3.7 Independent Review

This report has undergone the first round of an independent critical review by a third-party reviewer, Control Union, in accordance with ISO 14071.

The final critical review document has been attached to the Annexure 1 for reference.

4. Inventory Analysis

The Life Cycle Inventory (LCI) analysis represents the core quantitative phase of the study, during which all biophysical foreground material flows, water resource extractions, transport logistics metrics, and energy demands were collected, validated, and normalized.

The inventory data collected and calculation approaches adopted within the assessment are described in the following sections.

4.1 Primary Data Collection

In accordance with the direct operational boundaries established in Chapter 3, data collection was restricted to active foreground operations managed within the project framework. To ensure absolute numerical traceability, data collection relied entirely on primary activity logs, farm surveys, transport invoices, and utility meters.

The structural scope & tracking mechanisms for each life cycle stage are summarized in Table 4:

Value Chain Stage	Core Activity Tracking Parameters	Primary Data Collection Source
Agricultural Cultivation	• Cultivated land footprint (hectares) • Final crop yield logs (kg Kapas) • Direct field input quantities (Urea, DAP, NPK formulations, SSP, MOP) • Applied Farm Yard Manure (FYM) mass • Applied active crop protection volumes	Direct face-to-face farmer surveys
Irrigation Management	• Irrigation water pump mechanism type (Electric / Solar / Diesel) • Total pump capacity rating (HP) • Pump installation depth (feet) • Cumulative runtime operation logs (Hours)	
Biochar Pilot Interventions	• Residual cotton stalk feedstock mass collection & transportation • Pyrolysis operational round counts (Firings & Temperature) • Final biochar production yield mass (kg) • Consumptive quenching water volumes • Final biochar transportation to farm and its application (kg)	
Farm-to-Ginnery Transport	• Logistic point-to-point transit distance (km) • Transportation vehicle class (Truck / Tractor / Bullock cart) • Total shipping fare and commercial log data	
Centralized Ginning	• Total seed cotton input processed (MT) • Metered electrical energy draw associated with ginnery operations (Grid for baseline) • Consumptive industrial conditioning water (L) • Metered grid and solar PV electricity consumptin associated with ginnery operations • Loader diesel fuel and auxiliary packaging inputs	Centralized utility meters, billing statements, loader fuel logs and final fiber output balances at Amit Cot Fibres

Table 4: Primary Data Sources used in Assessment

4.2 Secondary Data Collection

Secondary research references were derived from Textile Exchange Life Cycle Assessment report (2026) for global warming potential and blue water consumption and Better Cotton Initiative (BCI) life cycle assessment report (2017) for primary energy consumption, exclusively to establish the Conventional Baseline (Business-As-Usual) scenario for regional comparison. As the BCI study reports primary energy consumption per ton of seed cotton produced at the farm gate, the inventory data were first converted to a per kilogram of seed cotton basis and subsequently adjusted using the applicable ginning ratio to align with the functional unit of 1 kg of cotton lint at the gin gate adopted in this assessment.

In the absence of primary farm-level data on irrigation water consumption, blue water use was estimated using field data on irrigation practices together with pump efficiency assumptions obtained from the Bureau of Energy Efficiency (BEE)4. This approach enabled the estimation of irrigation water consumption consistent with the study's system boundary and functional unit.

4.3 Sampling Methodology

The target data model captures an active agricultural program composed of approximately 1,200 participating project farmers associated with the production of nearly 3,000 Kasturi cotton bales. To construct a statistically robust inventory without evaluating the entire population, a representative field sample framework was designed using cluster and stratified random sampling of 250 farmers with 5-6% buffer across regional village nodes.

The sampling approach was designed to ensure representative coverage of varying cultivation practices, irrigation conditions, and regenerative agricultural interventions across the assessed cotton production systems.

Initially, farmers were categorized into two primary operational clusters:

- Regenerative Kasturi Cotton farmers
- Biochar-Enhanced Regenerative Kasturi Cotton farmers (Project 2) and

The regenerative agriculture farmers, i.e. non-biochar farmer category, was further stratified into cohorts to isolate moisture delivery energy dynamics:

- Irrigated and
- Non-irrigated farming systems.

Subsequently, stratified sampling was conducted across villages to capture geographic and operational variability within the study area and improved representativeness of collected inventory data.

The finalized distribution of evaluated project farmers consists of 264 primary data profiles, detailed in Table 5:

Operational Farmer Cluster	Moisture Management Profile	Validated Active Sample Size (n)	Percentage of Total Sample
Regenerative Interventions	Irrigated (Groundwater Pump Dependent)	240	90.91%
Regenerative Interventions	Rainfed (Strictly Non-Irrigated)	4	1.51%
Biochar-Enhanced	Hybrid Managed / Pilot	20	7.58%
Interventions	Plots		
Total Evalution Sample	**Cross-Regional Supply Cohort**	**264**	**100.00%**

Table 5: The distribution of participating farmers included within the assessment

[4] https://beeindia.gov.in/sites/default/files/4Ch7.pdf

4.4 Carbon Footprint Calculation Methodology

Carbon footprint calculations were performed using activity-based emission estimation approaches in accordance with ISO 14040:2006, ISO 14044:2006, and ISO 14067:2018 requirements. Activity data collected from participating farmers and ginnery operations was multiplied with corresponding emission factors to estimate greenhouse gas emissions associated with cultivation, irrigation, transportation, ginnery, and biochar-related activities.

4.4.1 Fertilizer Emission Calculations

Fertilizer-related emissions were calculated using fertilizer application quantities and corresponding emission factors applied for individual fertilizer types. Nutrient composition assumptions were utilized for derivation of nitrogen (N), phosphorus (P), and potassium (K) quantities from reported fertilizer application data.

The generalized fertilizer emission calculation approach adopted within the assessment is represented below:

Fertilizer Emissions (kg CO2e)
= Total Fertilizer Quantity Applied (kg) × Emission Factor

Fertilizer Emissions (kg CO2e)
= Total Fertilizer Quantity Used (kg) × Emission Factor

In order to account for both the embedded emissions and post application emissions, the fertilizer emissions were calculated as per the emission factors of both the parameters.

4.4.2 Agrochemical Emission Calculations

Agrochemical-related emissions were calculated using reported agrochemical application quantities and corresponding emission factors applied for herbicides, insecticides, and fungicides utilized within the cultivation systems.

Agrochemical Emissions (kg CO2e)
= Total Agrochemical Quantity Applied (kg) × Emission Factor

4.4.3 Irrigation & Energy Emission Calculations

Irrigation and energy-related emissions were calculated using electricity consumption, diesel consumption, pump operational parameters, and corresponding electricity and fuel emission factors adopted within the assessment methodology. Irrigation-related electricity consumption was estimated using farmer-reported pump specifications, pump operating duration, pump depth, and standardized engineering assumptions where direct electricity metering data were unavailable.

➢ Electricity-related emissions from irrigational pumps were estimated using:

Electricity Emissions (kg CO2e)
= Total Electricity Consumption (kg) × Electricity Emission Factor

➢ Fuel-related emissions from agricultural machineries were estimated using:

Fuel Emissions (kg CO2e)
= Total Fuel Consumption (kg) × Fuel Emission Factor

4.4.4 Transportation Emission Calculations

Transportation-related emissions associated with movement of harvested cotton to ginnery facilities were calculated using transportation distance, vehicle fuel consumption, and corresponding diesel emission factors.

Transport Emission
= Total Distance/Truck Average × Electric Emission Factor

4.4.5 Ginnery Emission Calculations

Primary cotton processing emissions were calculated using operational data collected from Amit Cot Fibres, including electricity consumption, diesel consumption, plastic usage, and khol (cotton cloth material for Bale wrap)) bag consumption. Grid electricity emissions were estimated using applicable electricity emission factors, while solar electricity generation was tracked separately within the energy inventory. Environmental burdens associated with ginnery operations were subsequently allocated between cotton lint and cottonseed using the mass-economic allocation methodology described in Section 3.6.

➢ Grid-energy emissions were estimated using:

Grid Emissions (kg CO2e)
= Total Grid energy Consumption per kg of lint × Electric Emission Factor

➢ Fuel-related emissions were estimated using:

Fuel Emissions (kg CO2e) =
Fuel Consumption (L) × Fuel Emission Factor

➢ Plastic-related emissions were estimated using:

Plastic Emissions (kg CO2e) =
Plastic Consumption (kg) × Plastic Emission Factor

➢ Khol-related emissions were estimated using:

Khol Emissions (kg CO2e) =
Khol Consumption (kg) × Khol Emission Factor

4.4.6 Biochar Emission Calculations

For selected biochar farmers, carbon accounting additionally incorporated biomass collection, biochar production, transportation, and field application activities. Biogenic carbon removals associated with biochar production and field application were quantified in accordance with ISO 14067:2018 requirements. Carbon removals were reported separately from life cycle greenhouse gas emissions and were not deducted from gross emissions during environmental impact reporting.

➢ The generalized stable carbon estimation approach adopted within the assessment is represented below:

Stable Carbon Stored (kg CO2e) = (Biochar Mass Applied in kg
× Permanence Factor × Stable Carbon to Gross Atmospheric tCO2e) / 1000

4.4.7 Total Carbon Footprint Calculations

The total carbon footprint associated with the assessed cultivation systems was estimated through aggregation of emissions associated with all included activities within the defined system boundary.

$$\text{Total Carbon Footprint} = \sum \text{Emissions from Included Activities}$$

4.4.8 Carbon Footprint per kg of Cotton Lint

The carbon footprint per kilogram of cotton lint was calculated by normalizing total greenhouse gas emissions associated with each assessed cultivation system against cotton output quantities derived for participating farmers.

Cotton lint quantities derived using ginnery output percentage data were utilized for estimation of carbon footprint intensity per kilogram of cotton lint produced within the assessment boundary

The generalized calculation approach adopted within the assessment is represented below:

- Farm emissions were estimated using:

$$\text{Carbon Footprint per kg Cotton Lint} = \frac{\text{Total Carbon Footprint}}{\text{Cotton Lint Output Quantity}}$$

- Ginner emissions were estimated using:

$$\text{Carbon Footprint per kg Cotton Lint} = \frac{\text{Total Carbon Footprint}}{\text{Total Cotton Lint Output Quantity at Ginnery level}}$$

4.5 Water Footprint Calculation Methodology

Water footprint calculations were performed to evaluate the direct net consumptive water utilization across the defined cradle-to-ginner end gate system boundary. In accordance with the study's scope, the assessment models the consumption of "Blue Water" (fresh surface or groundwater extraction used for irrigation or processing) and explicitly accounts for the distinct moisture delivery profiles of the participating farm cohorts.

The mathematical equations and structural modeling approaches applied across each process step are defined below:

The assessment considered water consumption associated with:

- Irrigation activities during cotton cultivation
- Water utilization during ginnery operations
- Biochar-related operational activities where applicable

4.5.1 Irrigation Water Consumption Calculations

For the Kasturi regenerative irrigated farmers, direct field water application represents the primary resource draw. In the absence of primary direct-flow meters on agricultural pumps, the total volumetric water consumption (m3) extracted from groundwater aquifers was derived using standard fluid mechanics and engineering pump efficiency parameters based on pump horsepower ratings, pump depth and field runtime records:

$$\text{Irrigation Pump Electricity Consumption} = \frac{(\text{Pump Capacity} \times 0.746) \times \text{Pump Usage Duration}}{0.7\ (\text{Assumed Pump Efficiency})}$$

Where:

- 0.746 represents the conversion factor from horsepower (HP) to kilowatts (kW)[5]
- 0.7 represents the assumed pump efficiency[6]

Subsequently, irrigation water pumped was estimated using electricity consumption, pump efficiency & pump depth parameters based on the following generalized calculation approach:

$$\text{Water Pumped (m3)} = \frac{365 \times \text{Pump Capacity (HP)} \times 0.746 \times 0.7 \times \text{Pump Usage Duration (hrs)}}{\text{Pump Depth (m)}}$$

Where:

- 365 is the standard metric conversion constant used in hydraulic calculations to determine pump or turbine power in kilowatts (kW).[7]

[5] https://www.scribd.com/document/413734158/Hydraulic-Conversion-Chart

[6] https://beeindia.gov.in/sites/default/files/4Ch7.pdf

[7] https://www.powderprocess.net/Tools_html/Pumps/Tools_Pump_Power.html

4.5.2 Biochar Quenching Water Consumption

For the specialized subset of 20 pilot farmers integrating soil carbon-stabilization protocols, the water footprint incorporates the direct consumption of water used to cool and quench incandescent biochar. This step immediately follows the thermochemical pyrolysis phase inside the artisanal earth cone pits to halt active combustion:

Biochar Quenching Water (L)
= Total Biochar Produced (kg) x Quenching Factor (L/kg biochar)

Where the quenching factor is tracked as a controlled operational parameter averaging 1.5 Liters of fresh water per kilogram of dry biochar generated. Because this direct waterquenching interaction yields negligible wastewater discharge due to instantaneous vaporization and retention, it is modelled strictly as a 100% consumptive resource use.

4.5.3 Ginnery Processing Water Consumption

Industrial water consumption at the primary processing gate of Amit Cot Fibres accounts for the water utilized for industrial humidification, fiber conditioning, and localized facility maintenance during active mechanical ginning. Consumptive processing water is calculated based on daily processing logs and raw cotton throughput.

4.5.4 Total Supply Chain Water Footprint

The total cumulative water footprint is determined through the mathematical aggregation of all direct operational consumption parameters across the lifecycle stages:

Water Consumption for Regenerative Kasturi Cotton (overall project)
= Total water consumed (L) / Total cotton production (kg)

Water Consumption for Regenerative Kasturi Cotton with Biochar (project 2)
= Total water consumed (L) / Total cotton production (kg)

To establish the relative water footprint intensity matching the chosen functional unit, this total volumetric value is calculated against the final allocated cotton lint output mass derived through ginnery mass-economic allocation percentages:

Blue Water Consumption (L/kg lint) = Water Consumption for Regenerative Kasturi Cotton (overall project) x Ginnery Lint conversion ratio

Blue Water Consumption (L/kg lint) = Water Consumption for Regenerative Kasturi Cotton with Biochar (project 2) x Ginnery Lint conversion ratio

Thereafter, it is further calculated as per the economic value of cotton lint and cotton seed, as our allocation approach is mass-economic allocation. Below is the calculation done to identify blue water consumption based on economic values provided by the project ginner.

Formula:

= (2056.55+0.002) x (economic value of cotton lint x 0.34) / ((economic value of cotton lint x 0.34) + (economic value of cotton seed x 0.66))

Where,

2056.55 = represents mass allocated blue water consumption of all farmers
0.002 = represents mass allocated blue water consumption of ginner
0.34 = represents the percentage of lint extracted from 1kg of seed cotton
0.66 = represents the percentage of seed extracted from 1kg of seed cotton

Energy Footprint Calculation Methodology

Energy footprint calculations were performed to evaluate the cumulative primary and operational energy utilization across the defined cradle-to-ginner end gate system boundary. In accordance with the study's scope, the assessment models the consumption of direct thermal energy from liquid fossil fuels, electrical utility inputs from the regional grid, and self-generated zero-emission renewable energy source. The mathematical equations and structural modeling approaches applied across each process step are defined below.

4.5.5 Irrigation Energy Consumption Calculations for electricity

The resulting electrical consumption as mentioned in Section 4.5, sub-section 4.5.1., was converted into primary energy units using the standard energy equivalent conversion factor for electricity:

Irrigational Electrical Energy Demand (MJ)
= Pump Electricity Consumption (kWh) x 3.6 MJ/kWh

For solar-powered irrigation pumps integrated within the project scenario, the operational electrical energy requirements were calculated identically but tracked separately under the renewable energy matrix to isolate fossil-fuel displacement metrics.

4.5.6 Irrigation Energy Consumption Calculations for fossil fuels

Thermal energy consumption from liquid fossil fuels during field-level cultivation activities was determined using direct volumetric fuel usage logs reported by participating farmers. The assessment aggregates fuel consumption associated with mechanized operations, including:

- Tillage activities
- Ploughing activities
- Rotavator operations
- Knapsack operations

The volumetric diesel consumption (L) was converted to primary thermal energy equivalents using a standard lower heating value (LHV) calorific constant of 43.676 MJ/L for diesel fuel:

Field Operational Fuel Energy (MJ)
= ∑ Fuel used in Agricultural Operations (L) x 43.676 MJ/kWh

4.5.7 Transportation Energy Consumption Calculations

Logistical energy consumption covers the inbound transport of harvested seed cotton (Kapas) from individual farm gates to the centralized processing facility. Where primary logistics fuel records were unavailable, transportation fuel requirements were derived using transit distances combined with vehicle payload classes (Tractor/Truck) and localized transit efficiencies:

Transportation Energy Demand (MJ)
= Derived Transport Fuel Volume (L) x 43.676 MJ/L

4.5.8 Ginnery Energy Consumption Calculations

Operational energy consumption associated with primary industrial processing was modeled using utility tracking sheets collected from the processing lines of Amit Cot Fibres. Because the ginnery operates a clean-tech hybrid matrix using an on-site solar PV plant under a net-metering setup, total electrical energy requirements are evaluated by isolating the respective loads of renewable solar generation and supplemental utility grid consumption:

Total Ginnery Electricity Demand (MJ) = (Grid Power Consumed [kWh] + Solar PV Power Consumed kWh × 3.6 MJ/kWh

Auxiliary thermal energy consumed during internal ginnery material handling is calculated using loader diesel tracking records:

Ginnery Auxiliary Fuel Energy (MJ) = Loader Diesel Consumed (L) × 43.676 MJ/L

4.5.9 Total Supply Chain Energy Footprint

The primary energy consumption associated with each value chain scenario represents the cumulative mathematical sum of all electrical and thermal primary energy demands generated within the system boundary.

Further, each value chain scenario was divided by total cotton production and multiplied with the ginning ratio to derive Primary Energy Consumption per kg of cotton lint based on mass allocation. After that the following calculation was conducted for economic allocation to conclude to the actual primary energy consumption:

Formula:

= 5.24 x (economic value of cotton lint x 0.34) / ((economic value of cotton lint x 0.34) + (economic value of cotton seed x 0.66))

Where,

5.24 = represents the sum of all mass-based energy consumption per kg of cotton lint
0.34 = represents the percentage of lint extracted from 1kg of seed cotton
0.66 = represents the percentage of seed extracted from 1kg of seed cotton

The same calculation was used to calculate the economic allocation results of the Regenerative Kasturi Cotton with Biochar (Project 2), where the total production of seed cotton by the 20 project farmers was considered for calculations.

4.6 Biochar and Biogenic Carbon Accounting Methodology

For the specialized pilot sub-cohort of 20 project farmers participating in biochar application, biogenic carbon removals were quantified separately from product greenhouse gas emissions in accordance with the reporting principles of ISO 14067:2018. The estimation of long-term carbon storage followed the requirements of the Global Artisan C-Sink Standard by Carbon Standards International. Carbon removals were reported independently of operational life-cycle emissions to avoid double counting and to distinguish product emissions from long-term carbon sequestration.

The biogenic carbon extraction, conversion efficiencies, and long-term storage permanence are modelled sequentially using the following calculation steps:

4.6.1 Biomass Feedstock Allocation and Biochar Pyrolysis Yields

Residual cotton stalk biomass collected from participating farms was recorded as the gross dry biomass input. Biochar production was estimated to use the measured conversion efficiency of the artisanal earth-cone pit pyrolysis system using Global C-Sink Registry standard:

$$\text{Biochar Yield Produced (kg)} = \text{Gross Dry Biomass Feedstock (kg)} \times \text{Pyrolysis Conversion Factor (\%)}$$

where the project-specific pyrolysis conversion factor ranged from 30-35%, based on observed operational performance.

4.6.2 Biochar Carbon Quantification

The mass of stable carbon contained within the produced biochar was estimated from the biochar yield and measured carbon content.

$$\text{Carbon Stored (kg C)} = \text{Biochar Yield (in kg)} \times \text{Permanence Factor} \times C_{organic}$$

Where,

$C_{organic}$ represents the measured organic carbon content of the produced biochar.

For qualifying soil-applied biochar, the Global Artisan C-Sink Standard conservatively assigns 75% of the carbon to the Persistent Aromatic Carbon (PAC) fraction and 25% to the Semi-Persistent Carbon (SPC) fraction. The PAC fraction represents long-term carbon storage, whereas the SPC fraction is treated using the persistence functions prescribed by the project methodology.

4.6.3 Conversion to Atmospheric Carbon Dioxide Equivalent

The quantified carbon stored in biochar was converted to carbon dioxide equivalent using the molecular weight ratio of carbon dioxide to carbon (44/12 = 3.67):

$$\text{Stable Carbon Stored } (tCO_2e) = (\text{Carbon Stored (kg C)} \times 3.67)/1000$$

Where, the carbon stored corresponds to the stable carbon retained in biochar under the project methodology.

4.6.3 Isolation and Protection of Sequestration Credits

Biochar-related carbon removals were quantified exclusively for the subset of 20 pilot farmers practicing biochar application. These removals were reported separately from the product life cycle greenhouse gas emissions and were not averaged across the broader regenerative farmer population. Accordingly, the quantified removals are presented as an additional climate benefit associated with biochar application and are not deducted from the reported product carbon footprint, consistent with the reporting principles of ISO 14067:2018.

4.7 Assumptions and Limitations

The quantitative modeling of the Life Cycle Inventory (LCI) incorporates specific localized operational assumptions, engineering defaults, and technical boundary parameters. These methodological assumptions are necessary under ISO 14044 to ensure calculation transparency and mathematical consistency across the cradle-to-gate boundary where direct, continuous volumetric meters were unavailable.

The structural assumptions and constants applied across the calculation models are systematically aggregated in *Table 6*:

Table 6: Assumptions & Limitations Considered in the Assessment

Parameter	Description	Source
Pump Efficiency Assumptions	A conservative pump efficiency value of 0.7 was assumed for irrigation - related electricity and water consumption calculations	Standard baseline engineering default applied for hydraulic calculations [8]
Conventional Data on Farming	The baseline data for cotton farming was derived from secondary research references. The data set from Textile Exchange Life Cycle Assessment Report 2026 was considered for global warming potential and blue water consumption, where blue water consumption unit was harmonized as per our study unit as mentioned in Section 4.7, sub section 4.7.2. Also, the data set from Better Cotton Initiative LCA report 2017 was used for primary energy consumption, where the system boundary was harmonized as per our LCA study, and the calculations are mentioned in Section 4.7, sub-section 4.7.1	Textile Exchange Life Cycle Assessment Report 2026 and Better Cotton Initiative Life Cycle Assessment report, 2017 and conventional Cotton 9[10]
Biochar Yield Assumption	Biochar yield was assumed to range between 30-35% of biomass feedstock quantity and conversion factor was adopted for calculations	Derived directly from field pyrolytic operational tracking data
Biochar Permanence Factor	Biochar permanence was assumed to range between 74%-75% of the carbon in the soil matrix over a 100-year horizon	Based on Comparative Analysis of Biochar Carbon Stability Methods and Implications for Carbon Credits (Sirjana & Moon; Adhikari; Ellen & Paz-Ferreiro; Jorge & Timms; Wendy et al., 2023) [11]
Ginnery Water Consumption Assumption	Ginnery water consumption was estimated using an average reported operational range of 40,000 L for the entire season	Derived directly from centralized ginner facility logs
Secondary Emission Factors	Secondary emission factors and reference datasets were utilized for carbon footprint calculations where required	CBAM Default factor 2025 / DEFRA 2025 / Ecoinvent 3.12 / CEA v21.0 / UNFCCC / Ademe v17.0 / IPCC 2019 guidelines to refinement from 2006 guidelines
Derived Irrigation Calculations	Irrigation water consumption and electricity consumption were estimated using pump operational parameters and standardized assumptions	Hydrodynamically computed from capacity (HP) and runtime duration [12] [13]
Farmer-Reported Activity Data	Several cultivation, transportation, and operational parameters were based on farmer-reported activity data collected during field-level surveys	Based on field application data

[8] https://beeindia.gov.in/sites/default/files/4Ch7.pdf

[9] https://link.springer.com/chapter/10.1007/978-3-319-66981-6_8

[10] https://textileexchange.org/knowledge-center/reports/cotton-life-cycle-assessment

[11] https://www.sciencedirect.com/science/article/pii/S0048969723082372

[12] https://www.powderprocess.net/Tools_html/Pumps/Tools_Pump_Power.html

[13] https://www.scribd.com/document/413734158/Hydraulic-Conversion-Chart

4.7.1 Study Limitations and Scope Boundaries

While this assessment relies on high-resolution primary foreground data collected from 264 field inventories, several systemic boundaries and limitations must be acknowledged when interpreting the final environmental indicators:

- **Logistics Fuel Derivations:** Where primary transportation fuel logs were not available, vehicle diesel consumption was calculated based on distance covered (point-to-point) and vehicle average.

- **Regional Micro-Climate Variances:** On-farm activity data, chemical fertilizer behaviors, irrigation frequencies, and average crop yields are intrinsically subject to seasonal variations. The metrics quantified in this report reflect the specific agroecological conditions of the 2025-2026 crop cycle within the Jalgaon district of Maharashtra.

- **Data Completeness Boundaries:** In strict alignment with the direct operational focus detailed in Section 3.2, this inventory excludes upstream capital equipment infrastructure footprints. The results must be interpreted strictly within these direct cradle-to-ginnery end gate operational boundaries.

4.7.2 Conventional Cultivation Baseline Assumptions

To establish a rigorous comparative benchmark against the project scenario for global warming potential and blue water consumption, data set derived from Textile Exchange Life Cycle Assessment 2026 report was used.

However, due to the inconsistency of unit for blue water consumption in reference document which is in kg water/kg fibre, the harmonization was done according to the unit used for our LCA study, which is m3/kg lint. Hence, the calculation is described below:

Formula:

Water Consumption (m3/kg lint) = Water consumption in kg water per kg fibre/1000

Where,

1000 represents the standard value for the universal standard density of pure water at room temperature [14]

Furthermore, to compare the project's primary energy consumption, the conventional data from the Better Cotton Initiative Life Cycle Assessment report 2017 was considered after harmonizing the project boundary.

Furthermore, to compare the project's primary energy consumption, the conventional data from the Better Cotton Initiative Life Cycle Assessment report 2017 was considered after harmonizing the project boundary.

Harmonization for Primary Energy Consumption:

Formula:

Primary Energy Consumption (1 kg seed cotton)

5375 MJ (1 ton seed cotton) = 5375 / 1000 = 5.375 MJ / kg seed cotton

[14] https://stickmanphysics.com/density-of-fluids/

Then,

Primary Energy Consumption (1 kg lint cotton)

5.375 MJ (1 ton seed cotton) = 5.375 x 2.95 (project ginner ratio) = 15.86 MJ / kg lint

Assuming same allocation and ginnery consumption,

Formula:

mass-based energy consumption x (economic value of cotton lint x 0.34) / ((economic value of cotton lint x 0.34) + (economic value of cotton seed x 0.66))
= 15.86 x 0.67

= 10.67 MJ/kg lint

Where,

0.34 = represents the percentage of lint extracted from 1kg of seed cotton
0.66 = represents the percentage of seed extracted from 1kg of seed cotton
0.67 = represents mass-economic allocation of lint cotton

Finally,

Cradle-to-Ginnery end Gate Primary Energy Consumption
10.67 + 0.29 MJ/kg lint (primary energy consumption of ginnery) = 10.96 MJ/kg lint

Inventory Context: This reference establishes the standard "Business-As-Usual" agricultural dataset for India, characterized by unmitigated flood irrigation regimes, multi-pass intensive mechanical tillage, and high applications of synthetic crop inputs (including Urea, DAP, and Ammonium Nitrate) with zero structural crop residue recycling.

4.8 Data Quality Assessment

A rigorous Data Quality Assessment (DQA) was conducted to evaluate the reliability, completeness, and representativeness of the Life Cycle Inventory (LCI) dataset. In accordance with ISO 14044 requirements, the assessment systematically checks the dataset across five core metrics to validate that the final environmental indicators are mathematically sound and legally compliant.

4.8.1 Temporal Representativeness

The primary activity inventory collected from participating project farmers (n = 264) and processing lines at Amit Cot Fibres reflects the exact operational parameters of the 2025–2026 agricultural crop cycle. This ensures that contemporary field management practices, energy grids, and manufacturing input behaviours are accurately represented. All secondary emission factors were selected from updated databases (DEFRA, Ecoinvent, and the Central Electricity Authority) to match this operational timeframe.

4.8.2 Geographical Representativeness

The physical boundaries of this study are perfectly aligned with its geographical scope. Primary field-level data points were gathered directly from verified cotton-growing zones within the Jalgaon district region of Maharashtra, India. This localized boundary ensures that the data accurately reflects the specific soil typologies (loam profiles), localized semi-arid micro-climates, monsoon dependency curves, and regional agricultural logistics networks of the target supply chain.

4.8.3 Technological Representativeness

The inventory parameters directly mirror the real-world operational technologies utilized across the supply chain:

- **Cultivation Stage:** Captures the exact shift from intensive baseline synthetic applications to conservation tillage and heavy organic Farm Yard Manure (FYM) soil applications.
- **Irrigation Stage:** Explicitly models the power capacities (HP) and runtimes of electric and solar-powered groundwater pumps.
- **Biochar Pilot Loop:** Models the direct thermochemical parameters of localized artisanal earth cone pits operating at verified firing temperatures ranging from 600 to 700 degree Celsius.
- **Processing Stage:** Directly accounts for the mechanical ginning operations at Amit Cot Fibres, specifically distinguishing between the zero-emission solar PV generation and municipal grid load balancing under the active net-metering setup.

4.8.4 Completeness and System Closure

The cradle-to-ginner end gate operational boundary achieves mass and energy closure in compliance with the established 1% cut-off criteria. Primary data was successfully secured for most of the parts, and where data collection was not possible, certain assumptions were considered. This includes tracking complete chemical input quantities (Urea, DAP, NPK complex formats, SSP, MOP), organic additions, direct field diesel use, farm-to-ginnery transport distances, ginnery utility meter records, bale packaging material weights, and the exact by-product mass outputs (cotton lint, cotton seed and trash).

4.8.5 Data Consistency and Reliability

To maximize data reliability, primary field information was gathered using a combination of face-to-face farmer interviews, input receipt audits, and digitized factory ledger sheets. Automated consistency checks were built into the calculation architecture to eliminate reporting errors. For example, irrigation water pumped volumes were cross verified against technical pump performance curves using the horsepower capacity and operational duration equation specified in Section 4.4.1.

The overall quality of the compiled lifecycle inventory dataset is considered robust, highly reliable, and fully appropriate for executing the subsequent environmental impact calculations.

5. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) translates the compiled material and energy flows into explicit environmental indicators. In alignment with the study's scope, the environmental impacts are evaluated across three core areas: Product Carbon Footprint (Global Warming Potential), Product Water Footprint, and Primary Energy Consumption.

The results compare the environmental performance of the Conventional Baseline System, Regenerative Agriculture System, and Biochar-Enhanced Regenerative Agriculture System using the common functional unit of 1 kg cotton lint at the ginnery gate.

5.1 Product Carbon Footprint Assessment

The carbon footprint intensity evaluates the lifecycle greenhouse gas (GHG) emissions associated with cultivation, transportation, and ginnery-stage activities normalized against the functional unit of 1 kg cotton lint at the ginnery gate. Biochar-related carbon removals are quantified and reported separately and are not deducted from the reported product carbon footprint:

Table 7: Comparison of Product Carbon Footprint (GWP)

Evaluated Farming System Scenario	Carbon Product Footprint Intensity (kg CO2 e / kg seed cotton produced at farm gate)
Regenerative Kasturi Project System (Overall Project)	1.92
Regenerative Kasturi with Bichar enhanced Project System	1.69*
Conventional Baseline Scenario	4.17

*A carbon sequestration potential of 0.67 Kg CO2e per Kg of cotton lint hasn't been factored here to adhere to the reporting methodology but essentially this group is insetting carbon into the farms and supply chains for brands thus creating a overall reduction potential of 75% in comparison to conventional farmers (At 1 Kg CO2e per kg of lint post CDR / sequestration accounting).
Note: The comparative data for global warming potential was derived from the Textile Exchange Life Cycle Assessment report, 2026.

Table 7A: Separate Reporting of Biochar Carbon Removals

Parameter	Value
Gross Biochar Carbon Removal (20 pilot farmers)	31.58 tCO_2e
Carbon Emissions from Biochar Production Process	1.98 tCO_2e
Net Biochar Carbon Removal	29.61 tCO_2e
Reporting approach	Reported separately; not deducted from product carbon footprint

Note: For Table, 7A Biochar carbon removals were quantified only for the subset of 20 pilot farmers participating in biochar production and application. The biochar carbon removals presented are disclosed separately as an additional climate benefit and have not been deducted from the reported product carbon footprint, in accordance with ISO 14067:2018.

With the production and application of biochar with 20 project farmers, net 29.61 tCO2e is sequestered within the current Kasturi regenerative cotton value chain. Thus, reducing the climate impact of the cotton value chain in the project scenario. This also creates opportunity for insetting emissions by the apparel brands to meet their commitments of net-zero goals.

5.1.1 Key Evaluated Insights and GWP Hotspot Analysis

- **Systemic Field Mitigation Outcomes:** The project's Regenerative Agriculture Interventions reduces the product carbon footprint to 1.92 kg CO_2e/kg lint through a combination of lower synthetic fertilizer dependency, improved nutrient management practices, and reduced cultivation-stage emissions. Although it is observed that most of the emissions come from fertilizers, insecticides, and fungicides in the project scenario, on which the regenerative Kasturi cotton farmers are working to reduce as part of the year-on-year project implementation plan.

- **Processing-Stage Contribution:** Ginnery operations contributed a relatively small proportion of the overall product carbon footprint of 0.088 kgCO2e, compared with cultivation-stage activities. The dominant greenhouse gas emission sources across all assessed systems were fertilizer-related emissions, irrigation energy requirements, and fuel consumption associated with cultivation and transportation activities. The incorporation of solar electricity within ginnery operations further reduced processing-stage emission intensity.

5.2 Product Water Footprint Assessment

The water footprint intensity evaluates the net consumptive utilization of Blue Water (fresh surface or groundwater extraction used for field irrigation or industrial processing) normalized against the functional unit of 1 kg of cotton lint at the Ginnery end gate. The cumulative operational calculations across the value chain scenarios are:

Table 8: Comparison of Blue Water Consumption

Evaluated Farming System Scenario	Blue Water Consumption Intensity (m3 / kg lint)
Kasturi Regenerative Project System (Overall Project)	1.38
Kasturi Regenerative with Biochar enhanced Project System	1.52
Conventional Baseline Scenario	3.17

Note: The comparative data for blue water consumption was derived from the Textile Exchange Life Cycle Assessment report, 2026.The Kasturi Regenerative with Biochar sub-cohort exhibits a comparatively higher blue water footprint of 1.52 m3/kg lint, because groundwater is additionally required for quenching biochar following the pyrolysis process. This additional process water contributes to the increase in blue water consumption for the biochar sub-cohort and should be interpreted as an operational requirement specific to biochar production rather than a difference in agricultural irrigation practices.

5.2.1 Key Evaluated Insights and Water Hotspot Analysis

- **Systemic Irrigation Aquifer Draws:** For the Project Scenario, the lifecycle water footprint intensity tracks at 1.38 m3/kg lint for the irrigated group of farmers. Where localized weather allows for seasonal rainfed cultivation, the non-irrigated group of farmers cuts extraction drastically to a minor consumption, showcasing a clear method for reducing regional water dependencies.

- **Ginner Industrial Draw Decoupling:** At the centralized gate managed by Amit Cot Fibres, processing water utilization is kept remarkably low, registering an overall facility volume of 0.002 L/kg lint. This confirms that industrial humidification and conditioning draw represents a negligible fraction of the textile chain's total lifecycle water profile, contributing a minor allocated intensity parameter across both project cohorts.

5.3 Primary Energy Consumption Assessment

The Primary Energy Consumption assessment evaluates the total lifecycle cumulative energy demand (CED) extracted from both renewable and non-renewable (fossil) resources. The calculation framework accounts for all cumulative value chain energy flows, including on-farm land preparation (ploughing, rotavator, tiller), irrigation pumping, inbound transport logistics, and centralized ginnery operations (loader diesel, grid utility draw, and solar PV balancing).

The primary energy consumption intensities across the evaluated scenarios are detailed in Table 9:

Table 9: Comparison of Primary Energy Consumption

Evaluated Farming System Scenario	Primary Energy Consumption Intensity (m3 / kg lint)
Kasturi Regenerative Project System (Overall Project)	3.53
Kasturi Regenerative with Biochar enhanced Project System	3.50
Conventional Baseline Scenario	10.96

Note: The BCI study considers a cradle-to-farm gate system boundary, whereas the present study considers a cradle-to-ginner end gate system boundary, including transportation of seed cotton to the ginnery and ginning operations. Therefore, as mentioned in Section 4, Sub section 4.7.2, the system boundary has been harmonized and the conversion to lint cotton has been carried out.

5.3.1 Key Evaluated Insights and Energy Hotspot Analysis

- **Agricultural Fuel Optimization and Cohort Variances:** The lower primary energy demand associated with regeneratively grown Kasturi cotton is attributable to differences in cultivation practices, machinery use, irrigation energy requirements, transportation activities, and input management relative to conventional production systems. Collectively, these regenerative management practices improve energy-use efficiency and reduce dependence on non-renewable energy sources, thereby lowering the overall primary energy footprint of cotton production.

- **Grid Electricity and Solar PV Array Integration:** Primary processing and pumping energy demands are successfully mitigated through clean-tech integration at the ginning facility.

6. Life Cycle Interpretation

6.1 Scenario Analysis

The Life Cycle Interpretation phase evaluates the comparative environmental performance of the assessed cotton cultivation and primary processing systems under multiple operational scenarios established within the study boundary. The interpretation was conducted in accordance with ISO 14040:2006, ISO 14044:2006, and ISO 14067:2018 requirements.

The assessment compares the environmental implications associated with four major operational scenarios representing different cultivation and processing conditions within the regional cotton value chain.

6.1.1 Scenario 1: Farm Energy Consumption entirely on Non-Renewable Resources

Under this scenario, all agricultural operations associated with cotton cultivation, including irrigation and field activities, were assumed to be fully dependent on dieselbased energy sources. The purpose of this scenario was to evaluate the environmental implications of complete reliance on fossil-fuel-driven agricultural systems.

The assessment estimated a carbon footprint of 1.98 $kgCO_2e$ per kg of cotton lint produced, representing the highest greenhouse gas emission intensity among all scenarios evaluated. The elevated emissions are primarily attributed to direct combustion of diesel fuel during cultivation activities and irrigation operations, which contribute substantially to fossil carbon emissions across the cotton value chain.

The results demonstrate the significant influence of energy sources on the environmental performance of cotton production systems. Dependence on diesel-powered operations increases the carbon intensity of cultivation and limits opportunities for decarbonization within the agricultural sector.

Conclusion: Although fossil fuel -powered systems provide operational flexibility and reliability, complete dependence on diesel is environmentally unfavorable due to its high greenhouse gas emissions and reliance on non-renewable energy resources. Therefore, this scenario is not considered suitable for long-term sustainable cotton production and climate mitigation objectives.

6.1.2 Scenario 2: Complete Dependence on Grid Electricity at the Ginnery

This scenario assumes that the ginnery facility operates entirely on electricity supplied from the regional grid without any contribution from renewable energy sources. The objective was to evaluate the environmental impact associated with conventional processing operations powered exclusively through grid electricity.

The analysis estimated a carbon footprint of 1.93 $kgCO_2e$ per kg of cotton lint produced. Although lower than the diesel-dependent agricultural scenario, emissions remain relatively high due to the carbon intensity of the regional electricity grid, which is largely supported by fossil-fuel-based power generation.

The results indicate that processing-stage electricity consumption contributes to the overall product carbon footprint; however, its influence remains lower than the impacts associated with cultivation-stage activities such as irrigation energy demand, fertilizer use, and field-level fuel consumption. The scenario highlights the importance of energy transition measures at the processing stage.

Conclusion: This scenario indicates that complete solar-powered ginnery operations can reduce the overall carbon footprint of cotton lint production by replacing grid electricity with renewable energy. The findings demonstrate the potential environmental benefits of renewable energy integration in cotton processing. However, the practical implementation of a fully solar-powered system would depend on factors such as solaravailability, storage capacity, financial feasibility, and operational requirements, which should be considered when interpreting the results. Refer Section 1, sub-section 1.3 for Amit Cot Fibres (project ginner) energy system to understand the current power management system.

6.1.3 Scenario 3: Complete Dependence on Rainfed Cultivation

Under this scenario, cotton cultivation was assumed to rely entirely on natural rainfall without supplemental irrigation. The scenario was developed to understand the environmental implications of eliminating irrigation-related energy consumption and groundwater extraction activities.

The assessment estimated a carbon footprint of 1.81 kgCO_2e per kg of cotton lint produced, representing the lowest greenhouse gas emission intensity among all scenarios evaluated. The reduced emissions are primarily attributable to the elimination of irrigation-related energy consumption and the associated reduction in fuel and electricity requirements.

The findings demonstrate the substantial contribution of irrigation activities to overall agricultural emissions. By removing irrigation-related inputs, the environmental performance of cotton cultivation improves considerably from a carbon perspective.

Conclusion: Although the rainfed scenario exhibits the lowest carbon footprint, complete dependence on rainfall may not be operationally feasible in regions characterized by variable rainfall patterns, seasonal droughts, and climatic uncertainty. Dependence solely on rainfall may also increase production risks and affect yield stability. Therefore, while environmentally advantageous, this scenario may not be suitable as a standalone cultivation strategy across all production regions.

6.1.4 Scenario 4: Complete Dependence on Solar Energy at the Ginnery

This scenario assumes that all electricity requirements of the ginnery facility are supplied through solar photovoltaic (PV) energy systems, assuming an in-built battery energy storage system within the facility where solar power can be used even after daylight hours. The objective was to evaluate the potential environmental benefits associated with complete renewable energy integration at the cotton processing stage.

The analysis estimated a carbon footprint of 1.88 kgCO_2e per kg of cotton lint produced. The reduction in emissions compared to the grid-powered scenario is primarily due to the displacement of fossil-fuel-based electricity through renewable solar energy generation.

The results confirm that renewable energy integration at the processing stage can contribute meaningfully to supply-chain decarbonization and reduce the overall environmental burden associated with cotton lint production.

Conclusion: This scenario indicates that complete solar-powered ginnery operations can reduce the overall carbon footprint of cotton lint production by replacing grid electricity with renewable energy. The findings demonstrate the potential environmental benefits of renewable energy integration in cotton processing. However, the practical implementation of a fully solar-powered system would depend on factors such as solar availability, storage capacity, financial feasibility, and operational requirements, which should be considered when interpreting the results. Refer Section 1, sub-section 1.3 for Amit Cot Fibres (project ginner) energy system to understand the current power management system.

6.1.5 Comparative Interpretation of Scenario Analysis

For scenario analysis, the same structure as per our LCA methodology was considered, i.e. 20 Biochar-Enhanced Regenerative Farmers and 244 Regenerative Agriculture Farmers.

The scenario analysis demonstrates that farm-level interventions exert a greater influence on environmental performance than processing-stage interventions.

The complete dependence on rainfed irrigation scenario results in the lowest carbon footprint impacts as 1.81 kgCO_2e/kg lint, while complete diesel dependence on farm scenario resulted in the highest impacts 1.98 kgCO_2e/kg lint.
These findings indicate that irrigation energy demand and field-level fuel consumption are the dominant drivers of lifecycle impacts within the assessed cotton production system.

6.1.6 Interpretation of Assessed Production Systems

A consolidated summary of the environmental performance of the assessed production systems is presented in Table 10.

Table 10: Summary of Environmental Performance of the Assessed Production Systems

Indicator	Conventional Baseline Agriculture	Regenerative Agriculture (Overall Project)	Regenerative Cotton with Biochar
Functional Unit	1 kg lint at ginnery end gate	1 kg lint at ginnery end gate	1 kg lint at ginnery end gate
Carbon Footprint ($kgCO_2e$ / kg lint)	4.17	1.92	1.69*
Blue Water Consumption (m3 / kg lint)	3.17	1.38	1.52
Primary Energy Consumption (MJ / kg lint)	10.96	3.53	3.50

**A carbon sequestration potential of 0.67 Kg CO2e per Kg of cotton lint hasn't been factored here to adhere to the reporting methodology but essentially this group is insetting carbon into the farms and supply chains for brands thus creating a overall reduction potential of 75% in comparison to conventional farmers (At 1 Kg CO2e per kg of lint post CDR / sequestration accounting).*

The comparative assessment indicates that regenerative agricultural practices substantially reduce greenhouse gas emissions and primary energy demand relative to the conventional baseline. Across all scenarios, it is observed that cultivation-stage activities remain the dominant contributors to lifecycle environmental impacts.

6.2 Uncertainty Analysis

Life Cycle Assessment results are inherently subject to uncertainty due to variations in field conditions, data collection practices, emission factor selection, and modelling assumptions. In accordance with ISO 14044:2006 requirements, an uncertainty assessment was conducted to evaluate the robustness of the calculated product carbon footprint and to quantify the potential influence of variability within the input dataset.

The uncertainty assessment was performed using a Monte Carlo Simulation approach. The simulation was designed to evaluate the sensitivity of the final product carbon footprint to uncertainties associated with both activity data and emission factors utilized within the assessment.

For the purpose of the simulation, uncertainty ranges were assigned to the key input parameters based on data quality considerations and source characteristics. Primary activity data collected directly from participating farmers and ginnery operations were assigned uncertainty ranges of 5-10%, reflecting the relatively high confidence associated with fieldcollected data. Emission factors obtained from secondary databases and published references were assigned an uncertainty range of 20% to account for potential variations associated with regional applicability, methodological differences, and database limitations.

A total of 5,000 simulation iterations were performed. During each iteration, input parameters were randomly varied within their defined uncertainty ranges, and the product carbon footprint was recalculated. The resulting distribution of outcomes was used to evaluate the statistical reliability of the assessment results.

The Monte Carlo analysis produced an average product carbon footprint of 1.81 $kgCO_2e$ per kg of cotton lint. The standard deviation of the simulated results was 0.072 $kgCO_2e$ per kg of cotton lint, indicating relatively limited variability across the simulation runs.

The 95% confidence interval ranged from 1.673 $kgCO_2e$/kg lint to 1.948 $kgCO_2e$/kg lint. This indicates that, with 95% confidence, the actual product carbon footprint is expected to fall within this range when considering the uncertainty associated with the underlying inventory data and emission factors.

The relatively narrow confidence interval demonstrates that the overall assessment results are robust and are not significantly influenced by reasonable variations in the input parameters. Although individual activity data and emission factors exhibit inherent uncertainty, the overall environmental conclusions of the study remain consistent across the simulated range of outcomes.

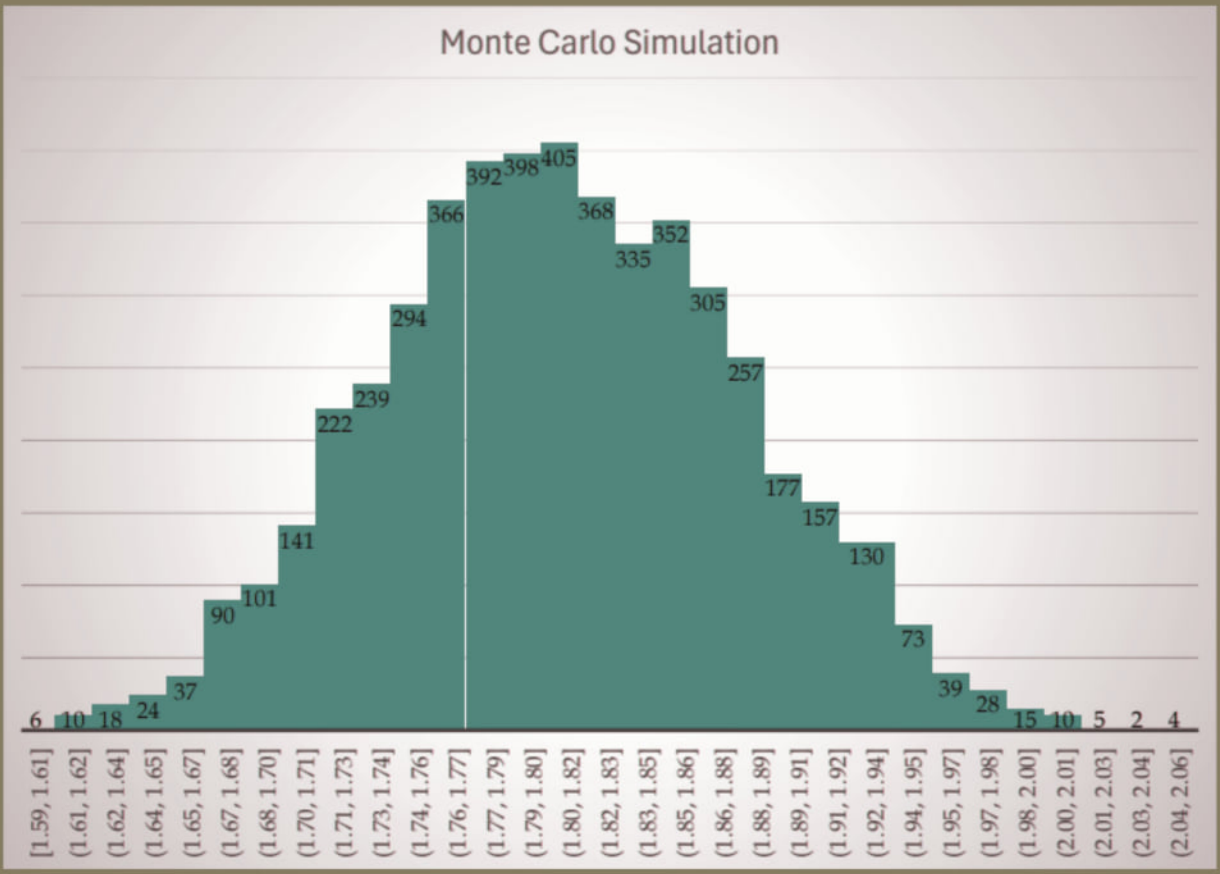
The uncertainty analysis therefore provides confidence that the comparative environmental performance observed across the assessed cultivation and processing systems is reliable and suitable for decision-making, sustainability reporting, and environmental performance evaluation.

Table 11: Monte Carlo Simulation Results

Parameter	Value
Monte Carlo Iterations	5,000
Primary Data Uncertainity	5 - 10%
Emission Factor Uncertainty	20%
Mean Carbon Footprint	1.81 kgCO_2e / kg lint
Standard Deviation	0.072 kgCO_2e / kg lint
95% CI Lower Bound	1.673 kgCO_2e / kg lint
95% CI Upper Bound	1.948 kgCO_2e / kg lint

The statistical summary of the Monte Carlo simulation results is presented in the table below.

Figure 5: Monte Carlo Simulation Distribution of Product Carbon Footprint



7. Conclusion

This Life Cycle Assessment provides a comprehensive environmental evaluation of regeneratively grown Kasturi Cotton produced in Jalgaon, Maharashtra, during the 2025 - 2026 cultivation season. Conducted in accordance with ISO 14040, ISO 14044, and ISO 14067, the study establishes a transparent and scientifically robust benchmark for assessing the environmental performance of regenerative cotton production in India.

The findings demonstrate that regenerative agricultural practices deliver measurable environmental benefits compared with conventional cotton production systems. Reductions in greenhouse gas emissions and primary energy demand highlight the effectiveness of improved nutrient management, optimized irrigation practices, renewable energy integration, and enhanced resource-use efficiency across the cotton value chain. Furthermore, the assessment confirms that integrating artisanal biochar production and field application within regenerative systems provides additional climate benefits through durable carbon sequestration while improving overall environmental performance.

The hotspot analysis identified cultivation-stage activities, particularly fertilizer application, irrigation energy requirements, and diesel consumption—as the dominant contributors to lifecycle environmental impacts. The scenario analysis further reinforces that farm-level interventions have a substantially greater influence on lifecycle emissions than downstream processing improvements. While renewable-powered ginning contributes additional emission reductions, strategies such as precision nutrient management, efficient irrigation, regenerative soil management, and renewable energy adoption at the farm level remain the most effective pathways for reducing the environmental footprint of cotton production.

The uncertainty assessment, based on 5,000 Monte Carlo simulations, demonstrates that the study findings are statistically robust. The narrow confidence intervals support the reliability of the comparative results despite the inherent variability associated with agricultural systems and the use of secondary emission factors.

Scientific Contribution

Based on information available in the public domain, this appears to be one of the first comprehensive Life Cycle Assessments of regeneratively grown Kasturi Cotton in India. The study therefore contributes valuable primary data to the growing evidence based on regenerative cotton production and establishes a benchmark for future environmental assessments.

The report is grounded in primary field data collected from actual production systems and therefore reflects on-ground farming practices rather than modelled assumptions. As such, the findings provide a practical reference for textile brands, regenerative sourcing programmes, policymakers, and supply chain stakeholders seeking to benchmark environmental performance and design climate-smart cotton sourcing strategies. The assessment also provides a credible scientific foundation for sustainability reporting, environmental product declarations, climate action strategies, and evidence-based decisionmaking across the textile value chain.

Opportunities for Further Improvement

The hotspot analysis highlights several opportunities to further reduce the environmental footprint of regenerative cotton production:

• Optimizing nitrogen fertilizer application through precision nutrient management, integrated nutrient management, and increased use of organic amendments can substantially reduce greenhouse gas emissions while maintaining crop productivity.

• Adoption of reduced or conservation tillage practices can further enhance soil carbon sequestration, improve soil health, and reduce fuel consumption associated with field operations.

• Transitioning irrigation pumps and other farm-level energy requirements to solarpowered systems can significantly reduce emissions associated with conventional electricity generation.

• Electrification of logistics and farm transport through the gradual adoption of electric vehicles (EVs) offers additional opportunities to reduce transportation-related greenhouse gas emissions.

• Wider integration of biochar produced from agricultural residues through pyrolysis under limited oxygen conditions can further stabilize soil carbon, improve soil fertility, and enhance long-term carbon storage. Under carbon accounting frameworks such as Carbon Standards International (CSI), biochar complements regenerative agricultural practices by supporting measurable carbon removal and creating significant opportunities for corporate carbon in setting programmes.

Limitations and Future Research

The absence of directly comparable LCA studies with equivalent system boundaries, functional units, geographical contexts, and production characteristics including sample size, irrigation conditions, and regenerative management practices, limits opportunities for benchmarking blue water consumption against published literature. The availability of Textile Exchange (2026) reference data enabled direct comparison of global warming potential and blue water consumption. However, comparable primary energy consumption data were unavailable for the selected functional unit and system boundary, necessitating the harmonization of data from the Better Cotton Initiative (BCI) LCA (2017).

The implementation of robust digital Monitoring, Reporting and Verification (dMRV) systems provides an important opportunity to enhance future Life Cycle Assessments through accurate, transparent, and verifiable primary data collection. Continued deployment of digital data systems will improve data quality, reduce uncertainty, strengthen environmental claims, and support reliable carbon accounting.

While this assessment represents a single cultivation season within a defined geographical boundary, it establishes a strong baseline for long-term environmental performance monitoring. Future assessments incorporating multi-season datasets, broader geographical representation, and additional impact categories including biodiversity, soil organic carbon dynamics, eutrophication, acidification, and water quality will further strengthen the scientific evidence supporting regenerative cotton systems and enable continuous improvement across sustainable textile supply chains.

Closing Statement

This report establishes a transparent, science-based performance benchmark for regeneratively grown Kasturi Cotton. By identifying key environmental hotspots and quantifying the climate mitigation benefits of regenerative agriculture, biochar application, soil carbon stabilization, and renewable energy adoption, the study provides robust evidence to support sustainable decision-making across the textile value chain.

Beyond quantifying environmental impacts, the assessment demonstrates the potential of regenerative cotton production to contribute to climate mitigation, resource efficiency, and resilient agricultural systems. The findings provide a strong foundation for regenerative sourcing programmes, corporate carbon in setting initiatives, sustainability reporting, and regional climate action strategies, while laying the groundwork for future Life Cycle Assessments that further advance the environmental performance of India's cotton sector.

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Glossary

Terms	Definitions
GHG	Greenhouse gas (GHG) emissions are gases that trap heat in the Earth's atmosphere, primarily comprising Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O).
SOC	Soil organic carbon (SOC) is the carbon component of soil organic matter. It acts as a foundational indicator of soil health, fertility, and structure.
LCA	Life Cycle Assessment (LCA) is a standardized, science-based methodology used to evaluate the environmental impacts of a product, process, or service across its entire lifespan; from raw material extraction to manufacturing, distribution, use, and final disposal.
Biochar	Biochar is a highly porous, carbon-rich charcoal produced by heating organic biomass (like crop residues, wood chips, or manure) in a low-oxygen environment, a process called pyrolysis. It is primarily used as a soil amendment to improve fertility, retain water, and sequester carbon.
Regenerative Agriculture	A holistic, outcomes-based ecosystem management strategy focused on restoring soil health, maximizing biodiversity, improving water retention, and enhancing biological carbon sequestration within the soil matrix.
Global Warming Potential	Global Warming Potential (GWP) is a standardized metric used to compare the heat-trapping ability of different greenhouse gases in the atmosphere relative to carbon dioxide (CO_2)
Blue Water Consumption	Blue water consumption refers to the use of freshwater from natural surface or groundwater bodies (rivers, lakes, aquifers) that is evaporated, transpired by plants, or incorporated into a product and thus does not return to its original source. It measures the actual depletion of regional water resources.
Kasturi Cotton	Kasturi Cotton Bharat is the program to brand the best of cotton that India has to offer. Cotton with staple lengths from 28 mm+ to Extra Long Staple cotton of 34 mm+ and 35 mm+ that meets predetermined benchmarks of quality will be tested at NABL Accredited Laboratories and certified as Kasturi Cotton.
Functional Unit	1 kg cotton lint at ginnery end gate
Conventional Agriculture	Conventional agriculture is a cropping system that uses synthetic chemicals that are used to maintain the plants. A significant amount of chemical & energy input is required in conventional agriculture to produce the highest possible yield of crops. "This method usually alters the natural environment, deteriorates soil quality and eliminates biodiversity."

Terms	Definitions
Biogenic Carbon Storage	Biogenic carbon storage refers to the natural or technological retention of carbon dioxide that plants and organic matter have absorbed from the atmosphere through photosynthesis.
ISO 14040	ISO 14040 is the leading international standard that outlines the foundational principles and framework for conducting a Life Cycle Assessment (LCA). It ensures environmental assessments are transparent, scientifically rigorous, and globally consistent.
ISO 14044	ISO 14044 is the international standard that specifies the detailed requirements and guidelines for conducting a Life Cycle Assessment (LCA). It dictates exactly how to measure the environmental impact of a product, service, or system across its entire life cycle; from raw material extraction to end-of-life disposal or recycling
ISO 14067	ISO 14067:2018 is the leading international standard for quantifying and reporting the carbon footprint of products (CFP). It tracks the total greenhouse gas (GHG) emissions measured in kilograms of CO_2e over a product's entire life cycle, from raw material extraction to disposal.
ISO 14071	ISO 14071 is an international standard that provides requirements and guidance for the critical review process of Life Cycle Assessment (LCA) studies. It specifies the required competencies for reviewers and ensures that environmental footprints and declarations are credible, transparent, and aligned with ISO 14040 and ISO 14044.
Monte Carlo Analysis	A statistical simulation technique used to evaluate the uncertainty and variability of LCA results by repeatedly running the model with randomly varied input parameters. It estimates the range and confidence of the results, helping assess their robustness and reliability.
CO_2e	Carbon dioxide equivalent is a standard unit of measurement used to express the total climate impact of all greenhouse gases combined. It converts the warming effects of different gases (like methane and nitrous oxide) into the equivalent amount of CO_2 that would cause the same global warming.
dMRV	dMRV is a system used in sustainability and carbon markets to track, record, and validate environmental impacts (like emissions reductions or carbon removal) in real-time using digital technologies like IoT sensors, AI, and satellite imagery.
Hotspot analysis	Hotspot analysis identifies the specific stages, materials, or unit processes within a product's value chain that disproportionately contribute to overall environmental impacts, such as carbon emissions, water use, or toxicity.
CSI	Carbon Standards International is a renowned registry that develops reliable solutions for the production of certified biochar and for delivering credible climate services.

Urea	Urea is an organic compound and waste product with the chemical formula $CO(NH_2)_2$
DAP	DAP most commonly refers to Diammonium Phosphate, the world's most widely used phosphorus fertilizer.
NPK	NPK stands for Nitrogen (N), Phosphorus (P), and Potassium (K), the three primary macronutrients essential for plant growth. These elements are the building blocks of most commercial plant foods and are displayed on packaging as a three-number ratio.
SSP	Single Super Phosphate (SSP) is a foundational, cost-effective phosphorus fertilizer. It typically contains 16% available P_2O_5, 11% to 12% sulfur, and around 21% calcium.
MOP	Muriate of Potash (MOP), chemically known as Potassium Chloride (KCl), is the most widely used potassium fertilizer in agriculture. It typically contains 60% water-soluble potash (K_2O), promoting healthy root development, disease resistance, and higher crop yields.
Monte Carlo Analysis	A statistical simulation technique used to evaluate the uncertainty and variability of LCA results by repeatedly running the model with randomly varied input parameters. It estimates the range and confidence of the results, helping assess their robustness and reliability.
Activity Data	Quantitative data describing the amount of material, energy, or activity responsible for environmental impacts (e.g., fertilizer applied, diesel consumed).
Allocation	The method used to distribute environmental burdens among multiple co-products. In this study, a mass-economic allocation approach was applied at the ginnery.
Baseline Scenario	The reference production system representing conventional cotton cultivation practices used for comparison.
Carbon Footprint	Total greenhouse gas emissions associated with a product, expressed as kg CO_2 equivalent.
Carbon Removal	The process of removing carbon dioxide from the atmosphere and storing it in stable reservoirs such as biochar-amended soils.
Carbon Sequestration	Long-term storage of atmospheric carbon in soils, vegetation, or other carbon sinks.
Co-product	A secondary valuable product generated during production. In this study, cottonseed is a co-product of cotton lint production.
Cradle-to Ginnery End Gate	System boundary covering all activities from raw material production through cotton cultivation, transportation, and ginning until cotton lint separation and preparation of bales and its packaging at the ginnery.
Cut-off Criteria	Rules defining which processes or materials can be excluded from the LCA because of their insignificant contribution.

Emission Factor	A coefficient used to estimate greenhouse gas emissions associated with a unit of activity (e.g., kg CO_2e per litre of diesel).
Functional Unit	The quantified reference unit against which all environmental impacts are reported. In this study, it is 1 kg of cotton lint at the ginnery end gate.
Farm Yard Manure (FYM)	Organic manure derived from livestock waste and crop residues used to improve soil fertility.
Ginnery	A processing facility where seed cotton is separated into cotton lint, cottonseed, and other co-products.
Hybrid Energy System	An energy system utilizing more than one source of electricity, such as grid electricity and solar photovoltaic power.
LCI	The phase of Life Cycle Assessment involves collection and quantification of material, energy, emissions, and resource inputs and outputs.
LCIA	Phase of LCA in which inventory results are translated into environmental impact indicators.
Mass-Economic Allocation	Allocation method combining both product mass and economic value for distributing environmental burdens among co-products.
Net Metering	A billing arrangement allowing electricity generated from solar panels to be exported to and imported from the utility grid.
PAC	The Persistent Aromatic Carbon is highly stable fraction of biochar that remains stored in soil over very long periods.
Primary Data	Data collected directly from farmers, transporters, and ginnery operations specifically for this study.
Quenching	Cooling freshly produced biochar with water to stop combustion after pyrolysis.
Pyrolysis	Thermal decomposition of biomass under oxygen-limited conditions to produce biochar, gases, and bio-oil.
Secondary Data	Published or existing datasets obtained from literature, databases, or previous studies.
SPC	The Semi-Persistent Carbon is a fraction of biochar carbon that gradually decomposes over time according to the applied methodology.
System Boundary	The processes and life cycle stages included within the assessment.
Uncertainty Analysis	Evaluation of the reliability and variability associated with calculated environmental impacts.
Project 2	A group of 20 farmers, within the study farmer population of 264, practicing regenerative agriculture along with biochar application on their farmland as a part of this project.

Critical Review Report

For the Life Cycle Assessment (LCA) of

1 kg of Regeneratively Grown Kasturi Cotton Lint,

Manufactured in the Jalgaon district region of Maharashtra, India.

Assessment Conducted by

Beetle Regen Solutions Pvt. Ltd.

Report Submitted to:

Beetle Regen Solutions Pvt. Ltd.

On-site data verification:

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CONTROLUNION

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Executive Summary

The final critical review of the Life Cycle Assessment of 1 kg of Regeneratively Grown Kasturi Cotton Lint produced by Beetle Regen Solutions Pvt. Ltd. was conducted by Control Union Inspections (Pvt) Ltd against the principles and requirements of ISO 14040:2006 and ISO 14044:2006. Since the assessment also includes product carbon footprint results and biochar-related carbon removals, the relevant principles of ISO 14067:2018 were also considered during the review.

The review focused on the adequacy of corrective actions taken against the initial critical review findings issued for the Kasturi cotton LCA. The revised documents reviewed included the Life Cycle Assessment Report on Regeneratively Grown Kasturi Cotton, Version 1.3 dated 04 July 2026, the revised calculation workbook, and the finalized critical review findings dated 26 June 2026.

The revised LCA report demonstrates substantial improvement in methodological consistency, calculation transparency, and reporting clarity. The functional unit is now clearly defined as 1 kg of cotton lint at ginnery gate, and the system boundary is consistently described as cradle-to-ginner gate, covering cultivation, irrigation, biochar activities, transportation, and ginning operations. The revised report also separates the cradle-to-ginner gate product result from the farm-gate comparison with the conventional BCI baseline, thereby addressing the initial boundary and comparison inconsistencies.

The review confirms that the major calculation-critical findings identified during the initial review have been addressed. These include corrections to fungicide unit conversion, biochar production unit conversion, functional unit normalization, diesel energy calculation, solar electricity treatment, cotton seed terminology, water result interpretation, and separation of biochar-related carbon removals from the gross product carbon footprint.

The revised report now presents the project scenario product carbon footprint as 1.92 kg CO_2e/kg lint at cradle-to-ginner gate, while the comparison with conventional cotton manufacturing in India as 4.17 kg CO_2e/kg lint at cradle-to-ginner gate. The ginner-stage carbon footprint is separately reported as 0.088 kg CO_2e/kg lint. The report also includes a Monte Carlo uncertainty analysis with 5,000 iterations, supporting the robustness of the reported product carbon footprint results.

The biochar carbon accounting methodology has also been strengthened. The revised report now includes clearer explanations on baseline counterfactual, permanence, decay, leakage, monitoring, uncertainty, reversibility, and separate reporting of carbon removals. This improves transparency and reduces the risk of misinterpretation between product-level greenhouse gas emissions and additional biochar-related climate benefits.

Overall, the corrective actions taken by Beetle Regen Solutions Pvt. Ltd. are considered satisfactory. The initial non-conformities and observations have been addressed to an acceptable level for finalization of the critical review. Minor remaining refinements, where applicable, are considered documentation and clarity improvements rather than calculation-critical issues.

Final critical review decision: The revised LCA report is accepted for critical review closure. The assessment is considered sufficiently transparent, methodologically consistent, and technically reliable for the stated goal and intended application, subject to maintaining the stated scope, assumptions, limitations, and claim boundaries in any future communication.

1. Introduction

This final critical review report is prepared for the Life Cycle Assessment of Regeneratively Grown Kasturi Cotton conducted by Beetle Regen Solutions Pvt. Ltd. The review has been conducted following the initial critical review findings issued for the Kasturi cotton LCA and the revised documents submitted by Beetle Regen Solutions.

The objective of the critical review is to determine whether the revised LCA report has taken the necessary corrective actions and whether the assessment is consistent with ISO 14040:2006 and ISO 14044:2006 in relation to goal and scope definition, inventory analysis, impact assessment, interpretation, and transparency of the final report.

Since the report also includes product carbon footprint results and biochar-related carbon removals, the relevant principles of ISO 14067:2018 were also considered, particularly in relation to separation of gross product emissions and carbon removals.

The following aspects were carefully examined:

- Goal and scope definition
- Life cycle inventory analysis
- Life cycle impact assessment
- Interpretation of results
- Final report consistency and transparency
- Closure status of initial review findings

2. Details of the Reviewers

The critical review was performed by:

- Piyumali Jayasundara, LCA Verifier / Lead Auditor, Control Union Inspections (Pvt) Ltd, specialized in Life Cycle Assessment, Chemical and Process Engineering, Energy Efficiency Improvement, and Process Data Analytics.

The onsite verification was performed by:

- Hrishabh Mishra, Senior Executive ESG, CU Inspections & Certifications India Pvt. Ltd.

3. Critical Reviewing Process

This critical review was conducted in accordance with ISO 14071:2024 guidance to verify that the LCA assessment adheres to the principles and requirements of ISO 14040 and ISO 14044. The review evaluated whether:

- The methods used to conduct the LCA are consistent with ISO 14044.
- The methods used are scientifically and technically valid.
- The data used are appropriate and reasonable in relation to the goal of the assessment.
- The interpretations reflect the limitations identified and the goal of the assessment.
- The final report is transparent, consistent, and not misleading to the intended audience.

The reviewer considered the following documents during the review process:

- Life Cycle Assessment Report on Regeneratively Grown Kasturi Cotton, Version 1.3, dated 04 July 2026;

- LCI calculation template 09072026_4883;
- Critical Review Findings – LCA – Regeneratively Grown Kasturi Cotton by Beetle Regen Solutions, dated 26 June 2026;
- Revised methodological descriptions, assumptions, and results included in the LCA report.

The closure assessment was performed by comparing the initial non-conformities against the revised final report and associated calculations. Each finding was classified as Addressed, mostly addressed, Partially addressed, or Not addressed based on the adequacy of corrective action and the remaining risk of misinterpretation.

4. Critical Review Findings

4.1 Goal and Scope Definition

As per ISO 14044:2006, the goal and scope of the LCA shall be clearly defined and consistent with the intended application. The review focused on the intended application, reason for carrying out the assessment, intended audience, product system, functional unit, system boundary, allocation approach, assumptions, limitations, and reporting format.

Non-Conformities Identified in the Initial Review

- The initial report included inconsistencies between cradle-to-ginner gate and cradle-to-farm gate comparisons.
- The conventional baseline was compared against project results using inconsistent boundaries.
- The functional unit and denominator used in some calculations were not consistently applied.
- The allocation approach was not adequately justified against the ISO 14044 allocation hierarchy.
- The report used strong or unsupported wording such as “verified baseline” without adequate evidence.
- The system boundary and exclusion statements required a clearer distinction between included operational input burdens and excluded capital infrastructure.

Adjustments Addressed in the Final Report

- ✓ The revised report clearly defines the functional unit as 1 kg of cotton lint at ginnery gate.
- ✓ The report now describes the system boundary as cradle-to-ginner gate, including cultivation, irrigation, biochar activities, transportation, and ginning operations.
- ✓ The revised report separates the cradle-to-ginner gate product result from the farm-gate comparison with the conventional BCI baseline.
- ✓ The farm-gate comparison is now presented using comparable boundary logic, with conventional cotton manufactured in India as 4.17 kg CO_2e/kg lint at cradle-to-ginner gate.
- ✓ The report now includes a more detailed explanation of biochar carbon removal accounting, including baseline counterfactual, permanence, decay, monitoring, leakage, uncertainty, and reversibility.
- ✓ The allocation section has been revised to state that allocation was avoided where possible and that mass-economic allocation was applied where required.
- ✓ System exclusions are clearly defined.

Comments

The goal and scope section has been substantially improved. The revised report is clearer than the initial version in distinguishing the project's cradle-to-ginner gate result from the conventional farm-gate baseline comparison, with properly mentioned allocation rules.

Conclusion: Addressed. The goal and scope definition is acceptable, subject to final harmonization of the independent review statement and fuller justification of the allocation hierarchy.

4.2 Life Cycle Inventory Analysis

The inventory phase of the LCA involves collection and quantification of inputs and outputs within the defined system boundary. The review focused on completeness, transparency, appropriateness of data aggregation, validity of calculations, and correct mapping between activity data and the functional unit.

Non-Conformities Identified in the Initial Review

- Fungicide values appeared to be treated as kg although inventory entries appeared to be recorded in grams.
- Biochar production data contained unit conversion errors.
- Functional unit normalization mixed seed cotton and cotton lint denominators.
- Transport fuel derivation was not transparent.
- Solar electricity was treated as zero without transparent recording of solar kWh.
- Cottonseed was included as an emission-generating activity without clarifying whether it referred to seed input or cottonseed co-product.
- Ginner water consumption basis was unclear.
- Wastewater was included in the system boundary but no treatment or disposal impact was calculated.
- Emission factors were sourced from broad databases, but source year, dataset, version, geography, and boundary coverage were not adequately disclosed.
- Data quality was overstated despite assumptions, missing data, and derived values.

Adjustments Addressed in the Final Report

- ✓ The fungicide unit issue has been corrected in the revised inventory. Fungicide values are now treated as grams/ml and converted to kg before applying emission factors.
- ✓ The biochar production unit error has been corrected. Cotton production values in the biochar sheet are now correctly converted from kg to MT.
- ✓ Farm and transport emissions are now converted to lint basis before being combined with ginner-stage emissions.
- ✓ The revised report records solar electricity consumption transparently and applies a zero operational emission factor.
- ✓ The cotton seed line has been clarified as cotton seed used for sowing, reducing ambiguity with cottonseed generated as a co-product during ginning.
- ✓ The diesel energy formula has been corrected using a lower heating value of 43.676 MJ/L.

- ✓ The report now includes more detailed assumptions for pump efficiency, quenching water, biochar yield, biochar permanence, conventional data, farmer-reported activity data, and derived irrigation calculations.
- ✓ The emission factor sources are identified, including DEFRA, Ecoinvent, CEA, CBAM, UNFCCC, ADEME, and IPCC. For improved reproducibility.

Comments

The revised inventory has addressed the most material calculation errors identified in the initial critical review. The corrections made to fungicide units, biochar production units, diesel energy conversion, and functional unit normalization are considered satisfactory. The inventory analysis has been substantially improved and further strengthening transparency and reproducibility. In addition, the data quality conclusion can be refined to better reflect the nature of the dataset, particularly where farmer-reported data, assumptions, or derived calculations were used. This will make the conclusion more balanced while maintaining confidence in the overall assessment.

Conclusion: Addressed. The main calculation-critical inventory findings have been corrected.

4.3 Life Cycle Impact Assessment

The purpose of this review stage was to verify the scientific and technical validity of the methods used in the Life Cycle Impact Assessment and to evaluate whether value choices, selected impact categories, characterization factors, assumptions, and exclusions were identified and justified.

Non-Conformities Identified in the Initial Review

- The initial report presented inconsistent carbon footprint baseline values.
- Some result tables and captions were incorrectly labelled.
- Water footprint interpretation contradicted the tabulated results.
- Scenario water results were inconsistent with the main LCIA results.
- The energy formula included incorrect unit treatment.
- Biochar removals were reported without sufficient methodology.
- The report did not clearly separate gross product emissions and carbon removals.
- “Primary energy” was reported, but the calculation was closer to direct operational energy demand.

Adjustments Addressed in the Final Report

- ✓ The initial conventional baseline inconsistency has been corrected.
- ✓ The report now separates cradle-to-ginner gate product carbon footprint from farm-gate comparison.
- ✓ The product carbon footprint is now reported as 1.92 kg CO_2e/kg lint for the project scenario at cradle-to-ginner gate.
- ✓ The ginner-stage carbon footprint is separately reported as 0.088 kg CO_2e/kg lint.
- ✓ Biochar carbon removals are separately reported and are not deducted from the gross product carbon footprint.
- ✓ Water footprint interpretation has been corrected. The report now identifies irrigation as the dominant driver of blue water consumption.
- ✓ The initial scenario water inconsistency has been removed.

- ✓ Energy calculation now uses the corrected diesel lower heating value.
- ✓ Monte Carlo uncertainty analysis has been included, using 5,000 iterations.

Comments

The impact assessment section has been technically strengthened, and the initial result inconsistencies have been largely corrected. The remaining points are mainly refinements to improve clarity, transparency, and claim robustness.

The report may further clarify whether the study is intended to represent a full multi-category LCA or a focused environmental indicator assessment covering Product Carbon Footprint, Blue Water Consumption, and Energy Consumption. The selected indicators are highly relevant to cotton cultivation and primary processing. However, for transparency, it is recommended to state that other potentially relevant impact categories, such as eutrophication, acidification, ecotoxicity, land use, particulate matter, water scarcity characterization, soil quality, and biodiversity impacts, are outside the current assessment scope.

Conclusion: Addressed. The LCIA result structure has improved, and major numerical inconsistencies have been corrected.

4.4 Interpretation of Results

The interpretation phase was reviewed to determine whether the findings are consistent with the goal and scope, reflect the assumptions and limitations of the assessment, and provide conclusions that are supported by the inventory and impact assessment results.

Non-Conformities Identified in the Initial Review

- ✓ The initial report made reduction claims that were not supported by the tabulated values.
- ✓ Boundary differences between conventional and project scenarios were not adequately addressed.
- ✓ Biochar water interpretation contradicted the result tables.
- ✓ Scenario results were inconsistent with the main LCIA results.
- ✓ Data quality was overstated.
- ✓ Monte Carlo chart readability was poor.
- ✓ References and emission factor documentation were incomplete.

Adjustments Addressed in the Final Report

- ✓ ✓ The revised interpretation now compares farm-gate project results with farm-gate conventional baseline results.
- ✓ ✓ The initial unsupported water interpretation contradiction has been corrected.
- ✓ ✓ The scenario analysis has been revised and now focuses mainly on carbon footprint implications of energy and irrigation scenarios.
- ✓ ✓ The report correctly identifies cultivation-stage activities as the dominant contributors to lifecycle impacts.
- ✓ ✓ The report identifies fertilizers, insecticides, fungicides, irrigation energy, and field-level fuel use as important contributors.

✓ The report includes uncertainty analysis using Monte Carlo simulation, reporting a mean carbon footprint of 1.81 kg CO_2e/kg lint, a standard deviation of 0.072 kg CO_2e/kg lint, and a 95% confidence interval of 1.673–1.948 kg CO_2e/kg lint.

Comments

The interpretation section has improved and now correctly separates farm-gate comparison from cradle-to-ginner gate reporting. Remaining refinements are mainly related to strengthening clarity and transparency. Comparative claims should be clearly linked to the relevant boundary, denominator, and indicator, especially since the conventional baseline is based on secondary data. The Monte Carlo uncertainty analysis is a useful addition, but its methodology and link to the final PCF result should be better explained. The chart should also be reformatted for readability, and the interpretation should briefly discuss how data quality affects key conclusions. Overall, only minor refinements are needed before final communication.

Conclusion: Addressed. Interpretation has improved substantially, but remaining wording, uncertainty explanation, figure formatting, and claim limitation issues could be further improved.

4.5 Closure Status of Initial Review Findings

No.	Finding	Closure Status	Reviewer Comment
1	Conventional baseline inconsistency	Addressed	The revised report now presents the conventional GWP consistently having a fair comparison with conventional cotton manufactured in India, with 4.17 kg CO_2e/kg lint at cradle-to-ginner gate.
2	Invalid comparison statement	Addressed	The comparison has been revised and is now presented within an equivalent boundary and denominator.
3	Boundary inconsistency	Addressed	Cradle-to-ginner gate results and farm-gate baseline comparison are now clearly separated.
4	Allocation hierarchy not demonstrated	Addressed	The revised report states the use of mass-economic allocation and provides an improved explanation of the allocation approach.
5	Fungicide unit error	Addressed	Fungicide values have been converted from grams/ml to kg before applying the relevant emission factors.
6	Biochar production unit error	Addressed	The biochar sheet unit conversion from kg to MT has been corrected.
7	Biochar removals methodology incomplete	Addressed	The revised report now includes an improved biochar carbon removal methodology, including assumptions on baseline, permanence, decay, leakage, monitoring, uncertainty, and reversibility.

8	Water footprint baseline recalculation inconsistency	Addressed	The initial unsupported conventional water comparison has been removed from the revised report.
9	Water result interpretation contradiction	Addressed	The revised interpretation is now aligned with the reported water footprint results.
10	Scenario water result inconsistency	Addressed	The initial inconsistent scenario water results have been removed.
11	Energy formula error	Addressed	The diesel energy calculation now uses the corrected LHV value of 43.676 MJ/L.
12	Exclusion conflict	Addressed	The revised report provides improved clarification on included operational inputs and excluded infrastructure/capital items.
13	Data quality overstatement	Addressed	The revised report now describes key assumptions and limitations more transparently.
14	Unsupported "verified baseline" wording	Addressed	The wording has been revised to avoid unsupported claims on the conventional baseline.
15	Economic allocation misdescribed	Addressed	The allocation method is now described as mass-economic allocation, and the initial inconsistency has been corrected.
16	Transport fuel derivation not transparent	Addressed	The revised report provides improved explanation of transportation fuel derivation and related assumptions.
17	Solar electricity treatment unclear	Addressed	Solar electricity consumption is now recorded transparently, with the emission factor treated as zero for operational emissions.
18	Cottonseed emission line	Addressed	The line has been clarified as cotton seed used for sowing, avoiding confusion with cottonseed as a ginning co-product.
19	Ginner water basis unclear	Addressed	The revised report provides clarification on ginner-stage water consumption and reports the value separately.
20	Wastewater treatment/disposal	Addressed	The treatment of wastewater has been clarified within the scope and cut-off considerations of the study.
21	Functional unit normalization	Addressed	Farm and transport emissions are now converted to lint basis before aggregation with ginner-stage emissions.
22	Mixed denominators	Addressed	The initial seed cotton and lint denominator inconsistency has been corrected.
23	Energy units mislabeled	Addressed	Energy sheet unit labels have been corrected.
24	Table captions	Addressed	Table captions have been revised for improved consistency with the reported indicators.
25	Abbreviations and units	Addressed	Abbreviations and units have been clarified in the revised report.
26	Spelling and terminology	Addressed	Editorial corrections have been incorporated to improve wording and terminology.

27	References	Addressed	Reference information has been improved in the revised report.
28	Emission factor transparency	Addressed	Emission factor sources have been identified and improved for transparency.
29	CEA grid factor basis	Addressed	The grid electricity factor basis has been clarified in the revised documentation.
30	Biogenic carbon separation	Addressed	Biochar-related carbon removals are now reported separately from the gross product carbon footprint.
31	Monte Carlo figure readability	Addressed	The Monte Carlo uncertainty analysis has been included to support interpretation of result robustness.
32	Qualitative rating table	Addressed	The initial qualitative rating table issue has been resolved.
33	Primary energy definition	Addressed	The energy indicator and calculation basis have been clarified in the revised report.

5. Summary of the Findings

Section	Addressing of non-conformities	Comments
Goal & Scope Definition	Addressed	Corrective actions accepted. The functional unit, system boundary, intended application, and comparison basis are now clearly presented in the revised report.
Life Cycle Inventory Analysis	Addressed	Corrective actions accepted. Key unit conversions, functional unit normalization, transport treatment, ginner-stage data, wastewater considerations, and emission factor documentation have been improved in the revised report.
Life Cycle Impact Assessment	Addressed	Corrective actions accepted. Major numerical inconsistencies have been corrected, and the selected indicators, biochar removals, energy use, and result presentation are now more clearly reported.
Interpretation of Results	Addressed	Corrective actions accepted. The interpretation is now aligned with the revised goal and scope, corrected system boundary, updated LCIA results, and uncertainty analysis.
Biochar Carbon Accounting	Addressed	Corrective actions accepted. The biochar carbon accounting methodology has been strengthened with clearer explanation of baseline, permanence, decay, leakage, monitoring, uncertainty, and separate reporting of removals.
Technical Corrections	Addressed	Corrective actions accepted. Report structure, terminology, table captions, references, emission factor source identification, and editorial consistency have been improved for final communication.

6. Conclusion

The revised Life Cycle Assessment report for Regeneratively Grown Kasturi Cotton prepared by Beetle Regen Solutions Pvt. Ltd. has adequately addressed the initial critical review findings raised during the initial review process. The corrective actions have improved the technical quality, transparency, and consistency of the assessment.

The review confirms that the following key issues have been satisfactorily addressed:

- ✓ The functional unit is clearly defined as 1 kg of cotton lint at the ginnery gate.
- ✓ The cradle-to-ginner gate system boundary is now clearly described.
- ✓ Farm-gate comparison with the conventional BCI baseline is separated from cradle-to-ginner gate product reporting.
- ✓ Conventional baseline inconsistencies have been corrected.
- ✓ Fungicide and biochar unit conversion errors have been corrected.
- ✓ Farm, transport, and ginner-stage emissions are now treated more consistently in relation to the functional unit.
- ✓ Diesel energy calculation has been corrected using the appropriate lower heating value.
- ✓ Solar electricity is transparently recorded and treated as zero operational emissions.
- ✓ Cotton seed input has been clarified separately from cottonseed generated as a co-product.
- ✓ Biochar-related carbon removals are reported separately from the gross product carbon footprint.
- ✓ Uncertainty analysis has been included to support result robustness.
- ✓ Interpretation of results is now better aligned with the revised goal, scope, and impact assessment results.

The review further confirms that the revised report provides a clearer and more balanced interpretation of the environmental performance of regeneratively grown Kasturi cotton. The report now appropriately distinguishes between product carbon footprint results, farm-gate baseline comparison, ginner-stage impacts, and biochar-related carbon removals.

Based on the documents reviewed and the corrective actions incorporated in the revised report and calculation workbook, the LCA study is considered technically acceptable and consistent with the applicable principles of ISO 14040:2006 and ISO 14044:2006. The relevant principles of ISO 14067:2018 have also been considered for the treatment of product carbon footprint and biochar-related carbon removal reporting.

Final critical review decision: The critical review findings are considered addressed. The revised LCA report is accepted for critical review closure and is considered suitable for finalization, provided that any future use of the results remains aligned with the defined functional unit, system boundary, assumptions, limitations, and stated claim conditions.

7. Declaration of Independence

Control Union Inspections (Pvt) Ltd, Sri Lanka and the reviewer hereby declare that:

- The reviewer is not a full-time or part-time employee of the commissioner or practitioner of the LCA assessment.
- The reviewer has not been involved in defining the scope or carrying out the work to conduct the LCA assessment at hand.
- The reviewer has not been part of the commissioner's or practitioner's project team.
- The reviewer does not have vested financial, political, or other interests in the outcome of the assessment.

We declare that the above statements are truthful and complete.

Date: 07/07/2026

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