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COTTON SEED DELINTING: IMPLICATIONS FOR SEED PHYSIOLOGICAL QUALITY

DESLINTAMENTO DE SEMENTES DE ALGODÃO: IMPLICAÇÕES PARA A QUALIDADE FISIOLÓGICA DE SEMENTES

DESLINTADO DE SEMILLAS DE ALGODÓN: IMPLICACIONES PARA LA CALIDAD FISIOLÓGICA DE LAS SEMILLAS

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Abstract

This review article addresses the impacts of delinting on the physiological quality of cotton seeds, highlighting the importance of this process for the production chain. The main delinting methods, such as chemical, mechanical, and flaming, are presented, discussing their advantages and limitations. The review shows that, when properly performed, delinting contributes to better water absorption, pathogen reduction, and uniformity in seed germination. Furthermore, it discusses emerging technologies for quality assessment, including image analysis with artificial intelligence and near-infrared spectroscopy (NIR), which provide faster, more accurate, and less subjective evaluations. Sustainable delinting techniques are also addressed, highlighting simple and accessible equipment for small producers, aligning with agroecological practices. The reuse of residual lint as raw material for pulp and paper production reinforces the focus on sustainability and circular economy in the cotton sector. Despite the advances, the review points to limitations such as the scarcity of integrated studies that evaluate the physiological, sanitary, and biochemical aspects of seeds and the lack of methodological standardization, which hinders comparisons and meta-analyses. It is recommended that future research explore sustainable methods, biochemical effects, and the behavior of seeds under different storage conditions. Finally, the need to expand the scientific and technological base to improve delinting is emphasized, ensuring seed quality and the competitiveness of Brazilian cotton farming.
Keywords: Quality assessment; Cotton farming; Linters; Sustainability; Seed technology.

Resumo

Este artigo de revisão aborda os impactos do deslintamento na qualidade fisiológica de sementes de algodão, destacando a importância desse processo para a cadeia produtiva. São apresentados os principais métodos de deslintamento, como o químico, mecânico e por flambagem, discutindo suas vantagens e limitações. A revisão evidencia que, quando realizado adequadamente, o deslintamento contribui para a melhor absorção de água, redução de patógenos e uniformidade na germinação das sementes. Além disso, discute as tecnologias emergentes na avaliação da qualidade, incluindo análise de imagens com inteligência artificial e espectroscopia de infravermelho próximo (NIR), que proporcionam avaliações mais rápidas, precisas e menos subjetivas. Também são abordadas técnicas sustentáveis para o deslintamento, com destaque para equipamentos simples e acessíveis para pequenos produtores, alinhando-se a práticas agroecológicas. A reutilização do línter residual como matéria-prima para produção de celulose e papel reforça o enfoque em sustentabilidade e economia circular no setor algodoeiro. Apesar dos avanços, a revisão aponta limitações como a escassez de estudos integrados que avaliem aspectos fisiológicos, sanitários e bioquímicos das sementes e a falta de padronização metodológica, o que dificulta comparações e meta-análises. Recomenda-se que pesquisas futuras explorem métodos sustentáveis, efeitos bioquímicos e o comportamento das sementes em diferentes condições de armazenamento. Por fim, enfatiza-se a necessidade de ampliar a base científica e tecnológica para aprimorar o deslintamento, garantindo a qualidade das sementes e a competitividade da cotonicultura brasileira.

Palavras-chave: Avaliação da qualidade; Cotonicultura; Línter; Sustentabilidade; Tecnologia de sementes.

Resumen

Este artículo de revisión aborda los impactos del deslintado en la calidad fisiológica de las semillas de algodón, destacando la importancia de este proceso para la cadena de producción. Se presentan los principales métodos de deslintado, como el químico, el mecánico y el flameado, y se discuten sus ventajas y limitaciones. La revisión muestra que, cuando se realiza correctamente, el deslintado

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Pages: 1-19

contribuye a una mejor absorción de agua, la reducción de patógenos y la uniformidad en la germinación de las semillas. Además, se analizan las tecnologías emergentes para la evaluación de la calidad, incluyendo el análisis de imágenes con inteligencia artificial y la espectroscopia de infrarrojo cercano (NIR), que proporcionan evaluaciones más rápidas, precisas y menos subjetivas. También se abordan técnicas sostenibles de deslintado, destacando equipos sencillos y accesibles para pequeños productores, en consonancia con las prácticas agroecológicas. La reutilización de la fibra residual como materia prima para la producción de pulpa y papel refuerza el enfoque en la sostenibilidad y la economía circular en el sector algodonero. A pesar de los avances, la revisión señala limitaciones como la escasez de estudios integrados que evalúen los aspectos fisiológicos, sanitarios y bioquímicos de las semillas y la falta de estandarización metodológica, lo que dificulta las comparaciones y los metaanálisis. Se recomienda que futuras investigaciones exploren métodos sostenibles, efectos bioquímicos y el comportamiento de las semillas en diferentes condiciones de almacenamiento. Finalmente, se enfatiza la necesidad de ampliar la base científica y tecnológica para mejorar el deslintado, garantizando así la calidad de las semillas y la competitividad del cultivo de algodón brasileño.
Palabras clave: Evaluación de la calidad; Cultivo de algodón; Deslintado; Sostenibilidad; Tecnología de semillas.

1. Introduction

Cotton is a crop of broad economic relevance in the global agricultural context, standing out for its versatility of use, which extends beyond the traditional textile industry to include the production of oil, seed meal, and hulls (Vaz-Tostes et al., 2024). The cotton production chain goes beyond primary production, functioning as a driver of socioeconomic development by generating employment and supplying raw materials to multiple industrial sectors, ranging from farming to research and technological innovation (Queiroga, Mendes, & Lima, 2022).

In Brazil, cotton cultivation is widely distributed geographically, with major production concentrated in the states of Mato Grosso, Bahia, Goiás, Mato Grosso do Sul, Minas Gerais, and Maranhão. The country ranks as the fifth largest global producer of cotton fiber, behind India, China, Pakistan, and the United States, and holds the second position among the world's leading exporters (Kumabe, Sansígolo, & Homczinski, 2021). The cultivated area has shown significant expansion in recent growing seasons, reaching 1,670.8 thousand hectares in the 2019/2020 crop year, with an estimated production of 2,853.7 thousand tons of lint (Mayrinck et al., 2020).

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Seed quality is a decisive factor for successful crop establishment and productivity in cotton cultivation. Seeds with high physical, physiological, and sanitary attributes promote vigorous and uniform seedlings, thereby favoring early field development (Silva, Queiroga, & Mendes, 2023). However, cotton seeds present a particular characteristic after ginning: short fibers, known as linters, remain adhered to the seed coat. The presence of linters compromises seed flowability during processing, chemical treatment, and mechanized sowing (Silva, Queiroga, & Mendes, 2023).

The persistence of linters represents a significant operational constraint, particularly in large-scale mechanized production systems. According to Queiroga, Mendes, and Lima (2022), the fibrous coating reduces distribution efficiency in seed drills, making chemical delinting an essential practice in the production sector. This procedure, commonly performed using sulfuric acid (H_2SO_4), aims to remove linters and improve seed handling and sowing performance. Nevertheless, excessive acid exposure may impair seed physiological quality (Vaz-Tostes et al., 2024).

Studies indicate that the presence of linters can delay water imbibition, favor microbial development, and reduce seed longevity during storage and germination (Mayrinck et al., 2020; Silva, Queiroga, & Mendes, 2023). Consequently, chemical delinting has been regulated in Brazil under Normative Instruction No. 45 issued by the Ministry of Agriculture, Livestock and Supply (MAPA), which mandates the commercialization and planting of cotton seeds without linters (BRASIL, 2013). In this context, understanding seed physiological quality becomes a strategic factor for preventing economic losses associated with poor germination and uneven crop establishment (Queiroga, Mendes, & Lima, 2022), while also representing a relevant field of scientific investigation.

Therefore, this review aims to analyze the main aspects related to the physiological quality of cotton seeds, with emphasis on comparisons between seeds with and without linters, the different delinting methods employed, and the effects of these processes on germination, vigor, and seed performance. In addition, emerging technologies for both delinting and seed quality assessment are

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Pages: 1-19

discussed, contributing to advancements in production, processing, and regulatory practices within the cotton sector.

2. Methodology

This study was conducted as a narrative literature review, following the approach described by Rother (2007). This framework was adopted to synthesize and critically interpret scientific evidence related to cotton seed delinting and its implications for physiological seed quality, integrating physiological, sanitary, technological, and environmental aspects.

2.1 Guiding question and thematic framework

The review was guided by the following research question:

"How do the presence of linters and different delinting methods affect the physiological quality of cotton seeds, and which technologies have been proposed to evaluate and optimize this process?"

The synthesis was structured into thematic axes:

(i) seed structure and linter characteristics;

(ii) delinting methods (mechanical, chemical, and flame-based);

(iii) physiological and sanitary impacts (germination, vigor, imbibition, pathogens);

(iv) seed quality assessment methods;

(v) technological innovations (artificial intelligence/image analysis and near-infrared spectroscopy – NIR); and

(vi) sustainability and residue management.

2.2 Databases and search period

Literature searches were conducted using Google Scholar and the CAPES Journal Portal, selected for their broad coverage and relevance to agricultural sciences and seed technology. The search covered publications from January 2020 to December 2025, prioritizing recent evidence. Normative documents and

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Pages: 1-19

classical methodological references were included when essential for regulatory or conceptual contextualization.

2.3 Search strategy and descriptor combinations

Search descriptors were defined in both Portuguese and English, incorporating Boolean operators and morphological variations. Terms related to linters, delinting, and physiological seed quality were combined to ensure comprehensive retrieval.

In Google Scholar, results were prioritized based on relevance and recency, followed by screening of titles and abstracts. In the CAPES Portal, filters were applied for subject area, language, and publication period when available.

2.4 Eligibility criteria

Inclusion criteria:

(a) peer-reviewed scientific articles;

(b) studies focusing on cotton seeds addressing the presence or removal of linters, delinting methods, and/or effects on germination, vigor, sanitary quality, and storage;

(c) publications in Portuguese or English;

(d) full-text availability.

Exclusion criteria:

(a) theses, dissertations, conference abstracts without full papers, and non-peer-reviewed materials;

(b) studies restricted to field agronomic performance without direct relation to physiological seed quality;

(c) publications outside the scope of the review (e.g., exclusively textile fiber studies without connection to seed science);

(d) duplicate records or studies without accessible full text.

2.5 Study selection process and number of included studies

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The selection process was conducted in three stages:

(i) title screening,

(ii) abstract screening, and

(iii) full-text reading to confirm eligibility and relevance.

2.6 Data extraction, organization, and evidence synthesis

From the selected studies, information was extracted regarding:

- Type of delinting method (mechanical, chemical, flame-based);
- Operational parameters (acid concentration and volume, exposure time, number of flame passes, drying and neutralization procedures);
- Seed quality variables (germination percentage, first count, vigor, electrical conductivity, tetrazolium test);
- Sanitary aspects (fungal incidence and pathogen occurrence);
- Technological innovations (image analysis/artificial intelligence, NIR spectroscopy, and chemometric approaches).

The evidence was synthesized using a descriptive and comparative approach, highlighting convergences, divergences, methodological limitations, and research gaps. Particular emphasis was given to the applicability of findings across different production scales, including both industrial systems and smallholder or agroecological contexts.

3. Literature Review

3.1 Cotton seed structure and linter characteristics

Cotton seeds exhibit a complex anatomical organization composed of specialized structures responsible for protection, regulation of water uptake, and support of embryonic development. According to Vaz-Tostes et al. (2024), the seed coat consists of outer and inner epidermal layers, a palisade layer, and subepidermal tissues, including the mesophyll. These layers function as a physical

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Pages: 1-19

barrier to the entry of water, oxygen, and microorganisms, while also providing mechanical resistance to the seed.

During cotton processing, particularly at the ginning stage, long fibers destined for the textile industry are separated from the seeds. However, short fibers known as linters remain adhered to the seed coat. These fibers range from 3 to 12 mm in length and may represent approximately 10% of the total seed mass (Vaz-Tostes et al., 2024), constituting a structurally relevant component of the external seed surface.

Linters are composed predominantly of cellulose with high structural purity, which confers significant potential for industrial applications, particularly in pulp and paper production (Kumabe, Sansígolo, & Homczinski, 2021). Despite this potential, a substantial portion of linters is still discarded as a by-product of cotton processing. Studies indicate that the degree of refinement directly influences industrial applicability, with classifications such as blue 40, blue 30, and bleached 30 reflecting different levels of processing and purity (Kumabe, Sansígolo, & Homczinski, 2021).

From a physiological perspective, the presence of linters interferes with seed imbibition dynamics. Vaz-Tostes et al. (2024) demonstrated that the fibrous coating may delay uniform water uptake, promoting heterogeneity during the initial phases of germination. In addition, the fibrous material can act as a substrate for microbial proliferation, negatively affecting seed sanitary quality and longevity during storage.

Conversely, some studies suggest that linters may exert a partial protective effect against pathogen penetration, functioning as an additional physical barrier (Mayrinck et al., 2020). Therefore, their effects are not exclusively detrimental but rather depend on storage conditions, seed moisture content, and overall sanitary status of the seed lot.

3.2 Delinting methods

REMUNOM
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Pages: 1-19

The removal of linters has become both a technical and legal requirement for the commercialization of cotton seeds in Brazil, as established by Normative Instruction No. 45 issued by the Ministry of Agriculture, Livestock and Supply (BRASIL, 2013). The regulation mandates the absence of linters and a minimum germination rate above 75%, reinforcing the importance of delinting for physiological seed quality and industrial standardization.

Delinting methods can be classified as mechanical, chemical, or thermal, each presenting distinct implications for operational efficiency and physiological seed quality (Silva, Queiroga, & Mendes, 2023).

3.2.1 Mechanical delinting

Mechanical delinting is based on the physical abrasion of fibers adhered to the seed coat. Although it significantly reduces the volume of linters, it does not achieve complete removal (Queiroga, Mendes, & Lima, 2022). Its primary advantage lies in the absence of chemical reagents, thereby minimizing direct environmental risks.

However, when applied as a standalone method, mechanical delinting may result in partial fiber removal, which can compromise seed flowability in mechanized sowing systems. In many industrial operations, mechanical delinting is employed as a preliminary step, followed by complementary chemical treatment to ensure complete linter removal.

3.2.2 Chemical delinting

Chemical delinting is the most widely adopted method at industrial scale. It may be performed via concentrated wet treatment with sulfuric acid (H_2SO_4), diluted wet treatment, or gaseous treatment using hydrochloric acid (HCl) (Queiroga, Mendes, & Lima, 2022).

The most common technique involves the application of concentrated sulfuric acid, approximately 98%, under controlled agitation for a predetermined

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Pages: 1-19

period (Vaz-Tostes et al., 2024). The acid promotes degradation of linter cellulose through acid hydrolysis reactions, facilitating complete fiber removal.

The process includes subsequent washing and neutralization, typically using calcium carbonate or calcium hydroxide, to stabilize pH and prevent additional physiological damage (Silva, Queiroga, & Mendes, 2023).

When properly controlled, chemical delinting enhances germination uniformity and seed flowability. Nevertheless, excessive acid concentration or prolonged exposure may compromise the structural integrity of the seed coat and negatively affect the embryo (Mayrinck et al., 2020; Vaz-Tostes et al., 2024).

3.2.3 Flame (thermal) delinting

The thermal method, commonly referred to as flame delinting, is based on superficial combustion of linters through controlled heat exposure. Seeds pass through a vertical tube equipped with strategically positioned burners, promoting partial or complete burning of the fibers (Silva, Queiroga, & Mendes, 2023).

Although this method does not involve chemical reagents, it requires strict control of temperature and exposure time. Excessive temperatures may cause thermal damage to the embryo, drastically reducing germination, particularly when seeds undergo multiple passes through the system (Silva, Queiroga, & Mendes, 2023).

3.3 Physiological effects of chemical delinting on the seed coat and embryo

Chemical delinting with sulfuric acid (H_2SO_4) does not act solely through physical removal of linters but also induces structural and physiological modifications in the seed coat, with potential implications for embryo integrity and germinative performance.

The seed coat of cotton seeds is composed of organized layers, including the outer epidermis, inner epidermis, palisade layer, and subepidermal tissues. Its primary function is to regulate water permeability and protect the embryo against mechanical injury and pathogen invasion. During chemical treatment, concentrated

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Pages: 1-19

H_2SO_4 acts predominantly on linter cellulose and on the outermost layers of the testa, promoting acid hydrolysis of the fibers and partial disruption of the external epidermis (Vaz-Tostes et al., 2024).

When the process is conducted under appropriate conditions of acid concentration, applied volume, and exposure time, the action of the acid remains restricted to superficial layers, preserving the palisade layer and mesophyll. Under such circumstances, chemical delinting may function similarly to a mild chemical scarification treatment, reducing the mechanical resistance of the seed coat and promoting greater uniformity of water uptake, a critical step in the initiation of germination.

From a physiological perspective, imbibition represents a highly sensitive phase of the germination process, characterized by rapid water uptake and structural reorganization of cellular membranes. According to membrane integrity theory in orthodox seeds, imbibition involves a transition from a glassy state to a metabolically active state, accompanied by reconstitution of lipid bilayers and restoration of cellular compartmentalization. Any prior structural damage to the seed coat or embryo membranes may result in solute leakage, a phenomenon detected by increased electrical conductivity and widely used as an indicator of seed vigor (Queiroz et al., 2024).

Under excessive exposure to H_2SO_4, corrosion may extend beyond the external epidermis and reach inner layers of the seed coat, leading to uncontrolled increases in permeability. Such structural alterations may facilitate acid penetration through microfractures and compromise the embryonic axis. Protein denaturation and degradation of structural polysaccharides may affect meristematic tissues of the radicle and hypocotyl, reducing initial growth capacity.

In addition to structural effects, prolonged contact with sulfuric acid may induce oxidative stress. Acid hydrolysis and cellular disorganization can promote the generation of reactive oxygen species (ROS). If not adequately neutralized by endogenous antioxidant systems, ROS accumulation may lead to lipid peroxidation.

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Pages: 1-19

Peroxidative damage compromises membrane integrity in the embryo, impairing reserve mobilization efficiency and ultimately reducing germinative vigor.

International studies on chemical scarification of seeds with hard seed coats indicate that the balance between controlled permeabilization and structural integrity is decisive for treatment success. Insufficient exposure may maintain physical barriers to water uptake, whereas excessive exposure compromises viability. This dose–time relationship is likewise observed in cotton seeds subjected to chemical delinting, where prolonged contact with H_2SO_4 resulted in significant reductions in germination percentage (Mayrinck et al., 2020; Vaz-Tostes et al., 2024).

Another relevant aspect concerns reserve mobilization. Germination of cotton seeds depends on coordinated activity of hydrolytic enzymes responsible for degradation of lipids and storage proteins accumulated in the cotyledons. Chemical injury to the embryo may impair enzyme synthesis and activation, thereby reducing metabolic efficiency during early germination.

However, when delinting is properly monitored, outcomes may be favorable. Vaz-Tostes et al. (2024) demonstrated that, under rigorous control, acid-induced abrasion predominantly affects the outer epidermis of the testa while preserving internal structural layers. Under these conditions, increased germination uniformity and improved first-count performance were observed, indicating maintenance of physiological integrity.

Therefore, the physiological effects of chemical delinting fundamentally depend on the interaction among H_2SO_4 concentration, applied volume, exposure time, agitation intensity, washing efficiency, and subsequent neutralization. Minor variations in these parameters may determine whether the treatment functions as a facilitator of germination or as a trigger for premature deterioration.

3.4 Sanitary impacts associated with the presence or removal of linters

The sanitary quality of cotton seeds is a determining factor for seed longevity, germinative performance, and early crop establishment. The presence of linters may directly influence the dynamics of fungal contamination, acting both as a

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Pages: 1-19

favorable substrate for microbial development and, under certain conditions, as a protective physical barrier.

Mayrinck et al. (2020) reported the occurrence of pathogens such as *Colletotrichum gossypii*, *Fusarium oxysporum*, *Penicillium* spp., and *Aspergillus* spp. in both linted and delinted seeds. Moisture retention within the fibrous layer may create microenvironments conducive to fungal proliferation during storage, particularly under conditions of high relative humidity.

Conversely, linter removal reduces the available surface area for spore adhesion and facilitates the homogeneous application of industrial fungicide treatments. However, if chemical delinting induces microfractures in the seed coat, susceptibility to pathogen penetration may increase.

Therefore, the sanitary effects of delinting depend on the balance between removal of potentially contaminated material and preservation of seed coat structural integrity. This consideration underscores the need for rigorous process control and subsequent sanitary monitoring to ensure maintenance of seed health and quality.

3.5 Evaluation of seed physiological quality

The assessment of physiological seed quality must encompass tests capable of estimating both viability and vigor, enabling reliable prediction of field performance.

The germination test remains the standard reference method for viability determination and is conducted under standardized conditions of temperature, substrate, and photoperiod. Vaz-Tostes et al. (2024) emphasize that both first count and final count provide relevant information regarding seed vigor and germinative capacity.

Among vigor tests, electrical conductivity stands out due to its sensitivity in detecting damage to cellular membranes. During imbibition, seeds with structurally compromised membranes release greater amounts of ions into the external

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Pages: 1-19

medium, resulting in increased electrical conductivity values. Queiroz et al. (2024) demonstrated that this test presents high precision in evaluating the physiological quality of cotton cultivars, being particularly useful for detecting adverse effects resulting from chemical delinting.

The tetrazolium test constitutes an important complementary tool, allowing rapid viability assessment and identification of localized damage in the embryo. Mayrinck et al. (2020) highlighted that this test enables monitoring of lesion extent and severity and can be applied at different stages of seed processing.

Furthermore, comparative studies indicate that properly delinted seeds tend to exhibit greater germination uniformity and improved performance in vigor tests when compared to linted seeds (Mayrinck et al., 2020; Vaz-Tostes et al., 2024). However, such outcomes are strongly dependent on processing parameters and storage conditions.

3.6 Emerging technologies in seed quality assessment

Technological advancements have driven the development of rapid, non-destructive, and highly accurate methods for seed quality evaluation.

Image analysis associated with artificial intelligence enables characterization of seed morphology, surface integrity, and presence of impurities, reducing the subjectivity inherent in traditional visual assessments (Vaz-Tostes et al., 2024). Machine learning-based systems allow automated cultivar classification and detection of irregularities in seed surface coating.

Near-infrared spectroscopy (NIR) represents another promising tool. This technique is based on the interaction between infrared radiation and chemical bonds present in seed constituents, allowing rapid and non-destructive inference of chemical composition and physiological quality.

Mayrinck et al. (2020) demonstrated that the combination of NIR spectroscopy with chemometric approaches, such as Partial Least Squares

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Pages: 1-19

Discriminant Analysis (PLS-DA), enabled correct classification of 96.91% of evaluated seeds in the first validation and 88.66% in the second validation, highlighting its strong industrial application potential.

These technologies contribute to greater process standardization, reduced analytical time, and increased reliability of results.

3.7 Sustainability and waste management

Chemical delinting using sulfuric acid generates acidic residues that require proper treatment to comply with current environmental regulations. According to CONAMA Resolution No. 430/2011, effluent pH must range between 5 and 9 for safe disposal (BRASIL, 2011).

Neutralization may be performed using calcium hydroxide, calcium carbonate, or dolomitic lime, promoting pH stabilization and enabling potential reuse of the residue as an agricultural soil amendment (Queiroga, Mendes, & Lima, 2022). This practice reduces environmental impacts and adds value to the by-product.

Flame delinting, by not employing chemical reagents, eliminates the generation of liquid waste. However, it involves energy consumption and gas emissions resulting from linter combustion and should therefore be evaluated from the perspective of energy efficiency and carbon footprint.

The development of low-cost, mobile delinting equipment, as proposed by Silva, Queiroga, and Mendes (2023), enhances the feasibility of agroecological systems and small-scale producers, contributing to sustainability within the cotton production sector.

Table 1. Summary comparison of cotton seed delinting methods

Method	Lint removal efficiency	Main effects on seed quality	Key advantages	Main limitations

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Pages: 1-19

Mechanical	Partial	Usually preserves seed integrity, but incomplete lint removal may affect water uptake and uniformity	Simple and chemical-free	Often requires complementary chemical treatment
Chemical (H_2SO_4)	High (near total removal)	Improves germination and uniformity when properly controlled; excessive exposure may reduce vigor	Highly efficient; industrial standard	Risk of seed damage; requires washing and neutralization
Flame (thermal)	Moderate to high	Maintains germination under controlled exposure; excessive heat reduces vigor	No chemical residues; suitable for small-scale systems	Requires strict temperature control; lower capacity

The main delinting methods differ in efficiency, operational complexity, and potential effects on seed physiological quality. Table 1 summarizes the key comparative aspects of mechanical, chemical, and thermal (flame) delinting.

4. Final Considerations

Delinting represents a strategic step in cotton seed production, directly influencing the physiological, sanitary, and operational quality of seed lots. The literature consistently indicates that linter removal improves seed flowability, enhances imbibition uniformity, and, when conducted under properly controlled conditions, promotes more uniform germination. However, the physiological consequences of the process are critically dependent on treatment intensity.

Chemical delinting with sulfuric acid remains the industrial standard due to its high efficiency in linter removal. Nevertheless, its application entails potential risks to seed coat integrity and embryo viability, particularly under excessive exposure or inadequate neutralization. Evidence indicates that minor variations in H_2SO_4 concentration, applied volume, and agitation time may determine the transition between improved physiological performance and the onset of premature deterioration, reflected in increased electrical conductivity and reduced seed vigor.

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Pages: 1-19

Mechanical and thermal methods present lower chemical aggressiveness but exhibit operational constraints or reduced industrial standardization. Flame delinting, although promising for small-scale and agroecological systems, requires strict temperature control to prevent thermal damage to the embryo.

From a sanitary perspective, the presence of linters may either promote microorganism retention or act as a physical barrier, indicating that the effects of linter removal are not unidirectional and depend on storage conditions and subsequent treatment practices.

A notable gap remains in the literature regarding integrated studies simultaneously addressing physiological, biochemical, structural, and sanitary aspects following delinting. Most research focuses primarily on germination and vigor assessments, with comparatively limited investigation into molecular alterations, oxidative stress responses, and membrane reorganization dynamics.

Technological advances, including image analysis assisted by artificial intelligence and near-infrared spectroscopy, represent promising tools for rapid and non-destructive seed quality monitoring. However, their consolidation requires greater methodological standardization and validation across cultivars and processing conditions.

Overall, optimizing delinting practices demands a multidisciplinary approach integrating rigorous control of operational parameters, detailed physiological evaluation, and environmentally sound waste management. Scientific advancement in this field is essential to ensure high-quality seed production, minimize losses along the production chain, and strengthen the competitiveness and sustainability of the cotton sector.

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