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A LITERATURE REVIEW ON THREE-DIMENSIONAL FOAM/PUFF PRINTING OF FLAX AND HEMP TEXTILES WITH NATURAL PIGMENTS AND CHT PRINTING SYSTEMS

BY

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Abstract Due to the growing demand for sustainable textile technologies, this study investigates the potential of three-dimensional foam/puff printing on ecological textile substrates using CHT printing pastes (Tubiscreen and Print Perfect) combined with natural pigments. Based exclusively on a comprehensive literature review and conceptual analysis, the research identifies suitable formulations and processing conditions for cellulosic fibers, particularly flax and hemp. The analysis focuses on thermal expansion mechanisms, polymer-binder stabilization, processing temperature and activation time, and paste–substrate interactions. Findings from the literature indicate that natural pigments represent a promising pathway toward more sustainable three-dimensional textile printing, however, their application remains constrained by limited color stability, pigment–polymer incompatibility, and insufficient process reproducibility. Moreover, the structural characteristics of natural fibers can significantly affect adhesion, surface uniformity, and volumetric stability. The findings emphasize the critical importance of systematically optimizing formulation composition and processing parameters through experimental investigation to ensure reproducibility, durability, and scalability for potential industrial scalable outcomes.

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1. Introduction

In the context of growing concerns regarding environmental protection and the responsible use of resources, the textile industry is considered one of the industrial sectors with a significant environmental impact. The production and finishing of textile materials involve considerable consumption of water, energy, and auxiliary chemicals and may generate effluents with high polluting potential (Muthu and Gardetti, 2020; Kant, 2012). Within textile printing, conventional pigment and dye systems provide important advantages in terms of color stability and reproducibility, however, their environmental implications have increased the interest in alternative approaches based on renewable and less environmentally demanding resources.

In this context, natural pigments have attracted increasing attention as potential alternatives for the development of more sustainable textile processes. Pigments obtained from natural sources, including plants, flowers, and roots, may offer advantages associated with biodegradability and reduced toxicity, while certain natural compounds may also provide additional functional properties, such as antimicrobial or antioxidant activity (Negi, 2025; Egelkamp *et al.*, 2025). Nevertheless, their application in textile printing remains challenging due to limitations related to stability, compatibility with polymeric printing systems, and process reproducibility. These aspects highlight the need for a better understanding of the interactions between natural pigments, printing matrices, technological parameters, and textile substrates.

The development of advanced textile printing technologies has progressively extended their application beyond conventional decorative purposes toward the creation of structured and functional textile surfaces. Among these technologies, three-dimensional foam/puff printing enables the formation of volumetric and tactile effects through the thermal expansion of specially formulated printing layers (Bošnjaković *et al.*, 2022). The performance of such systems depends on several interrelated factors, including paste composition, binder characteristics, processing conditions, and the properties of the textile substrate (Bošnjaković *et al.*, 2022; El-Kashouti *et al.*, 2019).

The use of ecological cellulosic substrates, particularly flax and hemp, is relevant in the context of sustainable textile development. However, the structural characteristics and absorption behavior of these fibers may affect the distribution, adhesion, and expansion of printing systems, with possible consequences for the uniformity and stability of three-dimensional effects (Tri and Bahari, 2023). Consequently, the interaction between natural pigments, polymeric printing systems, and ecological textile substrates represents an important aspect in assessing the potential of foam/puff printing as a sustainable textile technology.

Against this background, the objective of this work is to provide a critical and structured analysis of the possibilities of integrating natural pigments in three-dimensional foam/puff printing systems for ecological textile substrates, with particular reference to flax and hemp fibers and CHT printing systems such as Tubiscreen and Print Perfect. The study is exclusively theoretical and literature-based and does not include experimental testing or experimental validation. It focuses on the main challenges reported in the specialized literature concerning pigment stability, pigment–binder compatibility, process reproducibility, thermal activation, and substrate–paste interactions.

Rather than proposing a new experimental method or presenting original experimental results, this paper synthesizes and correlates information from the existing literature in order to identify the main limitations, critical factors, and research gaps associated with the application of natural pigments in three-dimensional foam/puff printing. The analysis provides a conceptual framework for understanding the relationships between material characteristics and printing conditions and outlines directions for future experimental research aimed at the optimization and validation of sustainable textile printing systems.

2. Characterization of Printing System Components

Materials: For this literature-based study, the materials were selected to reflect current trends in the textile industry regarding sustainability and the development of high-value-added products. The analysis considers three-dimensional foam/puff printing systems, natural pigments, and textile substrates based on cellulosic fibers.

Foam/puff printing systems: The printing systems considered in this analysis belong to the CHT range, specifically the **TUBISCREEN** and **PRINT PERFECT** series, which are used in water-based textile screen printing. According to the available technical and scientific information, these systems involve polymer binders, thermally expanding agents, and auxiliary additives that contribute to the processing characteristics and stabilization of the printed structure.

The **TUBISCREEN EX 160 FF** and **TUBISCREEN TS FF** systems are described as water-based systems used for obtaining three-dimensional effects through controlled thermal expansion. The reported activation range is approximately 140–170°C. **TUBISCREEN EX 160 FF** is intended for applications requiring controlled rheological and expansion characteristics, whereas **TUBISCREEN TS FF** is oriented toward standard textile screen printing applications.

Common characteristics reported for these systems include the presence of thermally activated expanding agents, compatibility with water-based formulations, the possibility of applying relatively thick printing layers,

controlled development of the three-dimensional effect during thermal fixation, and dimensional stability following cooling.

The PRINT PERFECT family comprises binders and functional bases intended for water-based textile printing systems. Their reported role is related to the adhesion, elasticity, and stability of the polymer film. In foam/puff configurations, these components may influence the development and stability of the expanded structure through their effect on the properties of the polymer matrix.

PRINTPERFEKT EX AR FF is described as an anchor-type binder intended to improve adhesion between the printed layer and the textile substrate, whereas **PRINTPERFEKT EX FF** is an elasticizing base used to modify the mechanical properties of the printing system. These components may be incorporated into multilayer configurations consisting of an under base, foam layer, and top-coat, depending on the intended application.

The foam/puff printing mechanism is generally associated with the thermal activation of expanding agents, which results in gas generation and an increase in the volume of the printed layer. The polymer binder contributes to maintaining the cohesion and structural integrity of the expanded layer (Bošnjaković *et al.*, 2022). The rheological properties of the printing paste, particularly viscosity and thixotropic behavior, may influence layer deposition, distribution, and uniformity across the textile substrate (El-Kashouti *et al.*, 2019).

Natural pigments: The natural pigments considered in the literature analysis include curcumin and henna, selected because of their relevance to natural coloration and their potential application in sustainable textile processes.

Curcumin is the principal bioactive pigment associated with rhizome of *Curcuma longa* and is characterized by a conjugated molecular structure responsible for its intense yellow coloration. Its low water solubility and sensitivity to environmental conditions, including pH and light are relevant considerations for its application in coloration systems (Priyadarsini, 2014).

Henna, obtained from the leaves of *Lawsonia inermis*, is a natural colorant traditionally used for skin, hair, and textile coloration. Its principal active compound, lawsone, contributes to the characteristic reddish-brown coloration and interacts with natural substrates (Joshi *et al.*, 2025).

Natural pigments have been considered potential alternatives to synthetic colorants because of their renewable origin, biodegradability, and potentially lower environmental impact. However, their application in modern printing systems remains associated with limitations related to environmental sensitivity, color stability, and compatibility with polymer matrices (Negi, 2025; Egelkamp *et al.*, 2025).

Textile Substrates: The textile substrates considered in this analysis are natural cellulosic fibers, particularly flax and hemp, selected because of their relevance to sustainable textile development.

The fibrillar structure and absorption characteristics of these fibers may influence paste distribution and penetration within the textile substrate. Consequently, variations in deposited layer thickness and in the development of foam/puff structures may occur depending on substrate characteristics (Tri and Bahari, 2023). The compatibility between the textile substrate, printing system, and natural pigment is therefore considered an important factor in the development of uniform and stable three-dimensional structures.

Theoretical Considerations on Curcumin Migration in Foam/Puff Printing Systems

The migration of curcumin within a water-based foam/puff printing system can be theoretically considered as a molecular transport process occurring within a semi-solid polymer matrix and, under specific conditions, involving transfer toward the textile substrate. The extent and direction of such transport depend on the physicochemical characteristics of the colorant, the structural and viscoelastic properties of the polymer matrix, and the thermal conditions applied during drying and activation.

During drying and thermal activation, several interdependent transformations may occur, including water evaporation, polymer particle coalescence, changes in matrix viscosity and viscoelasticity, and thermal expansion of the foam structure. These transformations may modify the molecular mobility of the colorant and consequently influence its redistribution within the printing layer (Wicks *et al.*, 2007). In a foam/puff system, the development of the three-dimensional structure further introduces changes in the internal geometry and free volume of the matrix, making the transport process more complex than diffusion in a homogeneous polymeric medium.

As a general theoretical framework, molecular transport can be described by Fick's second law Eq. (1):

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad (1)$$

where C represents the local concentration of curcumin, t is time, x is the coordinate along the thickness direction of the printed layer, and D is the diffusion coefficient. Under its classical formulation, this equation assumes a homogeneous medium and constant transport properties. Therefore, it should be regarded in the present study as a conceptual framework for understanding pigment redistribution rather than as a predictive model for the specific CHT printing systems investigated in the literature.

The temperature dependence of molecular mobility can additionally be described using an Arrhenius-type relationship Eq. (2):

$$D(T) = D_0 e^{-\frac{E_a}{RT}} \quad (2)$$

where D_0 is the pre-exponential factor, E_a is the activation energy, R is the gas constant, and T is the absolute temperature. This relationship provides a theoretical basis for discussing the influence of temperature on molecular transport. During thermal activation, changes in polymer mobility may affect the ability of the colorant to redistribute within the printing layer. However, the actual temperature dependence of curcumin diffusion in a particular CHT formulation cannot be established without experimentally determined transport parameters.

The interaction between the printing layer and the textile substrate represents another relevant aspect of pigment redistribution. In a printed textile system, the polymer matrix and the fibrous substrate constitute two physically different domains, and transfer across their interface may be influenced by the structural characteristics of both materials. In cellulosic fibers, parameters such as moisture content, porosity, surface structure, and intermolecular interactions may affect the retention and redistribution of colorants within the fiber assembly (Hearle and Morton, 2008). These considerations are particularly relevant for flax and hemp substrates, whose morphological characteristics may influence paste penetration, adhesion, and pigment distribution.

The thermal expansion associated with foam/puff printing introduces an additional complication to the theoretical description of molecular transport. As the matrix expands, changes in density, free volume, and transport pathways may occur. Consequently, the diffusion coefficient cannot necessarily be assumed to remain constant throughout the printing and activation process. From a conceptual perspective, the system may therefore be regarded as a time-dependent and structurally evolving medium rather than as a simple homogeneous layer (Zhang *et al.*, 2019). The main factors potentially influencing curcumin redistribution during these transformations are summarized conceptually in (Fig. 1). The interaction between the printing layer and the textile substrate represents another relevant aspect of pigment redistribution.

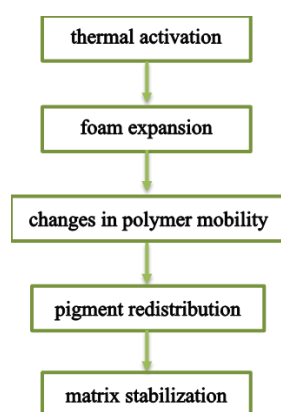


Fig. 1 – Conceptual representation of the factors potentially influencing curcumin redistribution in foam/puff printing systems.

The relative importance of molecular transport and matrix stabilization can also be discussed using characteristic transport relationships. For example, a dimensionless Péclet-type parameter may be expressed as Eq. (3):

$$Pe = \frac{L^2}{D \cdot t_s} \quad (3)$$

where L represents the characteristic thickness of the printing layer, D the diffusion coefficient, and t_s the characteristic solidification time. In qualitative terms, the relationship provides a means of considering whether pigment redistribution may occur on a comparable or longer timescale than matrix stabilization. Similarly, the characteristic diffusion time can be expressed as Eq. (4):

$$t_{diff} \sim \frac{L^2}{D} \quad (4)$$

These relationships are useful for interpreting the potential competition between pigment mobility and the progressive stabilization of the polymer matrix. Nevertheless, their quantitative application to curcumin-containing CHT printing systems would require experimentally determined values for diffusion coefficients, layer thickness, thermal history, and solidification kinetics.

The presence of inorganic particles such as TiO_2 may further influence the internal transport environment of the printing layer. Particulate components can modify the effective transport pathway and the structural characteristics of the polymer matrix, potentially affecting molecular mobility (Buxbaum and Pfaff, 2006). For heterogeneous systems, an effective diffusion coefficient may be conceptually expressed as Eq. (5):

$$D_{eff} = D \cdot \frac{\varepsilon}{\tau} \quad (5)$$

where D represents the diffusion coefficient of the corresponding homogeneous medium, ε an effective porosity factor, and τ the tortuosity of the transport pathway. This expression illustrates the potential influence of structural heterogeneity on molecular transport. However, no quantitative value of D_{eff} can be assigned to the TUBISCREEN or PRINT PERFECT systems considered in this review without experimental characterization of their composition and microstructure.

The theoretical analysis therefore suggests that the redistribution of curcumin in foam/puff printing systems may be influenced by the combined effects of temperature, polymer-matrix mobility, foam expansion, substrate structure, and pigment-matrix interactions. The thermal activation stage is expected to be particularly relevant because changes in matrix mobility and structure may modify the conditions under which molecular redistribution occurs. However, the available literature does not provide sufficient experimental

evidence to establish a specific migration profile or to quantitatively determine the extent of curcumin transfer in TUBISCREEN or PRINT PERFECT formulations applied to flax and hemp substrates.

For this reason, the equations discussed in this section are considered conceptual analytical tools supporting the interpretation of mechanisms reported in the literature. They do not constitute a validated predictive model of curcumin transport. In particular, the present review does not provide experimental diffusion coefficients, activation energies, concentration profiles, boundary conditions, or independently measured thermal and rheological parameters for the investigated CHT systems. Consequently, quantitative conclusions regarding the kinetics or magnitude of curcumin migration cannot be drawn from the present analysis.

From an industrial perspective, the theoretical considerations indicate that pigment stability and distribution should be evaluated in relation to the formulation of the printing paste, the characteristics of the textile substrate, and the thermal activation profile. These factors should be considered jointly when designing sustainable foam/puff printing systems. Experimental investigations combining thermal analysis, rheological characterization, microscopic examination, and colorimetric or spectroscopic measurements would be necessary to verify the proposed transport mechanisms and to establish quantitative relationships between formulation, processing conditions, and pigment stability.

Methods

The research methodology is grounded in a theoretical and conceptual approach, combining a review and critical analysis of the specialized literature with a conceptual examination of the mechanisms involved in foam/puff printing and the identification of critical factors influencing system performance. No experimental investigations or laboratory validation were performed within the present study.

Documentary and Bibliographical Analysis

The documentary and bibliographical analysis constituted the main methodological component of the study and involved a critical examination of specialized literature addressing textile printing, natural pigments, sustainable textile materials, and three-dimensional printing technologies.

The analysis focused on identifying the main advantages and limitations reported for natural pigments, as well as their behavior in different textile printing systems. Particular attention was given to aspects relevant to sustainable textile processing, including pigment stability, compatibility with printing formulations, and the influence of processing conditions (Muthu and Gardetti, 2020).

The reviewed literature was also examined to identify the formulation and technological factors reported to influence process stability and

reproducibility when natural pigments are incorporated into modern textile printing systems (Egelkamp *et al.*, 2025). These observations were subsequently used as a basis for the comparative and conceptual analyses presented in the following sections.

Comparative Analysis

A comparative analysis was conducted based on the findings reported in the specialized literature to examine the differences between natural and synthetic pigments, as well as among different approaches to three-dimensional textile printing.

The reviewed literature indicates that modern textile printing technologies enable the development of complex surface structures with enhanced aesthetic and functional characteristics. In particular, three-dimensional printing approaches have been associated with distinctive tactile and visual effects compared with conventional two-dimensional printing methods (Rainert *et al.*, 2024; Rahman *et al.*, 2023).

Within this comparative framework, foam/puff printing was considered in relation to alternative textile printing approaches, with particular attention to its potential advantages for generating three-dimensional surface effects and to the limitations associated with the incorporation of natural pigments. The comparison was based on characteristics and limitations reported in the literature and was not supported by experimental testing within the present study.

Mechanism of Foam/Puff Printing

Foam/puff printing is a textile screen-printing technique used to obtain three-dimensional surface effects through the thermally induced expansion of a functional printing layer applied to a textile substrate. According to the literature, the formation of the expanded structure involves a sequence of interrelated processes, including paste deposition, drying, thermal activation, expansion, and stabilization of the printed layer.

The mechanism can be conceptually described through the following successive stages:

1. **Paste Deposition:** The foam/puff formulation is applied to the textile substrate by screen printing, forming a continuous printed layer whose thickness depends on the formulation and printing conditions.
2. **Drying Stage:** During drying, water is progressively removed from the printing formulation, while the polymer binder and expanding components become increasingly concentrated within the printed layer. The extent of drying may influence the subsequent thermal expansion and stabilization processes.
3. **Thermal Activation:** During thermal treatment, the expanding components undergo thermally induced transformations that promote volumetric expansion of the printed layer. The resulting expansion is influenced by the formulation composition, thermal conditions, and rheological behavior of the

polymer matrix. Depending on the formulation, the expansion process may generate a porous, raised structure with distinct three-dimensional characteristics.

4. Structural Stabilization: Following expansion, further changes within the polymer matrix contribute to the stabilization of the three-dimensional structure. The ability of the matrix to retain the expanded configuration after cooling depends on the interaction between the formulation, thermal conditions, and textile substrate.

Overall, the foam/puff printing mechanism can be understood as a balance between thermally induced expansion and the ability of the polymer matrix to support and stabilize the developing structure. The conceptual sequence of the process is illustrated in (Fig. 2). This description is based on mechanisms reported in the literature and does not represent experimental observations obtained for the specific CHT formulations or textile substrates considered in the present study.

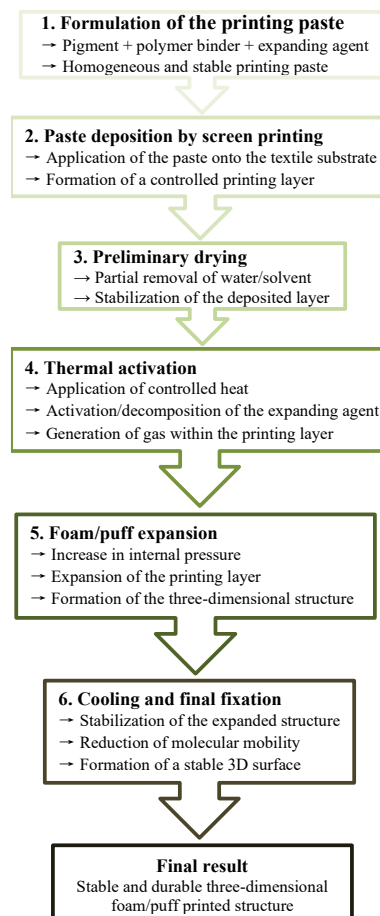


Fig. 2 – Conceptual representation of the principal stages involved in foam/puff printing.

Conceptual Modeling

Conceptual modeling was used to organize and describe the interactions reported in the literature between the main components of foam/puff printing systems, particularly the natural pigment, polymer binder, expanding components, and textile substrate.

Based on the reviewed literature, the conceptual framework considers the main stages associated with foam/puff printing, including paste deposition, preliminary drying, thermal activation, expansion of the printed layer, and subsequent structural stabilization (Bošnjaković *et al.*, 2022). The model also considers the potential influence of formulation characteristics, thermal conditions, and substrate properties on the development and stability of the three-dimensional structure.

This conceptual approach provides a framework for interpreting the relationships between material composition, processing conditions, and the resulting structure. It is intended to support the critical interpretation of findings reported in the literature and to identify variables that may require further experimental investigation. The conceptual model is not a predictive mathematical

model and has not been experimentally validated for the specific CHT formulations and flax or hemp substrates considered in this study.

Identification of Critical Process Parameters

Based on the reviewed literature, the main process parameters reported to influence foam/puff printing performance were identified as:

- Rheological properties of the paste;
- Deposited layer thickness;
- Screen printing mesh type;
- Squeegee parameters;
- Thermal activation temperature and duration.

The literature indicates that these parameters may influence paste deposition, layer uniformity, adhesion, and the development of the three-dimensional structure. In particular, thermal activation is consistently reported as an important factor affecting expansion behavior and the stability of foam/puff structures, although its influence depends on the specific formulation and processing conditions (El-Kashouti *et al.*, 2019; Cheung and Choi, 2023).

Critical Information Evaluation

A critical evaluation of the reviewed literature was conducted to identify the principal limitations, challenges, and research gaps associated with the use of natural pigments in foam/puff printing systems.

The literature consistently highlights pigment stability, compatibility with polymer matrices, and process reproducibility as major challenges affecting the broader implementation of natural-colorant-based textile printing systems.

Additional limitations relate to the variability of natural raw materials and the sensitivity of foam/puff processes to formulation and processing conditions (Egelkamp *et al.*, 2025; Muthu and Gardetti, 2020).

The critical analysis also revealed that further experimental investigations are required to better understand the interactions between natural pigments, polymer binders, and textile substrates under industrially relevant processing conditions.

Methodological Justification

The selected methodology was considered appropriate for the objectives of the present study, which focuses on the critical analysis and synthesis of existing knowledge regarding natural pigments, foam/puff printing technologies, and ecological textile substrates.

The combination of documentary analysis, comparative evaluation, and conceptual modeling enabled the identification and organization of the principal factors reported in the literature to influence system performance. This approach facilitates a structured interpretation of published findings and supports the identification of current limitations, knowledge gaps, and future research directions. Because the present work is based exclusively on literature analysis and conceptual interpretation, the conclusions should be regarded as literature-based observations rather than experimentally validated findings.

Limitations Identified in the Specialized Literature

A critical assessment of the specialized literature indicates that the integration of natural pigments, foam/puff three-dimensional printing technologies, and natural textile substrates offers promising opportunities for sustainable textile development, while also presenting a number of technical, material-related, and industrial limitations. These limitations concern pigment stability, formulation compatibility, process control, substrate-related variability, reproducibility, and the potential transition from laboratory-scale applications to industrial production.

1. Limitations of Natural Pigments

Several studies report that, despite their potential as alternatives to synthetic colorants, natural pigments present limitations that may affect their application in textile printing:

- **Limited color stability:** Natural pigments may exhibit lower resistance to environmental factors than conventional synthetic colorants, which can contribute to changes in shade and reduced color consistency during storage or use. Such variability represents an important consideration for applications requiring reproducible coloration (Negi, 2025).
- **Sensitivity to environmental conditions:** The stability of natural pigments may be influenced by factors such as UV exposure, temperature,

moisture, and pH. Consequently, their performance may vary depending on the conditions to which the printed textile is exposed (Egelkamp *et al.*, 2025).

- **Compatibility with polymer matrices:** The incorporation of natural pigments into polymer-based printing formulations may be affected by dispersion, particle–matrix interactions, and pigment concentration. Inadequate compatibility may contribute to aggregation or non-uniform distribution within the printing layer, potentially affecting its visual and functional characteristics (Egelkamp *et al.*, 2025).

2. Limitations of Foam/Puff Systems (3D Textile Printing)

Although foam/puff printing enables the formation of raised surface structures, the literature identifies several factors that can affect the reproducibility and uniformity of the expansion process:

- **Variability of the expansion process:** The development of the three-dimensional structure depends on the interaction between formulation characteristics and thermal processing conditions. Variations in paste composition, activation temperature, or treatment duration may therefore result in differences in the degree and uniformity of expansion (Bošnjaković *et al.*, 2022).

- **Rheological sensitivity:** The rheological properties of the printing paste influence its deposition, spreading, and retention on the textile substrate. Variations in viscosity and flow behavior may affect layer uniformity and adhesion, while non-uniform distribution of expanding components may contribute to structural irregularities (El-Kashouti *et al.*, 2019).

- **Sensitivity to thermal conditions:** Thermal activation represents an important process variable because temperature and treatment duration influence the development and stabilization of the expanded structure. The appropriate thermal conditions are formulation-dependent, which may complicate the transfer of reported processing conditions between different printing systems (Cheung and Choi, 2022).

3. Limitations of Natural Textile Substrates

The use of natural cellulosic substrates such as flax and hemp is consistent with sustainability objectives, but their structural characteristics may introduce additional variability into the printing process:

- **Structural heterogeneity:** Natural fibers may exhibit variations in fiber diameter, surface morphology, porosity, and absorbency. Such characteristics can influence the distribution and penetration of the printing formulation within the textile structure (Tri and Bahari, 2023).

Paste penetration and absorption: The absorption behavior of cellulosic substrates may promote penetration of the printing formulation below the textile surface. From a conceptual perspective, excessive penetration may reduce the

amount of material available for surface expansion and consequently influence the development of the final three-dimensional profile.

4. Overall Technical Process Limitations

At the process level, the literature indicates that foam/puff printing involves the interaction of multiple technological parameters, which may complicate process control and reproducibility:

- Multiple interacting parameters: Variables such as screen characteristics, squeegee conditions, printing speed, deposited layer thickness, paste rheology, and thermal treatment may interact during the printing process. Their combined influence makes it difficult to attribute changes in the final structure to a single parameter (El-Kashouti *et al.*, 2019).
- Process adaptation requirements: The adoption of sustainable materials may require adjustments to existing formulations and processing conditions. Consequently, the transition toward more sustainable textile printing systems may involve optimization at several stages of the technological process rather than modification of a single material component (Muthu and Gardetti, 2020).

5. Limitations Regarding Reproducibility and Industrial Scaling

Reproducibility and scalability represent further challenges identified in the literature, particularly when natural pigments are incorporated into three-dimensional printing systems:

- Formulation standardization: Variability in the composition and properties of natural pigments may complicate the establishment of standardized formulations and processing conditions. This issue may affect color reproducibility and consistency between different production batches (Egelkamp *et al.*, 2025).
- Laboratory-to-industrial transition: Conditions optimized at laboratory scale cannot necessarily be transferred directly to industrial production because of differences in equipment, process control, substrate characteristics, and production environment. The literature therefore emphasizes the need for further validation and process optimization before broader industrial implementation can be considered (Muthu and Gardetti, 2020).

Integrative Conclusion on Limitations

Overall, the reviewed literature indicates that the integration of natural pigments into foam/puff printing systems for ecological textile substrates represents a promising direction for sustainable textile development, while remaining subject to several technical and technological limitations. The main challenges identified concern pigment stability, compatibility with polymer-based formulations, process control, reproducibility, and the lack of standardized processing conditions. These limitations indicate the need for further research

focused on formulation optimization, improved compatibility between pigments, printing systems and textile substrates, and the development of more consistent processing parameters. Such investigations may contribute to the future assessment of the feasibility and scalability of these systems for industrial textile applications.

Scope and Contribution of the Present Review

In response to the limitations identified in the specialized literature concerning the use of natural pigments and three-dimensional foam/puff printing technologies on ecological textile substrates, the present study provides a critical literature-based analysis of the main material and technological factors associated with these systems. The analysis focuses on the reported interactions between natural pigments, polymer-based printing formulations, expanding components, and textile substrates, with particular attention to their potential influence on the development and stability of three-dimensional printed structures.

One of the main aspects addressed in the reviewed literature concerns the formulation of foam/puff printing pastes, particularly the relationship between pigment, polymer binder, and expanding components. The literature suggests that formulation composition may influence pigment dispersion, paste rheology, substrate adhesion, and the development of the expanded structure. These relationships are considered in the present review to identify formulation-related factors that may require further experimental investigation.

A further aspect concerns the behavior of natural pigments obtained from different plant sources. Reported characteristics such as color stability, environmental sensitivity, and compatibility with polymer matrices are considered in relation to their potential application in foam/puff printing systems. The reviewed evidence suggests that pigment chemical characteristics and interactions with the polymer matrix may influence coloration, stability, and reproducibility; however, the available literature does not provide sufficient experimental evidence to establish universal relationships applicable to all natural pigments and printing formulations.

The influence of technological parameters is also examined, particularly thermal activation temperature, treatment duration, deposited layer thickness, and preliminary drying conditions. Based on the literature, these parameters may affect the degree of expansion, structural stability, and uniformity of foam/puff printed layers. However, their effects are formulation- and substrate-dependent, and the processing conditions reported for one printing system cannot necessarily be transferred directly to another system without experimental verification.

The interaction between the printing formulation and ecological textile substrates, particularly cellulosic materials such as flax and hemp, represents another relevant aspect of the analysis. Differences in fiber morphology, porosity, surface characteristics, and absorption behavior may influence paste distribution and penetration within the textile structure. These substrate-related factors are

therefore considered when interpreting the potential differences in the development and stability of three-dimensional printed structures.

The reviewed literature also indicates that the assessment of foam/puff printed structures should consider both aesthetic and functional characteristics, including expansion uniformity, structural stability, adhesion, and resistance to environmental or mechanical factors. However, differences in experimental protocols and evaluation methods reported across studies limit the direct comparison of published results.

On the basis of the reviewed evidence, the present study proposes a conceptual framework linking formulation characteristics, printing parameters, thermal activation, and substrate properties with the development of three-dimensional foam/puff structures. The framework comprises the principal stages of paste formulation, deposition, preliminary drying, thermal activation, expansion, and structural stabilization. It is intended as an interpretative framework derived from the literature rather than as a predictive or experimentally validated model.

Overall, the contribution of the present review consists in structuring and critically correlating the available literature concerning natural pigments, foam/puff printing systems, and ecological textile substrates. The analysis highlights the principal limitations, material–process interactions, and research gaps that should be considered in future experimental studies aimed at assessing the feasibility, reproducibility, and potential industrial application of sustainable three-dimensional textile printing systems.

Critical Analysis and Interpretation of the Reviewed Literature

The critical analysis of the reviewed literature indicates that three-dimensional foam/puff printing with natural pigments on ecological textile substrates involves complex interactions between formulation characteristics, processing conditions, and substrate properties. Rather than representing experimentally obtained results, the findings discussed in this section constitute a synthesis and interpretation of relationships reported across the specialized literature.

Regarding printing paste formulation, the reviewed studies indicate that the relative proportions and interactions between pigment, polymer binder, and expanding components may influence paste stability, pigment dispersion, deposition behavior, and subsequent expansion. Rheological properties are particularly relevant because they affect the flow and deposition of the paste onto the textile substrate. However, the magnitude and direction of these effects depend on the specific formulation and processing conditions, limiting the direct transfer of conclusions between different printing systems (El-Kashouti *et al.*, 2019).

Natural pigments represent a further source of variability. The literature reports limitations related to color stability, sensitivity to environmental factors,

and compatibility with polymer-based printing matrices. These characteristics may influence color reproducibility, pigment dispersion, and the stability of the printed layer, particularly under thermal or light exposure. However, the reported behavior varies according to pigment type, chemical composition, formulation, and processing conditions; therefore, general conclusions cannot necessarily be extended to all natural pigments (Negi, 2025; Egelkamp *et al.*, 2025).

With respect to foam/puff expansion, the reviewed literature emphasizes the combined influence of formulation characteristics and thermal processing conditions. Temperature and activation duration may affect the degree of expansion and the subsequent stabilization of the three-dimensional structure (Bošnjaković *et al.*, 2022; Cheung and Choi, 2023). This interaction represents an important challenge for reproducibility because processing conditions optimized for one formulation cannot necessarily be considered directly applicable to another. The literature therefore supports the need for formulation-specific optimization rather than the adoption of universal thermal parameters.

Substrate characteristics introduce an additional source of variation. Natural cellulosic fibers such as flax and hemp may differ in morphology, porosity, surface characteristics, and absorption behavior, potentially affecting paste penetration and distribution within the textile structure. These characteristics may influence the development and uniformity of the resulting three-dimensional profile. Compared with more structurally uniform substrates, the variability associated with natural fibers may therefore require additional consideration when assessing printing performance (Tri and Bahari, 2023).

At the process level, parameters such as squeegee conditions, printing speed, screen characteristics, deposited layer thickness, and thermal treatment interact with one another. The literature suggests that considering these parameters independently may not adequately describe their combined influence on the final printed structure (El-Kashouti *et al.*, 2019). From an industrial perspective, this multi-parameter dependence may complicate process standardization and quality control. In addition, the adoption of sustainable materials may require adjustments to existing production procedures and may involve additional considerations related to cost, equipment compatibility, and process reproducibility (Muthu and Gardetti, 2020).

A comparison of the reviewed literature indicates that the principal challenges are interconnected rather than attributable to a single material or processing variable. Pigment stability and polymer compatibility influence formulation behavior; formulation characteristics interact with thermal activation; and substrate morphology affects paste distribution and the development of the three-dimensional structure. This interdependence helps explain why standardized processing conditions remain difficult to establish across different natural pigments, printing formulations, and textile substrates.

An important limitation of the present analysis is the heterogeneity of the available literature. The reviewed studies differ in terms of pigment sources,

polymer systems, textile substrates, printing conditions, and evaluation methods. Consequently, direct quantitative comparison of reported findings is limited, and the relationships identified in the literature should be interpreted as system-dependent rather than universal. Furthermore, the absence of experimental validation for the specific combination of natural pigments, CHT printing systems, and flax or hemp substrates considered in this study prevents definitive conclusions regarding their actual performance under industrial conditions.

From an industrial perspective, the literature suggests that the transition toward sustainable foam/puff printing should focus not only on the substitution of synthetic colorants with natural pigments, but also on the compatibility between formulation, printing equipment, thermal processing, and textile substrate. Standardization of raw materials, formulation procedures, processing conditions, and evaluation methods may therefore represent an important prerequisite for improving reproducibility and assessing scalability.

Overall, the reviewed evidence supports the potential of natural pigments for application in three-dimensional textile printing while simultaneously highlighting significant limitations related to stability, formulation compatibility, process control, reproducibility, and industrial scalability. These findings should be regarded as conclusions derived from the critical analysis of the literature rather than as experimentally validated results. Further experimental research is required to determine the behavior of specific natural pigment–CHT–textile combinations and to establish processing conditions suitable for reproducible industrial application.

3. Conclusions

The critical review of the specialized literature concerning the use of natural pigments in three-dimensional foam/puff printing on ecological textile substrates allows for the formulation of general conclusions regarding material behavior, processing conditions, and the main challenges associated with process reproducibility and industrial implementation.

The reviewed literature indicates that natural pigments may exhibit variable behavior depending on their chemical composition, formulation, and processing conditions. Compared with synthetic pigments, they may present limitations related to color stability and sensitivity to environmental and thermal factors. Their compatibility with polymer-based printing systems may also influence pigment dispersion, color uniformity, and the reproducibility of the resulting printed structures.

The literature analysis further indicates that foam/puff printing performance is strongly influenced by technological parameters, particularly activation temperature and treatment duration. Variations in these parameters may affect the degree of expansion and the structural stability of the resulting three-dimensional layer. Consequently, precise control of thermal processing

conditions represents an important requirement for achieving consistent results, while the optimal conditions remain dependent on the specific printing formulation and substrate.

Substrate characteristics also play an important role in the behavior of foam/puff printing systems. Natural cellulosic substrates such as flax and hemp may exhibit variations in morphology, porosity, and absorption capacity, which can influence paste penetration and distribution. These characteristics may contribute to differences in the uniformity and development of three-dimensional printed structures.

From a system-level perspective, printing performance cannot be attributed to a single material or processing parameter. Instead, it results from the interaction between paste formulation, pigment properties, textile substrate characteristics, and technological conditions. Rheological behavior, layer deposition, thermal activation, and substrate–paste interactions therefore need to be considered together when assessing the potential of sustainable foam/puff printing systems.

Overall, the literature supports the potential of natural pigments for application in foam/puff printing on ecological textile substrates, while also highlighting significant limitations related to color stability, formulation compatibility, process control, reproducibility, and industrial scalability. These limitations indicate the need for further experimental research aimed at validating specific natural pigment–CHT–textile combinations, optimizing printing formulations and processing conditions, and establishing standardized operating ranges suitable for reproducible industrial application.

The main contribution of the present work therefore lies in providing a structured critical synthesis of the available literature and in identifying the principal material, technological, and process-related factors that should be considered in future experimental investigations of sustainable three-dimensional textile printing.

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O ANALIZĂ A LITERATURII DE SPECIALITATE PRIVIND IMPRIMAREA
TRIDIMENSIONALĂ DE TIP FOAM/PUFF A MATERIALELOR TEXTILE DIN IN
ȘI CÂNEPĂ CU PIGMENȚI NATURALI ȘI SISTEME DE IMPRIMARE CHT

(Rezumat)

Datorită cererii tot mai mari de tehnologii textile sustenabile, acest studiu investighează potențialul imprimării tridimensionale cu spumă/puf pe substraturi textile ecologice utilizând paste de imprimare CHT (Tubiscreen și Print Perfect) combinate cu pigmenți naturali. Bazată exclusiv pe o analiză cuprinzătoare a literaturii de specialitate și o analiză conceptuală, cercetarea identifică formulări și condiții de procesare adecvate pentru fibrele celulozice, în special în și cânepă. Analiza se concentrează pe mecanismele de dilatare termică, stabilizarea polimer-liant, temperatura de procesare și timpul de activare, precum și interacțiunile pastă-substrat. Constatările din literatura de specialitate indică faptul că pigmenții naturali reprezintă o cale promițătoare către o imprimare textilă tridimensională mai sustenabilă, cu toate acestea, aplicarea lor rămâne constrânsă de stabilitatea limitată a culorii, incompatibilitatea pigment-polimer și reproductibilitatea insuficientă a procesului. Mai mult, caracteristicile structurale ale fibrelor naturale pot afecta semnificativ aderența, uniformitatea suprafeței și stabilitatea volumetrică. Constatările subliniază importanța critică a optimizării sistematice a compoziției formulării și a parametrilor de procesare prin investigații experimentale pentru a asigura reproductibilitatea, durabilitatea și scalabilitatea pentru rezultate potențial scalabile la nivel industrial.